THE STRATIGRAPHY AND SEDIMENTOLOGY OF THE UPPER JURASSIC AND LOWER CRETACEOUS ROCKS OF NORFOLK

by

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1983

Thesis submitted for the degree of Doctor of Philosophy of the University of London and for the Diploma of Membership of the Imperial College.

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ABSTRACT

The Upper Jurassic and Lower Cretaceous rocks of Norfolk crop out in a strip of low-lying ground 20 to 40 km in width running through the western part of the county from Hunstanton to the River Little Ouse, a distance of about 60 km. They are composed almost entirely of soft mudstones and loose sands and are deeply weathered at outcrop; there is only one natural exposure (Hunstanton cliffs) in the area. Much of the outcrop is concealed beneath the thick Holocene deposits of Fenland and The Wash or beneath Pleistocene deposits. However, the structure of the area is simple and this has enabled the stratigraphy to be worked out by means of a field survey and continuously cored boreholes. The sequence falls naturally into three parts - the almost wholly argillaceous Upper Jurassic Kimmeridge Clay and Lower Cretaceous Gault separated by the predominantly arenaceous top Jurassic - Lower Cretaceous Sandringham Sands, Dersingham Beds, Roach and Carstone.

The Kimmeridge Clay of Norfolk is largely composed of mudstones, calcareous mudstones and oil shales, and has a rich marine fauna that includes ammonites, bivalves, brachiopods, crinoids, serpulids, foraminifera, ostracods, coccoliths, dinoflagellates, crustaceans, fish and marine reptiles, and land-derived plants. Variations in the local stratigraphy, the mineralogy of the formation and its lithological and faunal associations suggest that it was deposited on a broad marine shelf, in warm, relatively shallow, quiet water, close to a land area (the London Platform) composed predominantly of argillaceous Palaeozoic rocks. Rhythmic variations in the sequence suggest that the early stages of deposition were marked by transgression, and the later stages by stillstand or regression.

Widespread, earth-movements occurred in the late Jurassic in north-west Europe; these were related to the separation of Europe and Africa from the Americas. In Norfolk, they caused the Kimmeridge Clay to be uplifted and eroded; the amount of erosion is greatest adjacent to the London Platform and declines northwards away from its margin.

Marine conditions returned to Norfolk in the latest Jurassic (Volgian) but gave rise to predominantly arenaceous sediments; this change probably reflects a rejuvenation of the land areas that supplied the siliciclastic fraction of the Kimmeridge Clay. The succeeding Lower Cretaceous deposits are composed largely of variable amounts of sand, clay and chamosite (and limonitized chamosite) oolite with lesser amounts of glauconite, pebbles and siderite mudstone. The lithologies, sedimentary features and faunas indicate deposition in a variety of shallow, near-shore marine environments. Renewed earth-movements occurred in the mid Cretaceous (Aptian and Albian) but, although they caused considerable erosion of the Lower Cretaceous sequences close to the London Platform, they probably had little effect on sedimentation in Norfolk. Argillaceous sediments, closely similar to the Kimmeridge Clay, were deposited in the area in the late mid Cretaceous (Albian) in response to the final denudation and inundation of the London Platform.

ACKNOWLEDGEMENTS

This thesis has been prepared under the University of London scheme for persons working at Public Research Institutions and is based on work carried out by the author in his capacity as a Principal Scientific Officer at the Institute of Geological Sciences. Dr P.A. Sabine, D.Sc., ARCS, FRSE C. Eng., FIMM of the Institute has acted as Supervisor and Dr G. Evans, Ph.D., DIC of the Geology Department, Imperial College has acted as Director of Studies for the work.

In any study such as this it is inevitable that some conflict of interest arises between the research and official work of the author due to the changing pressures which affect governmental research stations. In the present case this conflict has been small because the stratigraphical and sedimentological research element has been maintained throughout the projects which have provided the data for this thesis. These are the geological survey of west Norfolk, a study of the stratigraphy and engineering properties of the Upper Jurassic clays for the Wash Water Storage Feasibility Study and a study of the stratigraphy and sedimentology of oil-shale occurrences in the Kimmeridge Clay.

The primary six-inch geological survey carried out by the author for parts of the Institute's 1:50,000 Geological Sheets 129 (The Wash), 145 (King's Lynn) and 159 Wisbech) covers more than 300 sq km (Fig. 1) and included the drilling of six continuously cored stratigraphical boreholes. Part of the Upper Jurassic - Lower Cretaceous outcrop on the King's Lynn Sheet was surveyed by a colleague, Mr B. Young, B.Sc., under the author's supervision. Reconnaissance field work and drilling was also carried out to prepare a provisional edition of Geological Sheet 173 (Ely) using the soil maps of Mr R.S. Seale, B.Sc. of the Soil Survey of England and Wales as the basis for the exposed geological boundaries. This last named work

has enabled the author to examine the remainder of the outcrop of the Upper Jurassic and Lower Cretaceous rocks in Norfolk.

Thirty continuously cored boreholes were drilled through all or part of the Kimmeridge Clay and two through the Lower Cretaceous, as part of the site investigation for the Wash Feasibility Study. Continuously cored boreholes were also drilled through the whole of the Kimmeridge Clay in Norfolk and through the oil-shale-rich parts of the formation elsehwere in England as part of a study of Kimmeridgian oil shales. The stratigraphical interpretation of some of these boreholes has been made in collaboration with Dr B.M. Cox, Ph.D. and Mr A.A. Morter, B.Sc. who have identified the Kimmeridgian and Lower Cretaceous faunas respectively.

The author has enjoyed the collaboration of a number of other specialist colleagues in the Institute, notably Dr R. Casey, D.Sc., F.R.S. and Dr A.W. Medd, Ph.D. of the Palaeontology Department. The results of X-ray diffraction analyses made by Mr R.J. Merriman, B.Sc. and Mr G.E. Strong, B.Sc. of the Petrographical Department for the Wash Feasibility Study and the Oil-Shale Project are quoted in the present work. So too are the results of various analyses of oil shales made by Mr D.M. Green, B.Sc. and Mr E.C. Hunt, B.Sc. of the Laboratory of the Government Chemist for the same projects. Dr C.V. Jeans, M.A., Ph.D. (Cambridge) and Dr P.F.V. Williams, Ph.D. (Newcastle University) have generously provided data on the clay mineralogy of the Lower Cretaceous and the organic chemistry of oil shales respectively. References are made in the text to work carried out in collaboration with these specialists; in most cases the results are published and the publications are quoted.

Part of the work on the Kimmeridge Clay was carried out on a re-payment basis for the former Water Resources Board as part of the Wash Feasibility Study. The author gratefully acknowledges the assistance received during site work from the Board's staff, their consulting engineers Messrs. Binnie and Partners and their drilling contractors. Boreholes were drilled in The Wash for stratigraphical purposes and in association with the feasibility study, by the Wimpey drilling ship m.v. Whitethorn under the supervision of Dr C.D. Evans, Ph.D. and Dr R.T.R. Wingfield, Ph.D. of the Institute's Continental Shelf Unit. The onshore stratigraphical boreholes were drilled by the Institute's drilling rig under the supervision of Mr S.P. Thorley. Miss M.B. Simmons, B.Sc. of the Institute's Mineral Assessment Unit and Mr J. Dangerfield, B.Sc. of the Petrographical Department assisted with the oil-shale project and their help is gratefully acknowledge.

The author is also indebted to all the landowners who gave permission for access to their lands in Norfolk, and to the support staff in the Institute and contracting firms, without whose help the work would not have been possible.

CONTENTS

	Page No.
CHAPTER 1. INTRODUCTION	1
CHAPTER 2. KIMMERIDGE CLAY	7
2.1. History of research	7
2.2. Lithology and palaeontology and their relationship	25
2.2.1. Lithology	25
2.2.1.1. Clay minerals	33
2.2.1.2. Quartz	46
2.2.1.3. Calcium carbonate	50
2.2.1.4. Kerogen	54
2.2.1.5. Pyrite, phosphate and other minerals ..	58
2.2.1.6. Mudstones	67
2.2.1.7. Limestones	72
2.2.1.8. Oil shale	92
2.2.2. Palaeontology	100
2.2.2.1. Introduction	100
2.2.2.2. Ammonites	109
2.2.2.3. Bivalves	129
2.2.2.4. Brachiopods and other invertebrates ..	135
2.2.2.5. Microfauna and microflora	142
2.2.2.6. Plants and vertebrates	145
2.2.2.7. Trace fossils	146
2.2.2.8. Calcispheres	152
2.2.3. Faunal and lithological associations ..	154
2.3. Stratigraphy	161
2.3.1. Introduction and methods	161

Page No.

2.3.1.1. Faunal and lithological features .. 164

2.3.1.2. Geophysical logging.. 170

2.3.2. Norfolk outcrop and subcrop 183

2.4. Depositional environments 201

2.4.1. Introduction 201

2.4.2. Evidence for palaeogeography 203

2.4.3. Sources of clastic materials 212

2.4.3.1. Clay minerals 212

2.4.3.2. Calcium carbonate 226

2.4.3.3. Phosphate, pyrite and quartz .. 229

2.4.4. Faunal and floral evidence 231

2.4.4.1. Introduction 231

2.4.4.2. Origin of the mudstones 232

2.4.4.3. Origin of the oil shales 237

2.4.5. Rhythmic sedimentation 249

2.4.6. Concluding remarks 257

CHAPTER 3. LATE JURASSIC EARTH MOVEMENTS 260

3.1. Introduction 260

3.2. Norfolk 262

CHAPTER 4. TOP JURASSIC - LOWER CRETACEOUS.. 273

4.1. Introduction and history of research .. 273

4.2. Sandringham Sands 285

4.2.1. Introduction 285

4.2.2. Roxham Beds 293

4.2.3. Runcton Beds 304

4.2.4. Mintlyn Beds 311

4.2.5. Leziate Beds 325

Page No.

4.3. Dersingham Beds 348

4.4. Roach 368

4.5. Skegness Clay, Sutterby Marl and Woburn Sands.. 379

4.6. Carstone, Red Chalk and Gault 392

4.6.1. Introduction 392

4.6.2. Carstone 401

4.6.3. Red Chalk 421

4.6.4. Gault 434

4.7. Depositional environments 450

4.7.1. Evidence for palaeogeography 451

4.7.2. Sources of sedimentary components 452

4.7.2.1. Pebbles 452

4.7.2.2. Heavy minerals and quartz sand.. .. 458

4.7.2.3. Clay minerals 462

4.7.2.4. Chamosite and siderite 463

4.7.2.5. Glauconite 466

4.7.2.6. Phosphate.. 468

4.7.3. Summary of geological history 469

CHAPTER 5. CONCLUDING REMARKS 485

BIBLIOGRAPHY 488

LIST OF FIGURES

1. Geological sketch map of the area described in the thesis.
2. Map showing the Kimmeridge Clay outcrop and land area subcrop and the position of the study area.
3. Sites of boreholes drilled for oil-shale exploration in Norfolk in 1916 - 23.
4. Sites of boreholes drilled by IGS and for the Wash Feasibility Study.
5. Generalized Kimmeridge Clay rhythms.
6. Diagrammatic representation of the bulk chemistry of some of the more distinctive Kimmeridge Clay lithologies.
7. X-ray diffractograms of typical Kimmeridge Clay samples from Norfolk.
8. Van Krevelen diagram showing variation of atomic H/C and O/C ratios for kerogens of differing origins.
9. Relationship of mineralogy to potential oil yield in the North Runcton Borehole.
10. Generalized vertical section of the Kimmeridge Clay of Norfolk showing the distribution of lithologies.
11. Examples of glacially-filled valleys in which the shape of the subglacial surface appears to be controlled by limestones in the Kimmeridge Clay.
12. Distribution of coccolith-rich bands on the Kimmeridge Clay.
13. Correlation of coccolith-rich bands close to the eudoxus-autissiodorensis zonal boundary.
14. Sites of the continuously cored boreholes drilled for the oil-shale projects.
15. Distribution and thickness of oil-shale seams in the North Runcton Borehole.

16. Relationship of oil-shale seams to potential oil yield in the North Runcton Borehole.

17. Correlation of the oil-shale-rich bands in the Kimmeridge Clay of the pilot study boreholes with those in the Dorset type section.

18. Correlation of the oil shales in the boreholes drilled for the oil-shale projects.

19. Relationship of density of sample to potential oil yield for oil shale/mudstone mixtures from the North Runcton and Donington on Bain boreholes.

20. Volume of observed oil shale plotted against potential oil yield.

21. Generalized vertical section of the Kimmeridge Clay of Norfolk showing ammonite ranges and faunal marker bands.

22. Graphic log of part of the North Wootton Borehole showing bed classification and the main lithological and faunal features.

23. Relationship of the total gamma-ray log to lithology for the Kimmeridge Clay of the IGS Hunstanton Borehole.

24a. Correlations between the gamma-ray logs of the Kimmeridge Clay in the Skegness, Hunstanton, Gayton and Marham boreholes.

24b. Stratigraphical correlations between the four boreholes in Fig. 21a based on gamma-ray logging and lithological marker bands.

25. Comparison of gamma-ray and lithological correlations for Type A rhythms in the basal beds (Beds 1 to 8) of the Kimmeridge Clay.

26. Gamma-ray correlations for the whole of the Kimmeridge Clay between the North Runcton, North Wootton and Hunstanton No. 1 boreholes.

27. Geological sketch map showing the outcrop of the Kimmeridge Clay in Norfolk and the positions of measured sections.

28. Structure contours on the base of the Kimmeridge Clay in the Fenland part of Norfolk.

29. Geological section between Terrington Marsh and Denver Sluice.

30. Distribution of the Kimmeridge Clay in Norfolk: its outcrop and subcrop and the positions of deep boreholes referred to in the text.

31. Isopachytes for the preserved Kimmeridge Clay of the English land area.

32. Attenuation in the Lower Kimmeridge Clay between the southern part of the Wash (Bh. 513) and Denver Sluice (Bh. 1).

33. Attenuation in part of the Lower Kimmeridge Clay between North Wootton (Bh. 23), Denver Sluice (Bh. 1) and Roslyn Hole, Ely.

34. Attenuation and facies change in the Lower Kimmeridge Clay between Denver Sluice (Bh. 1) and Mundford (Bh. C).

35a. Correlation of the Lower Kimmeridge Clay sequences of the Dorset coast and the Warlingham Borehole with that of Norfolk.

35b. Correlation of the Upper Kimmeridge Clay sequences of the Dorset coast and the Warlingham Borehole with that of Norfolk.

36. Distribution of lithologies in the English Kimmeridge Clay in the cymodoce and pectinatus zones.

37. Postulated isopachytes for the original depositional thickness of the Kimmeridge Clay in southern Britain.

38. Geometrical construction to estimate the original depositional limit of the Kimmeridge Clay in south-west Norfolk.

39. Palaeogeography of the North Atlantic and N.W. Europe in mid Kimmeridgian times.

40. Palaeogeography of southern Britain in mid Kimmeridgian times.

41. Formation of detrital clay minerals.

42. Distribution of preserved Jurassic rocks in Norfolk.

43. Diagrammatic section showing the relationship of the Kimmeridge Clay mudstone associations to their presumed environments.

44. Possible models for the depositional environment of oil shales in the Kimmeridge Clay.

45. Large-scale argillaceous rhythms in the English Upper Jurassic.

46. Suggested mechanisms to explain the three types of Kimmeridge Clay rhythm.

47. Hypothetical representation of land/sea-level movements during deposition of the Kimmeridge Clay.

48. Isopachytes for selected intervals in the Ampthill Clay in west Norfolk.

49. Attenuation in the upper part of the Ampthill Clay and the overstep of the Kimmeridge Clay in west Norfolk.

50. Age of the youngest Kimmeridge Clay preserved beneath the Sandringham Sands, Woburn Sands or Norfolk Carstone.

51. Geological sketch map of south-west Norfolk showing the lines of section in Fig. 52.

52. Geological sections showing the overstep of the Woburn Sands and the Norfolk Carstone across folded Upper Jurassic strata in south-west Norfolk, west Suffolk and north Cambridgeshire.

53. A possible late Jurassic fault at North Runcton.

54. Correlation of the late Jurassic to mid Cretaceous sequences of Norfolk and Lincolnshire with those elsewhere in England.

55. Key localities and boreholes in the top Jurassic - Lower Cretaceous of Norfolk and The Wash.

56. Stratigraphical relationships of the top Jurassic - Lower Cretaceous formations of Norfolk to one another. Top of Kimmeridge Clay taken as arbitrary datum.

57. Geological sketch section along the line of the No. 4 gas-feeder-main trench between West Winch and Middleton.

58. Graphic section of the Roxham Beds sequence in the Gayton Borehole.

59. Geological sketch map of the Sandringham Sands outcrop in the King's Lynn area showing the positions of key sections referred to in the text.

60. Correlations between the Roxham Beds sequences in Norfolk.

61. Comparative sections showing the time occupied by the late Jurassic erosional gap in Lincolnshire and Norfolk.

62. Correlations between the Runcton Beds sequences in Norfolk.

63. Correlations between the Jurassic - Cretaceous boundary beds exposed in trenches at Brook Farm, North Runcton.

64. Correlations between the more complete Mintlyn Beds sequences in Norfolk.

65. Sketch map of the Leziate Beds outcrop and subcrop showing the positions of localities referred to in the text.

66. Correlations between the more complete Dersingham Beds sequences in Norfolk.

67. Correlation of generalized rhythms in the early Barremian sediments of the Wash area (not to scale).

68. Correlation between the Tealby Beds sequences in IGS Boreholes 72/77 and 72/78.

69. Graphic section showing the beds adjacent to the Roach-Carstone junction proved in trenches on Hunstanton beach.

70. Correlations between the Roach sequences in the Wash area.

71. Correlation of the Barremian to Albian sequence in the Skegness Borehole with that proved at Sutterby.

72. Correlations between the Aptian sequences of the Wash area, showing the ammonite faunas recorded to date.

73. Relationship of late Jurassic and early Cretaceous unconformities in south-west Norfolk and north-west Suffolk.

74. Sketch map showing the age of the strata on which the Carstone rests.

75. Geological sketch map of Hunstanton beach showing Carstone outcrops (based on 1972 air photographs) and sites of trenches.

76. Lithological comparison of the basal beds of the Carstone on Hunstanton beach with those in the Hunstanton Borehole.

77. Correlation of selected Albian sequences between Hunstanton and Mundford, south-west Norfolk.

78. Lithological comparison of Aptian and Albian sequences in the Wash area.

79. Generalized rhythms for the Red Chalk in the Skegness Borehole.

80. Distribution of the Gault and Red Chalk in East Anglia.

81. Lithological comparison of the highest Carstone and Red Chalk sequences in Hunstanton cliffs and the Hunstanton Borehole.

82. Correlations between the Albian sequences in the northern part of East Anglia.

83. Idealized rhythm for the Gault of East Anglia.

84. Generalized vertical section for the Gault of East Anglia.

85. Diagrammatic correlation of erosion surfaces in the upper part of the Lower Gault between Gayton and Mundford.

86. Geographical distribution of lithologies at selected times in the early to mid Cretaceous.

87. Cross-bedding orientations in the Leziate Beds (after Schwartzacher, 1953).

88. Reconstruction of the presumed depositional environment in the northern part of East Anglia immediately prior to the Upper Albian transgression.

89. Presumed maximum extensions of the late Jurassic to mid Cretaceous formations onto the northern edge of the London Platform.

LIST OF PLATES

1. Oil-shale workings at Setchey, c 1920.
2. Large-scale lithological variations in the Kimmeridge Clay.
3. Electron micrographs of mudstone textures.
4. Phosphate, pyrite and quartz.
5. Electron micrographs of calcispheres.
6. Selected kerogen components from the Kimmeridge Clay.
7. Secondary gypsum in Kimmeridge Clay cores.
8. Mudstone textures at natural size.
9. Cementstones in the Kimmeridge Clay.
10. Examples of coccolith-rich bands.
11. Comparative sizes of selected fossils in the Kimmeridge Clay.
12. Rasenia.
13. Aulacostephanus.
14. Pectinatites and Propectinatites.
15. Amoeboceras (Amoebites) and Amoeboceras (Nannocardioceras).
16. Laevaptychus, Sutneria and bivalves.
17. Brachiopods, echinoderms, crustaceans, serpulids and vertebrate fragments.
18. Burrows.
19. Sandringham Sands sections and scenery.
20. Details of the basal cemented bed of the Roxham Beds.
21. Type section of the Leziate Beds.
22. Sedimentary structures in the Leziate Beds.
23. Electron micrographs of solution features on Leziate Beds sand grains.
24. Electron micrographs of siliceous concretions in the Leziate Beds.
25. Sandringham Sands and Dersingham Beds; lithologies and features.
26. Roach and Carstone lithologies.
27. Carstone mineralogy and textures.

28. Sedimentary structures in the Carstone.

29. Red Chalk sequences in the Trunch Borehole and at Hunstanton.

30. Selected Lower Cretaceous lithologies.

CHAPTER 1

INTRODUCTION

Throughout the Jurassic period much of north-west Europe was occupied by a shallow, shelf sea. At times, variable sequences of clay, sand and limestone, such as the Great Oolite Series, Corallian Beds and Portland Beds, were deposited in this sea; at other times, relatively uniform clays such as the Lias, Oxford Clay and Kimmeridge Clay were deposited. In the late Jurassic, earth-movements associated with the early stages of the separation of the European and American plates and the opening of the Atlantic Ocean, caused major changes in the geography and pattern of sedimentation in the region. In eastern England, the London Platform, a Caledonian massif which had probably given rise to low-relief land during much of the Jurassic, was re-activated in the late Kimmeridgian with the result that the deposition of the thick clay sequence of the Oxford Clay, West Walton Beds, Ampthill Clay and Kimmeridge Clay was followed by erosion and then by predominantly arenaceous deposition in the latest Jurassic and early Cretaceous.

At no time in the British Mesozoic did tectonic activity cause such a profound and widespread change in sedimentation as in the late Jurassic, and nowhere can this change be better studied at outcrop than in Lincolnshire and Norfolk. The present work aims to provide a stratigraphical account of the Upper Jurassic (Kimmeridgian and Volgian) and Lower Cretaceous (Ryazanian to Albian) rocks of Norfolk (Table 1) and to trace, by means of their faunal and sedimentary features, the changes in depositional environment that occurred during that period.

This thesis describes the solid geology of the eastern part of

System	Stage	Formation		Relevant section of thesis
Upper Cretaceous (pars)	Cenomanian	Lower Chalk		not covered by thesis
Lower Cretaceous	Albian	Red Chalk, Gault, Carstone		Chapter 4
		Mid Cretaceous earth-movements		
	Aptian	Sutterby Marl, Skegness Clay Woburn Sands		
	Barremian	Roach		
	Hauterivian	Dersingham Beds (incl. Snettisham Clay)		
	Valanginian	Leziate Beds	Sandringham Sands	
	Ryazanian	Mintlyn Beds		
Upper Jurassic (pars)	Volgian	Roxham Beds; Runcton Beds		
		Late Jurassic earth-movements		Chapter 3
	Kimmeridgian	Kimmeridge Clay		Chapter 2
	Oxfordian	Oxford Clay (pars); West Walton Beds; Ampthill Clay		not covered by thesis

Table 1. Generalized table of strata showing the stratigraphical relationships of formations referred to in this thesis. Minor unconformities omitted.

The Wash, much of the fenland of Norfolk and a narrow strip of upland, up to 10 km in width, that lies between the eastern edge of Fenland and the Chalk escarpment (Fig. 1). The scenery of the area can be divided into two distinct types, both related to the geology. The low-lying area of Fenland and The Wash is underlain by Upper Jurassic clays that are now mostly concealed by Quaternary deposits; the upland, which itself has a maximum relief of less than 40 m, is made up of a series of small escarpments formed by predominantly arenaceous Lower Cretaceous deposits.

The Kimmeridge Clay is the oldest formation that crops out in Norfolk; all but the highest part of its outcrop is obscured by Pleistocene and Recent deposits. Its stratigraphy has therefore been studied in cored boreholes drilled for mineral exploration and site investigation. At any given stratigraphical level the formation is relatively uniform in lithology over large areas of southern England and the Norfolk outcrop is too small for regional trends to be determined. The stratigraphy of the Norfolk outcrop has therefore been compared with that of the Dorset type section and with that proved in cored boreholes elsewhere in England to determine which features, both faunal and lithological, can be used to interpret the palaeogeography and depositional environments.

The outcrop of the latest Jurassic to early Cretaceous deposits (Sandringham Sands to Gault) in Norfolk is less drift-covered than that of the Kimmeridge Clay. However, these sediments are soft, usually deeply weathered and for the most part poorly exposed. They are laterally variable in lithology and their stratigraphy can only be deduced by combining the evidence from geological surveys, exposures and cored boreholes. Most of the outcrop in Norfolk has

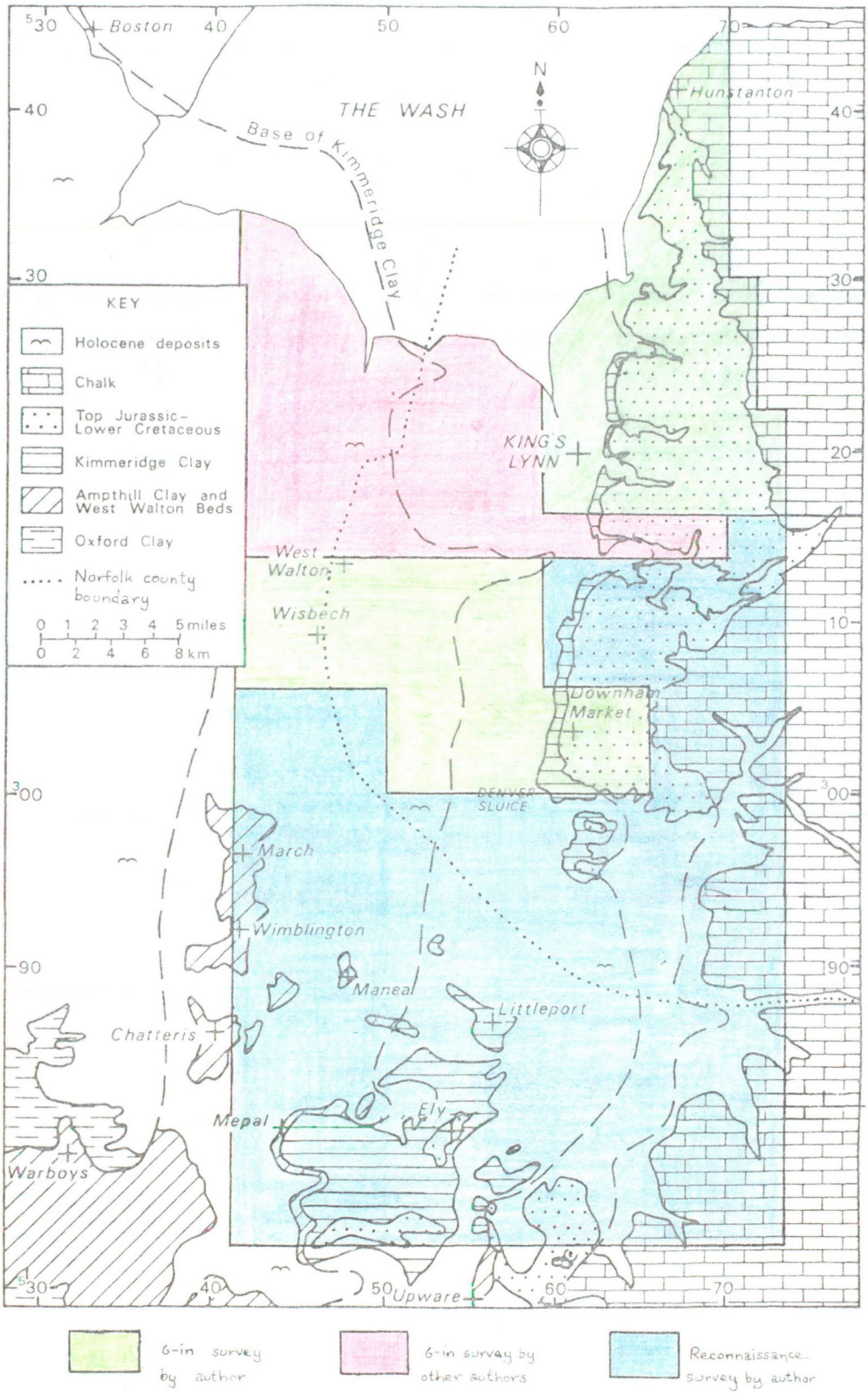


Figure 1. Sketch map of the solid geology of the area described in the thesis, showing areas surveyed by the author and by other authors.

been surveyed by the author on the scale of six inches to the mile (Fig. 1 and published 1 to 50,000-scale Geological Sheets 129/145 and 173). During this survey stratigraphical data were collected from quarries and temporary sections in road-works, gas pipeline trenches and purpose-dug trenches. Six continuously cored boreholes were drilled to obtain additional stratigraphical data from these beds.

The geology of west Norfolk, particularly the Sandringham Sands and Red Chalk, attracted the attention of several early geologists. Notable among these were William Smith, who delineated the Kimmeridge Clay and several of the Lower Cretaceous formations on his map of Norfolk (1819), and Woodward (1833) and Rose (1835-6) who produced the first systematic accounts of the geology of the county. Additional contributions to the stratigraphy of particular parts of the Lower Cretaceous formations were made by Taylor (1823), Fitton (1836), Wiltshire (1859, 1869), Seeley (1861 and 1864 a & b), Rose (1862, 1867), Lowe (1869), Teall (1875), Harmer (1877) and Keeping (1883), mostly within the framework of Rose's (1835-6) more general account.

The first comprehensive account of the geology of the Lower Cretaceous rocks was provided by the Geological Survey memoirs and one-inch maps, the area being covered by parts of Old Series Sheets 69 (map 1886; memoir by Whitaker and Jukes-Browne, 1899) and 65 (map 1886; memoir by Whitaker et al., 1893). These maps and memoirs clearly defined the main stratigraphical units of the area for the first time and form the basis for the modern classification. Because of the poorly exposed nature of the ground little work was done on the Upper Jurassic and Lower Cretaceous rocks between the time of the old one-inch survey and the modern six-inch survey.

The Kimmeridge Clay was the subject of an extensive drilling programme in Norfolk between 1916 and 1923 when its potential as a source of shale oil was explored, but there is little geological record of this work other than two accounts by Forbes-Leslie (1917a, 1917b) which give misleading data. An account of the stratigraphy of three oil-exploration boreholes in south-west Norfolk, based on limited sampling, was given by Pringle (1923), and this has remained the only attempt at a systematic description of the stratigraphy of the Kimmeridge Clay of the area until the present work.

The most important work on the latest Jurassic and earliest Cretaceous rocks of Norfolk (Sandringham Sands) has been that carried out in 1961 to 1972 by Dr R. Casey. His study of the ammonite sequences of the beds adjacent to the Jurassic-Cretaceous boundary (1961a, 1963, 1973) has provided a clear understanding of the relationship of that part of the Norfolk sequence to rocks of similar age elsewhere in Britain and in Russia. Furthermore, he established (1973) a zonal scheme at this stratigraphical level (Volgian and Ryazanian) for the first time in Britain. This work stimulated studies of selected aspects of the non-ammonite fauna (Ager 1971; Kelly 1977; Pinckney 1978) and the flora (Creber, 1972). These, together with more general work relevant to the stratigraphy of the area, are discussed in the text.

CHAPTER 2

KIMMERIDGE CLAY

2.1 History of research

The Kimmeridge Clay was first recognised as a discrete division by William Smith on his map of 1815, where it was named in the table of strata as the Oaktree Soil. Subsequently (1817), he used the name Oaktree Clay for the clays lying between the 'Coral Rag and Pisolite' and the 'Portland Rock'. Webster (1816) provided the first descriptive details of the formation and changed the name to Kimmeridge Clay after Kimmeridge Bay in Dorset.

The Kimmeridge Clay has an outcrop and subcrop in England which extends from Dorset to North Yorkshire. It is poorly exposed inland and almost all our understanding of the stratigraphy of the formation has been made through study of the coastal sections between Weymouth and Swanage in Dorset and borehole sequences elsewhere. Fitton (1836) described the general faunal and lithological characters of the formation in the Dorset cliff sections and further details were added by Waagen (1865), Blake (1875), Woodward (1895) and Strahan (1898).

As with most Jurassic stratal terms, it can be argued that the original definition of the Kimmeridge Clay was that of a chronostratigraphical unit, in that it embraced a lithological and faunal assemblage bounded by what were believed to be isochronous surfaces. D'Orbigny (1842-1851, p. 610) introduced the term 'l'étage kimméridgien' to cover the interval of time during which the Kimmeridge Clay was deposited and in recent years most British workers have treated the terms Kimmeridge Clay and Kimmeridgian as if synonymous.

The first successful attempt to zone the formation on the basis

of ammonites was that of Salfeld (1913, 1914), although d'Orbigny (1842-9) and Oppel (1856-8) had earlier attempted to define the Kimmeridgian stage in terms of a mixture of bivalve and ammonite zones. The modern zonation is based largely on the works of Salfeld (1913, 1914), Ziegler (1961, 1962, 1964) and Cope (1967, 1978), but it has resulted from much discussion and the zones and their definitions incorporate observations made by Buckman (1922-6), Chatwin and Pringle (1922), Kitchin and Pringle (1923), Neaverson (1924, 1925), Spath (1925, 1931, 1935, 1936), Arkell (1933, 1945, 1947, 1956), Casey (1967), Callomon and Cope (1971), Birkelund et al. (1978) and Cox and Gallois (1981).

The boundaries of most of the Lower Kimmeridgian zones were not accurately defined in the published descriptions of the Lower Kimmeridge Clay in Dorset because the exposures are mostly isolated small sections that were poorly correlated. Taken together, they were used to establish an approximate stratigraphy. In modern terminology, these zones are range or assemblage biozones (biostratigraphical units) because they have been defined in terms of the ammonite fauna and are unrelated to the lithological sequence. They cannot, in theory, be used alone to define the Kimmeridgian Stage because 'stages' are now considered to be units of chronostratigraphy (Hedberg,1976). However, in fossiliferous marine clays such as the Kimmeridge Clay where correlations have been achieved in the past almost entirely by the use of fossils, the practical distinction between biostratigraphy and chronostratigraphy is slight. A recent reexamination of the Dorset sections has shown that many of the zonal boundaries are coincident with minor but widespread erosion surfaces that can be regarded as isochronous for all practical

purposes (Cox and Gallois, 1981).

The Kimmeridge Clay has an almost continuous outcrop running from Dorset to North Yorkshire via Wiltshire, Berkshire, Oxfordshire, Buckinghamshire, Cambridgeshire, Norfolk, Lincolnshire and Humberside (Fig. 2). Throughout this area the formation consists of soft mudstones, calcareous mudstones and kerogen-rich mudstones with coarser sediments locally present near the margins of the outcrop and subcrop at Abbotsbury, Dorset (early Kimmeridgian sandy ironstones), Devizes to Aylesbury (late Kimmeridgian sands), east Kent (early Kimmeridgian sandstones) and Elsham, Lincolnshire (early Kimmeridgian sandstones).

Away from the Dorset coast, the stratigraphy of local outcrops and the subcrop (in boreholes) has been compared with that of the type area by various workers, mostly in Geological Survey memoirs. Other accounts include that of the stratigraphy of the Kimmeridge Clay in the IGS Warlingham Borehole, Surrey by Callomon and Cope (1971), which added much to the overall understanding of the palaeontology of the formation and noted for the first time the importance of the ammonites Aspidoceras and Sutneria in the English Kimmeridgian succession. During recent years several Ph.D. studies have included work on particular aspects of the Kimmeridge Clay. Morris (1968) has discussed the ammonite faunas of the earliest part of the Kimmeridgian (Pictonia and Rasenia zones) of Scotland and Dorset; Brookfield (1973a, 1973b) has discussed the palaeonenvironments of the earliest part of the Kimmeridgian of Dorset; research on the chemistry and post-depositional history of cementstones (thin muddy limestones) in the Kimmeridge Clay in Dorset has recently been completed (Irwin, 1979 and Bellamy, 1982, in prep.). Mr I. Scotchman (IGS/Sheffield CASE student) is currently extending Dr Irwin's work

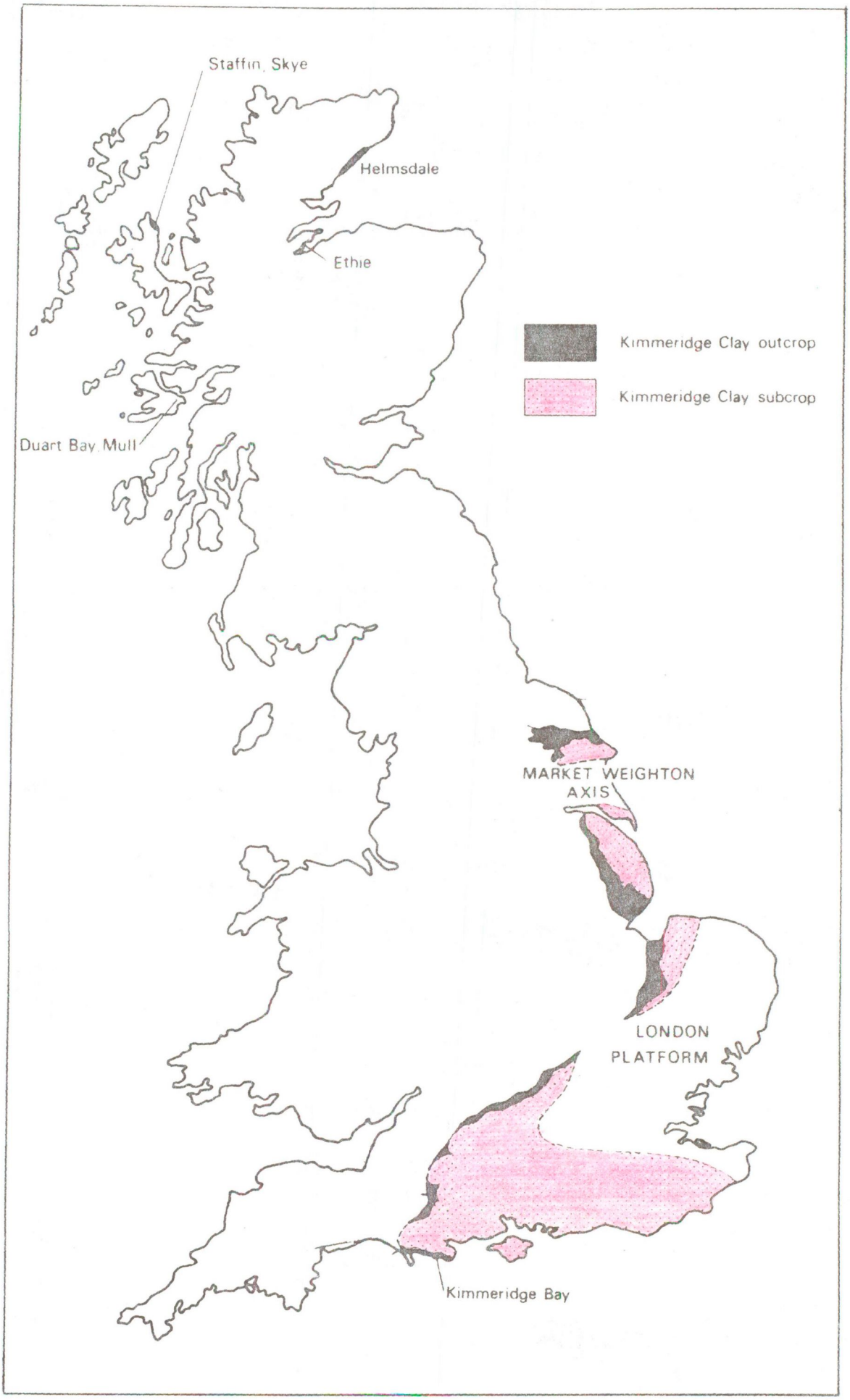


Figure 2. The onshore outcrop and subcrop of the Kimmeridge Clay.

on the chemistry of the cementstones to cover a wider geographical area and stratigraphical range within the formation.

Outcrops of Kimmeridge Clay occur in Scotland at Eathie, Cromarty (see Waterston, 1951 for summary); Helmsdale, Sutherland (see Linsley, 1972 for summary) and Staffin, Skye (see Anderson and Dunham, 1966 for summary), and there are extensive subcrops beneath the North Sea, English Channel, Western Approaches (including Bristol Channel) and the Hebridean Shelf. These areas include Kimmeridgian lithologies that are unknown in England and although their bearing on the interpretation of the Kimmeridgian geography of north-west Europe is referred to in Section 2.4, a discussion of these subcrops is beyond the scope of the present work.

The Kimmeridge Clay has had little economic value in the past. It has been used on a limited scale for brickmaking at many localities and most of the stratigraphical information obtained from the inland areas of England has come from small brickpits. Most of these are now completely degraded and, because of their geographical isolation from one another and from the Dorset coastal sections, the faunal and lithological material collected from them is stratigraphically useful only where the complete local sequence is known from continuously cored boreholes.

The most celebrated attempts to exploit the Kimmeridge Clay commercially have been those aimed at using thin seams of oil shale (kerogen-rich mudstone) as a fuel. The seams that crop out in the cliffs at Kimmeridge Bay, particularly the richest and thickest seam (the Blackstone), were probably used locally as a coal substitute continuously from the Iron Age to the 1930's (Arkell, 1947). During the 17th and 18th centuries these shales provided the fuel for an alum industry and later for glass making and a sea-salt works (Arkell, 1933).

Each of these ventures failed, but in the 19th century an oil-extraction works was set up and lubricating oil, pitch, naptha, paraffin wax and gas was produced by destructive distillation of the shales (Green, 1886; Strahan, 1918). These works were, however, short-lived because they were not competitive with contemporary Scottish oil-shale workings on account of the high sulphur content of the Kimmeridge Clay shale oil and the thinness of the seams.

In 1917-8 the Ministry of Munitions, stimulated by the submarine blockade of the First World War, drilled several boreholes at Kimmeridge and Portesham, Dorset and one at Donington on Bain, Lincolnshire to examine the oil shales. These boreholes, reported in Strahan (1920), provide useful stratigraphical information on the Kimmeridge Clay of inland Dorset and Lincolnshire. At about the same time,a large number of privately financed boreholes was drilled in Norfolk (see below) for the same purpose.

Details of the stratigraphy of the inland Kimmeridge Clay are given, area by area, in Arkell's classic account of the Jurassic rocks of Britain (1933) and in the various Geological Survey memoirs on which much of Arkell's summary is based. Because of the paucity of exposure little additional work has been done since that time. Parts of the Kimmeridge Clay of the Aylesbury area have been discussed by Ballance (1962) and Oates (1974), Callomon (in Bristow and Bazley, 1966) and Callomon and Cope (1971) have described the Kimmeridgian stratigraphy of a number of boreholes in the Weald, and Kent and Casey (1963) have described part of the Lincolnshire succession. Cope (1974) has described sections in the Upper Kimmeridge Clay in North Yorkshire.

The Kimmeridge Clay is poorly exposed in Norfolk and little work had been done on its stratigraphy prior to the present research. The highest part of the formation crops out along the eastern edge of

Fenland between King's Lynn and Denver. Although temporary sections have become available from time to time in that area they are usually deeply weathered and have produced little stratigraphical information. The lower part of the formation is everywhere covered by drift deposits within the county and is known only from boreholes. The nearest completely exposed succession to Norfolk is that in the Ely area of Cambridgeshire where Roberts (1892) estimated the total thickness of the formation to be 42.9 m (142 ft).

The first published record of oil shale in Norfolk was that of William Smith on his geological map of the county (1819) where he noted that the "Oaktree Clay" [Kimmeridge Clay] was "part slaty and bituminous as at Kimmeridge in Dorset". Rose (1835, p. 175) subsequently recorded inflammable shales "that burned like cannel coal" in the Kimmeridge Clay in a brickpit at Southery [TL 617 958] and oil seepages, supposedly derived from the Kimmeridge Clay, were later noted in the Puny Drain at Setchey [TF 626 146] (Forbes-Leslie, 1917a).

It was largely on the evidence of these seepages, and the possible prospect of finding oil shales comparable to those that had been worked at Kimmeridge, that oil-shale exploration was begun in Norfolk during the First World War. A pilot operation was set up at Setchey by English and Foreign Oil Finance Ltd in about 1916 with W. Forbes-Leslie as geologist. This received much publicity from two papers by Forbes-Leslie on the occurrence of petroleum in Britain in general (1917b) and on the occurrence in Norfolk in particular (1917a). In the latter account it was stated that at least three 6 ft (1.8 m)-thick oil-shale seams were present (pp. 16-17) and that two of these could be retorted to yield more than 50 imperial gal oil/long ton of shale. Up to 75% of the oil was described as free-oil filling cavities in the shale

(1917b, p. 181); yellow sandstones impregnated with bitumen were also said to be present (1917a, p. 16).

In 1918 a new company (English Oilfields Ltd) was formed with a share capital of £300,000 to exploit the Norfolk oil shales. Between 1918 and 1919 the thickness and quality of the proved oil-shale seams increased steadily in Forbes-Leslie's statements to the shareholders. Yields of 20 to 40 gal/ton are quoted in the 1918 share prospectus, the oil containing 4.5 to 8% sulphur. By September 1919 yields of 50 to 80 gal/ton of "practically sulphur free" oil had been achieved. By December 1919 an 85 to 95 gal/ton-seam had been discovered and it was envisaged that an exceedingly profitable industrial complex would be built which, in addition to the oil, would produce cheap Portland cement (from the shale waste and nearby Lower Chalk), high quality bricks (from the Kimmeridge Clay overburden), electricity (from the waste gas from the retorts) and metalliferous minerals (from the beds beneath the Kimmeridge Clay). In addition, it was claimed that large quantities of free oil had been discovered together with a widespread 70 ft (21.3 m)-thick seam of ozokerite (natural paraffin wax).

The shareholders of English Oilfields approved an increase in the share capital to £1.5 million in 1919 and in the next few years an opencast pit and a mine were dug, pilot retorts were operated, a rail link was built to the works and work was begun on four full-scale retorts with a view to processing 1000 tons of shale per day (Plate 1). The company acquired a petroleum-exploration licence covering about 1000 sq km of west Norfolk and between 1919 and 1923 probably drilled more than 50 cored boreholes* in the area between the Gaywood River at

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* Details of all the boreholes known to have penetrated the Kimmeridge Clay in Norfolk, including those drilled for oil shale, hydrocarbons, water and stratigraphical purposes, are on open file.

Plate 1. Oil-shale workings at Setchey, c 1920.

Oil shale was worked by Setchey by English Oilfields Ltd between about 1916 and 1923 in a mine and a small opencast pit. The company embarked upon an ambitious programme aimed at processing 1000 ton shale/day. The retorts were never completed, supposedly due to lack of capital. A more likely cause of failure was the diversion of capital into exploratory drilling and the difficulties of perfecting a technique, even on a laboratory scale, of producing a low-sulphur shale oil.

A. EOL wagons parked on the company's own railway spur, Clarke's Drove Siding, that connected the works with the main King's Lynn to London line (foreground).

B. Three retorts under construction, viewed from the top of the chimney stack that was to take their exhaust gases. Four Pumpherston-type retorts were planned, but none was completed. The waterlogged pit on the left was in Pleistocene flint gravels that were used for construction materials on the site. Temporary accommodation for the site workers can be seen on the right, adjacent to the A10 King's Lynn-London road.

C. The opencast pit worked oil shales in the wheatleyensis Zone (fissile beds in right foreground) beneath a thin overburden of cryoturbated gravelly head (top left) and calcareous mudstones in the hudlestoni Zone (face behind figures). Angular blocks of broken cementstone doggers from the hudlestoni Zone overburden can be seen in the spoil on the left.

D. The small amount of oil shale worked can be gauged from this and the previous picture which show the full extent of the opencast working. The pit appears to have been dug entirely by hand with a labour force of only three men.

Plate 1

King's Lynn and the River Wissey at Stoke Ferry (Fig. 3 and Table 2). Few details have survived from these boreholes because of the secrecy maintained by the company. The Petroleum (Production) Act of 1918 excluded the necessity to report oil-shale exploration boreholes and the Mining Industry Act, which compelled companies to provide geological details of their activities to the Geological Survey, was not passed until 1925. A description of the stratigraphy of each borehole for which specimens have survived has been placed on open file.

The full-scale retorts were never completed, the mine and opencast pit were abandoned and there was little activity after about 1923. The company operated on a small scale as a wholesale distributor of oils during the 1920s and 30s and produced oil for use in medicinal soaps under the trade name Icthyol (derivative of the Swiss 'icthyammol', not a contraction of 'icthyosaur oil' as sometimes suggested). However, none of this oil came from Norfolk. The company was wound up in 1966.

Several small syndicates of local landowners were formed to explore the oil shales in their particular parts of west Norfolk at the time when the activity at English Oilfields was at its peak. None of these found seam thicknesses or yields comparable to those reported by Forbes-Leslie, and the syndicates were disbanded after only a few boreholes had been drilled. One of them, the Pentney Syndicate, allowed Pringle to examine the cores from three exploratory boreholes in south-west Norfolk, and his account (1923) has remained the most complete description of the Kimmeridge Clay sequence in the county. Pringle deduced that the whole of the formation was present in two of the boreholes, Methwold Common [TL 6758 9419] and Severals House [TL 6921 9639], where it was 36.9 m (121 ft) and 38.1 m (125 ft) thick respectively; he thought that the sequence ranged from the

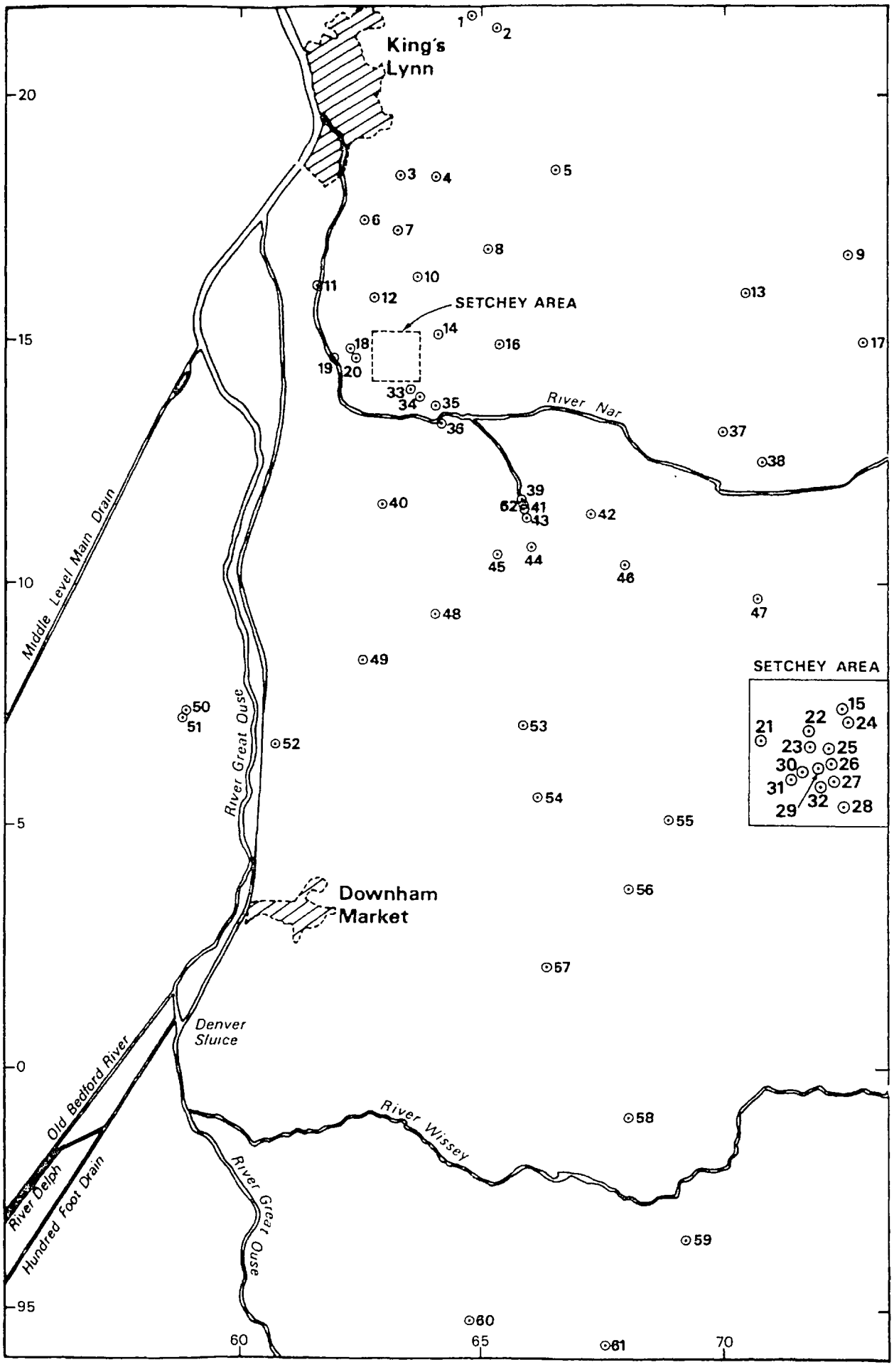


Figure 3. Sites of boreholes drilled for oil-shale exploration in Norfolk in 1916 to 1923.

Table 2. Norfolk oil-shale boreholes, 1916-23.

Key to companies: EOL - English Oilfields Ltd., NOSS - Norfolk Oil Shale Syndicate, FOSS - Fincham Oil Shale Syndicate, WS - Wissington Syndicate, PS - Pentney Syndicate.

Site number in Fig. 3	Borehole name	Grid Reference (TF)	Company	IGS Specimen numbers
1	Gaywood Bridge	6480 2158	NOSS	WM4621 to 30
2	Gaywood	6529 2132	EOL	
3	EOL 19	6330 1835	EOL	
4	EOL No. 7 East (Hardwick)	6405 1829	EOL	
5	Whitehouse Farm, Mintlyn	6650 1842	NOSS	WM4618 to 19; 4631 to 33
6	EOL 47	6257 1742	EOL	WM4610 to 14; 4637 to 39; 4734 to 40
7	EOL 49	6335 1720	EOL	
8	Fair Green,Middleton	6520 1684	NOSS	WM4634 to 37
9	East Walton	7251 1670	PS	WM4889 to 4904
10	EOL No. 3 East (West Winch)	6366 1628	EOL	Pe 1937
11	EOL No. 4 West (Saddlebow)	6160 1609	EOL	
12	EOL No. 1 East (J.Cooper's Field)	6280 1585	EOL	
13	East Winch Hall	7037 1593	PS	WM4856 to 58
14	EOL 44	6408 1510	EOL	
15	EOL 32	6338 1493	EOL	
16	EOL No. 2 East (Manor Farm, Blackborough)	6534 1490	EOL	
17	Magpie Farm, Pentney	7283 1492	PS	WM4850 to 53
18	EOL No. 3 West (Smith's Marsh)	6228 1482	EOL	
19	EOL No. 2 West (Nar Bank)	6194 1463	EOL	
20	EOL 21 (Setchey Mine)	6240 1453	EOL	Pe 1938 to 50
21	EOL 39	6284 1470	EOL	
22	EOL 27	6316 1483	EOL	
23	EOL 38	6317 1468	EOL	
24	EOL 40	6343 1480	EOL	
25	EOL 26	6335 1463	EOL	
26	EOL 34	6338 1453	EOL	

Table 2 (continued)

Site number in Fig. 3	Borehole name	Grid Reference (TF)	Company	IGS Specimen numbers
27	EOL 33	6339 1444	EOL	
28	EOL 42	6338 1425	EOL	
29	EOL 35	6326 1451	EOL	
30	EOL 36	6313 1447	EOL	
31	EOL 37	6303 1442	EOL	
32	EOL 28	6330 1443	EOL	
33	EOL No. 4 East (Jones Farm, Nar River)	6350 1400	EOL	
34	EOL 18	6370 1383	EOL	
35	EOL No. 6 East (Setch Fen)	6402 1368	EOL	
36	EOL 41	6415 1329	EOL	
37	EOL No. 41 East (White House Farm, West Bilney)	6997 1310	EOL	Pe 1929 to 34
38	Ashwood Lodge, Pentney	7077 1250	PS	WM4863 to 74
39	EOL 20	6582 1173	EOL	
40	EOL No. 4 South (Tottenhill Row)	6297 1163	EOL	
41	EOL 29	6585 1154	EOL	
42	EOL 22	6722 1141	EOL	
43	EOL No. 5 East (Wormegay)	6591 1134	EOL	Pe 1935 to 36
44	EOL 48	6602 1073	EOL	
45	EOL 45 (West Briggs)	6530 1059	EOL	
46	EOL 30	6796 1036	EOL	
47	EOL 54	7070 0966	EOL	
48	EOL 51	6405 0937	EOL	
49	EOL No. 2 (South Holme)	6252 0840	EOL	
50	EOL 53	5890 0734	EOL	
51	EOL No. 5 South (Stowbridge No. 2)	5882 0720	EOL	
52	EOL No. 3 South (Stowbridge)	6072 0664	EOL	WM4620
53	EOL 52	6585 0704	EOL	
54	EOL 24	6516 0515	EOL	

Table 2 (continued)

Site number in Fig. 3	Borehole name	Grid Reference (TF or TL)	Company	IGS Specimen numbers
55	Fincham	6886 0508	FOSS	WM4777 to 90
56	EOL 50	6804 0365	EOL	
57	EOL 46	6635 0201	EOL	
58	EOL No. 6 South (Wretton)	6803 9890	EOL	
59	Methwold No. 3 (=Severals House)	6921 9639	WS	WM4445 to 4527; 4640 to 4733
60	Methwold No. 1 (=Decoy Farm)	6487 9476	WS	WM4387 to 98
61	Methwold No. 2 (=Methwold Common)	6758 9419	WS	WM4399 to 4415
62	EOL 43	6582 1164	EOL	
63	Shouldham Common	672 104	PS	WM4854 to 55

'Perisphintes' pallasianus Zone (sensu Chatwin and Pringle 1922, p. 163; Pavlovia pallasiodes Zone of modern authors) downwards. He concluded (1923, p. 134) that, because the full sequence of zones appeared to be present, this unusually thin development of the Kimmeridge Clay (Arkell 1947, p. 64 estimated the same beds at Kimmeridge Bay, Dorset to be about 500 m thick) was due to an overall attenuation resulting from slow deposition, not to non-sequences within the Kimmeridge Clay nor to the overstep of the Sandringham Sands. Arkell (1937, p. 82) subsequently reclassified both boreholes, making the Kimmeridge Clay thicknesses 43.6 m (143 ft) and 44.8 m (147 ft), and upheld Pringle's conclusions concerning the attenuation.

In addition to his published account Pringle (IGS Palaeontology Department records) also commented on samples from the Kimmeridge Clay of other oil-shale boreholes in west Norfolk, but none of these is sufficiently well documented for a detailed stratigraphical sequence to be recognised.

In 1945 the D'Arcy Exploration Company drilled a deep borehole at North Creake [TF 8568 3864] in north-west Norfolk which passed through the full thickness of the Kimmeridge Clay. Kent (1947) recorded the formation as 48.8 m (160 ft) thick, consisting of fossiliferous clays and bituminous shales, but the borehole was rock-bitted at this level and yielded little faunal information. Between 1965 and 1972, as a result of gas finds in the southern North Sea, the search for possible hydrocarbons in the adjacent land area of Norfolk was intensified and 9 deep boreholes were drilled. Those at Hunstanton (Place Oil, 1969), South Creake (British Petroleum, 1969), Wiggenhall (Texaco, 1971) and possibly Lexham (Norris Oil, 1971) proved Kimmeridge Clay.

The upper part of the Kimmeridge Clay (upper part of the *Pectinatites (Virgatosphinctoides) wheatleyensis* Zone and above) crops out in Norfolk between King's Lynn and Denver Sluice at the foot of a low escarpment formed by the Sandringham Sands. The formation is nowhere naturally exposed but parts of the sequence have been recorded from time to time in temporary excavations. Whitaker et al. (1893) noted small brickpits in the Kimmeridge Clay at Fordham, Downham Market, Watlington, West Winch and Foddestone, the last named entirely within a large glacially transported erratic.

In 1970 the IGS drilled four continuously cored boreholes, at Skegness in Lincolnshire and Hunstanton, Gayton and Marham in Norfolk, to explore the Upper Jurassic and Lower Cretaceous sequences. Two additional cored boreholes, IGS 71/65 and 71/66, were subsequently drilled within The Wash by the drilling ship m.v. *Whitethorn* to provide a complete sequence through the Upper Kimmeridge Clay of the area in preparation for a proposed geological investigation of the floor of The Wash for a water-storage feasibility study.

The Institute was invited to take part in The Wash Water Storage Feasibility Study when it was commenced in 1972 and the author became responsible for the investigation and interpretation of the geology of the onshore area, and for the stratigraphical interpretation of the geology of the offshore area. A total of 28 cored boreholes was drilled onshore and 3 offshore (Fig. 4 and open file). The whole of the Kimmeridge Clay was cored in one borehole and large parts of the formation were cored in others. Most of the boreholes penetrated some part of the Lower Kimmeridge Clay since that stratigraphical level was of particular interest to the scheme.

In 1973, as a result of the rapid rise in OPEC oil prices, the

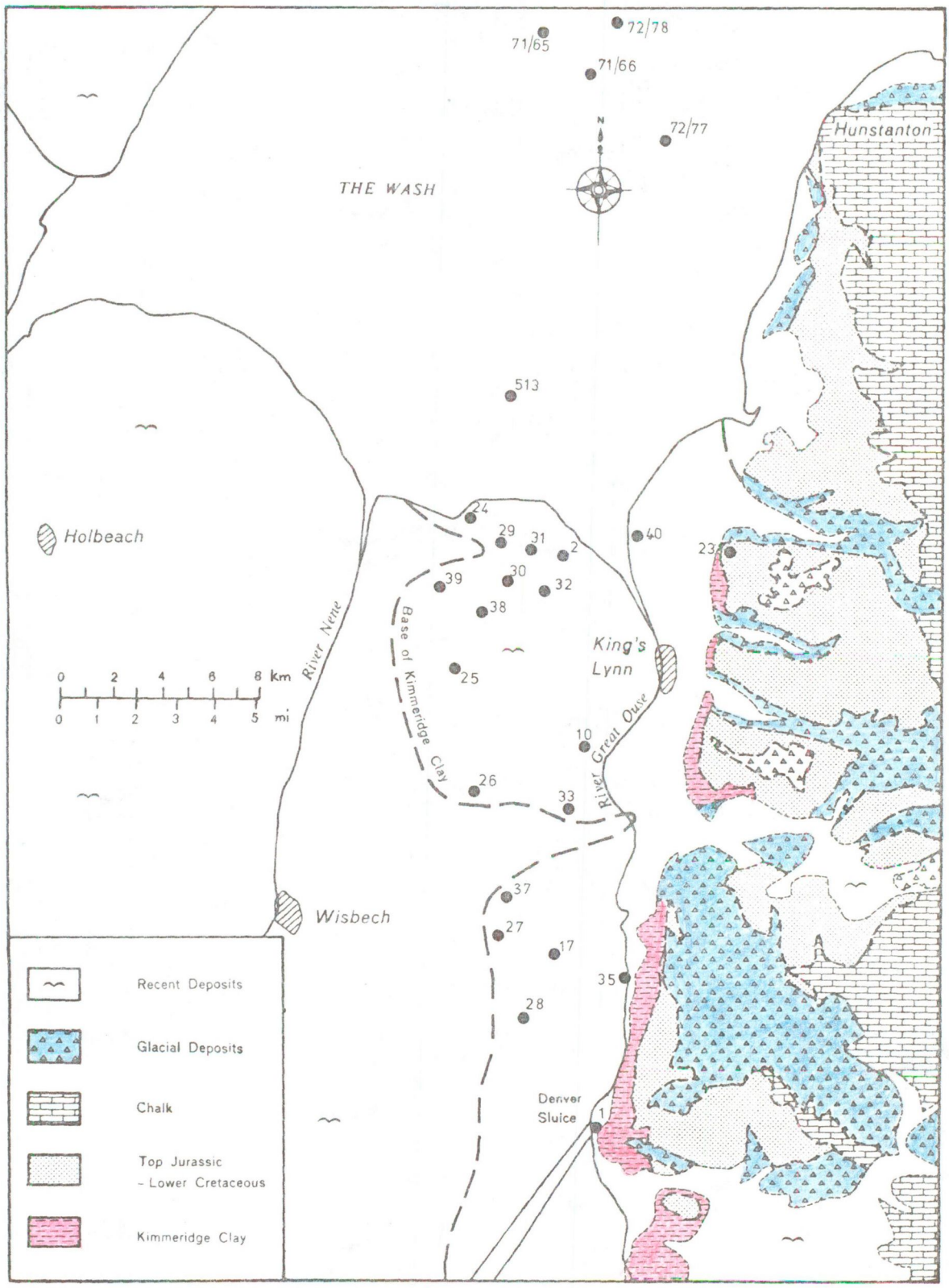


Figure 4. Geological sketch map of west Norfolk showing sites of cored boreholes drilled by IGS and for the Wash Feasibility Study through all or part of the Kimmeridge Clay.

oil shales in the Kimmeridge Clay again became a potentially interesting economic prospect and IGS initiated a pilot study of these occurrences in England under the author's supervision. Cored boreholes were drilled during 1974-5 through the complete Kimmeridge Clay sequences at Donington on Bain, Lincolnshire; North Runcton, Norfolk (close to the site of the former oil-shale works at Setchey) and Swindon and West Lavington (near Devizes), Wiltshire. In addition to providing stratigraphical information which has added to the understanding of regional variations within the Kimmeridge Clay, these boreholes yielded analytical data concerning the clay mineralogy and organic chemistry of the formation. A subsequent, more detailed, study of Kimmeridgian oil shales in Britain was commissioned by the Department of Energy in 1977. This has recently (1981) been released by the Department and some of the results that are relevant to the Norfolk outcrop are referred to in this thesis.

The author has recorded sequences in the Kimmeridge Clay in shallow site-investigation boreholes and electricity and gas pipeline trenches between North Wootton and West Winch, and in the Flood Relief Channel between King's Lynn and Denver Sluice and in the Cut-Off Channel between Denver Sluice and Fordham (Gallois, 1979a). All the sections were deeply weathered and yielded information which was stratigraphically useful only because it could be correlated with the detailed succession proved in the cored boreholes.

2.2 Lithology and palaeontology and their relationship

2.2.1 Lithology

The Kimmeridge Clay is made up of a complex sequence of rhythms. In much of the English outcrop and subcrop the lowest third of the formation consists of rhythms in which a thin bed of silt or silty mudstone is overlain by dark grey mudstone and pale grey calcareous

mudstone (Fig. 5, Type A). In the upper part of the Lower Kimmeridge Clay and in the Upper Kimmeridge Clay, the rhythms consist of brownish grey kerogen-rich mudstone (oil shale*) overlain by dark grey mudstone and pale grey calcareous mudstone; the last named sometimes includes thin tabular beds or doggers of muddy limestone (cementstone) (Fig. 5, Type B). Many of the individual rhythms can be correlated over distances of tens of kilometres. Superimposed on this rhythmic sequence are broader lithological changes, from more to less calcareous and from more to less kerogen-rich, which can be regarded as larger-scale rhythms and which can be correlated throughout the English outcrop (Plate 2). The bulk chemistry of the more common Kimmeridge Clay lithologies, based on analyses made from core samples from Norfolk, is summarised below.

Using the parameters of colour, texture, grain size and shell content the following lithologies can be readily recognised in bore-hole cores and exposures in the Kimmeridge Clay:

(i) mudstone, smooth textured, dark grey, barren, unbedded (straight fracture)

(ii) mudstone, smooth textured, medium grey, barren, unbedded (curved fracture)

(iii) mudstone, smooth textured, pale grey, barren, unbedded (tending to subconcoidal fracture)

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* There is at present no satisfactory alternative name for these rocks that is widely accepted. The term 'bituminous mudstone' is commonly used, but the 'bitumen' fraction of an organic-rich rock is that part which can be extracted with organic solvents, and the kerogen is that part which is <u>insoluble</u> in normal organic solvents. The use of the term 'bituminous' is therefore singularly inappropriate for kerogen-rich rocks. Hatch and Rastall (1965 p. 286) proposed the terms 'kerogenite' 'shale-kerogenite', 'dolomite-kerogenite' etc., but these have been ignored and the old term 'oil shale' (i.e. yielding oil on destructive distillation by breakdown of the kerogen) remains universally popular.

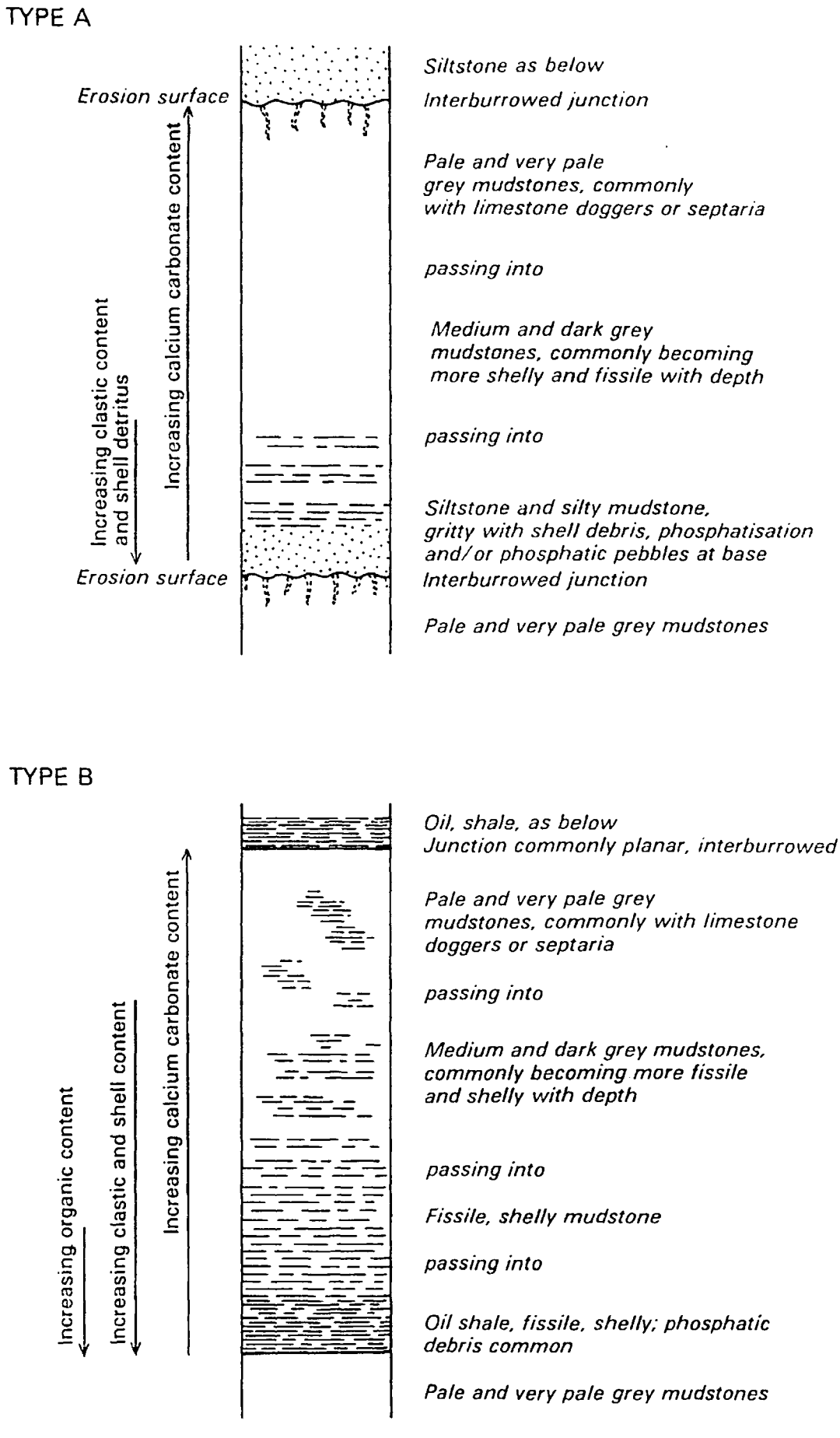


Figure 5. Generalized Kimmeridge Clay rhythms.

(iv) mudstone, smooth textured, dark grey, barren, fissile*

(v) mudstone, dark grey, shelly, fissile*

(vi) mudstone, medium grey, tough, shelly, burrow-mottled (irregular fracture)

(vii) mudstone, medium grey, silty to very silty, shelly; shells leached in part (irregular fracture)

(viii) oil shale, barren (blocky fracture)

(ix) oil shale, shelly, fissile

(x) limestone (various types)

These distinctive lithologies are made up of a limited number of clastic, biogenic and chemogenic components which occur in varying combinations. The principal components have been determined by microscope studies and X-ray diffraction analyses and are as follows:

Clastic components

(i) clay minerals: mostly clay mica and kaolinite with minor amounts of vermiculite, smectite and chlorite; generally 30 to 65% of whole rock

(ii) crystalline quartz: silt and rare clay-grade particles; generally 15 to 23%; silt grade quartz is the major component of the thin siltstone horizons in the Type A rhythms

(iii) re-worked biogenic and chemogenic materials: shell and plant debris; phosphatic pebbles

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* There has been much recent discussion concerning the relationship of fissility to lamination in fine-grained rocks. Lundegard and Samuels (1980) regard lamination as an important primary feature and fissility as a secondary feature of doubtful value. Spears (1976; 1981) has suggested that the two properties are intimately related and that lamination in borehole cores is commonly replaced by fissility at outcrop. In poorly lithified mudstones such as the Kimmeridge Clay fissility is commonly present in cores that have dried out, and it can be seen to be related to closely-spaced bedding planes that are picked out by variations in mineral composition.

Plate 2. Large-scale lithological variations in the Kimmeridge Clay.

The Kimmeridge Clay in Norfolk exhibits both large- and small-scale rhythmic variations in lithology, but these cannot readily be photographed in the borehole cores and they do not crop out. The same lithological variations are well displayed in the cliffs at and adjacent to Kimmeridge Bay in Dorset.

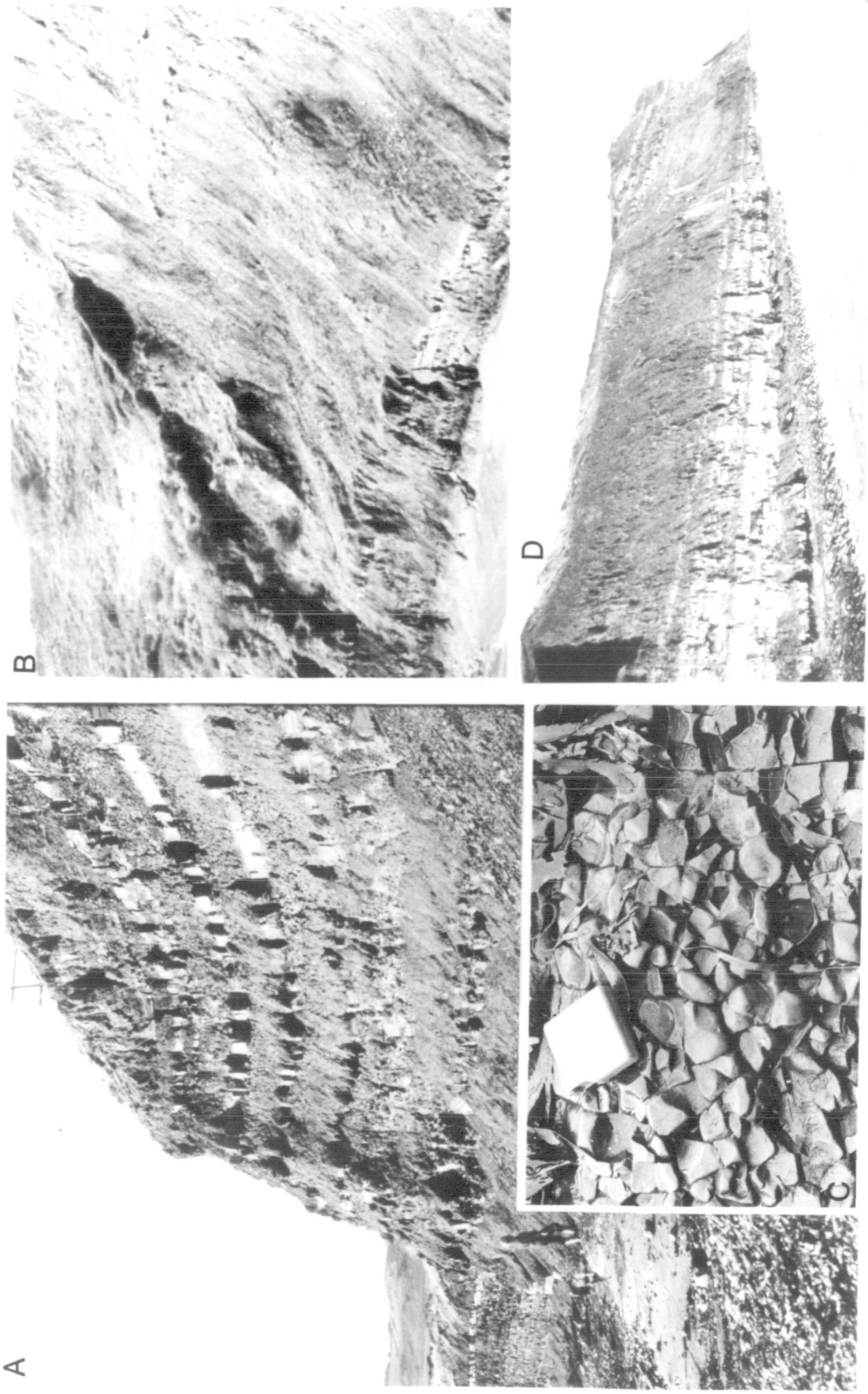
A. Small-scale Type B rhythms, autissiodorensis Zone Kimmeridge Bay. The organic-rich parts of the rhythms are more resistant to weathering than the calcareous parts and form prominent ribs that are characteristically well jointed.

B. Calcareous and sandy mudstones overlying mudstones with oil shales; Pavlovia zones, Chapman's Pool. The youngest oil shales in the Kimmeridge Clay (arrowed) form a series of prominent ribs and a steep cliff that is overlain by degraded slopes formed from calcareous mudstones (Type C rhythms). Harder ribs in the highest part of the cliff are formed by sandy mudstones that herald the upward passage from the Kimmeridge Clay into the Portland Sand.

C. Detail of 'dicey' weathering characteristic of the more calcareous mudstones. Hudlestoni Zone, foreshore below Rope Lake Head. Scale 5 cm wide.

D. Large-scale rhythms, hudlestoni and pectinatus zones between Clavell's Hard (foreground) and Rope Lake Head (distance). Concentrations of oil shales in the lowest part of the hudlestoni Zone (foreground) and the lowest part of the pectinatus Zone (upper distant cliff) form almost vertical cliffs separated by relatively uniform calcareous mudstones that form a very steep slope.

Plate 2



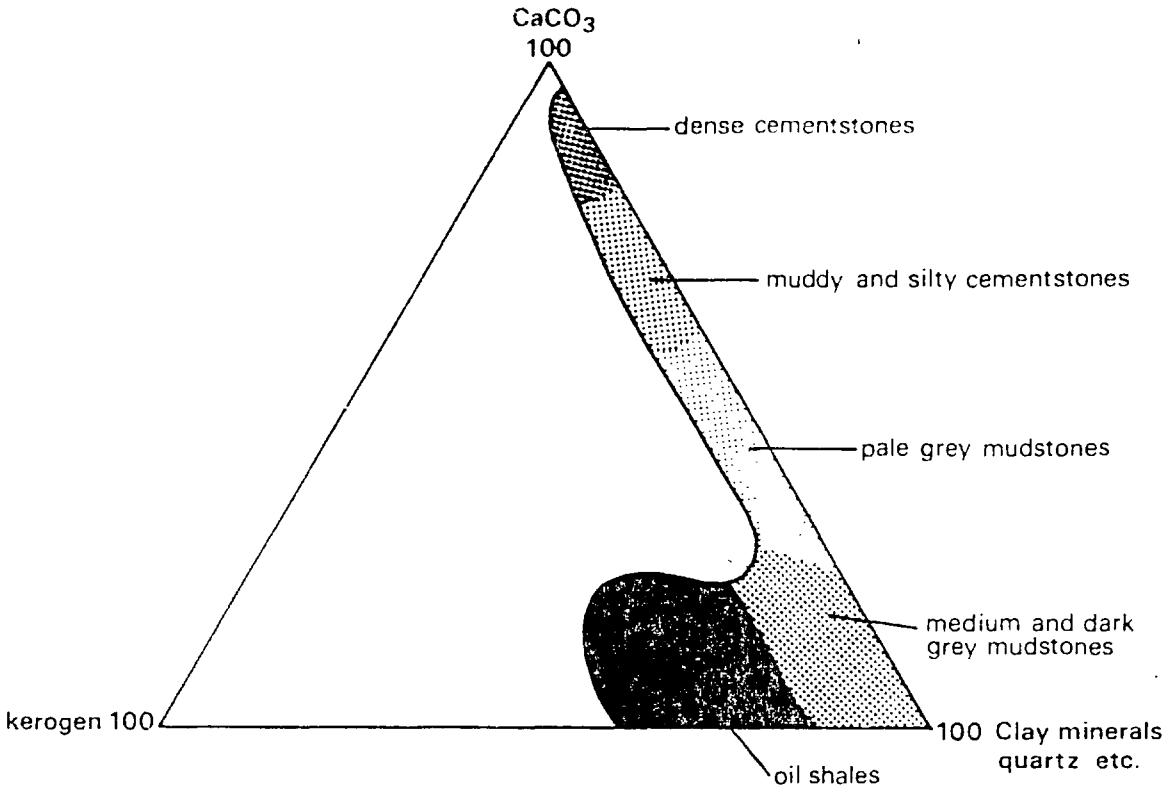


Figure 6. Diagrammatic representation of the bulk chemistry of some of the more distinctive Kimmeridge Clay lithologies.

Biogenic components

(i) calcareous macro- and microfauna and flora: predominantly ammonites, bivalves and foraminifera, with gastropods, brachiopods, serpulids, crinoids, ostracods and coccoliths important at some levels

(ii) phosphatized fauna: vertebrate debris, mostly fish scales, vertebrae and faecal pellets

(iii) kerogen: palynomorphs (e.g. pollen, acritarchs, dinoflagellates) and plant debris

Chemogenic components

(i) calcium and magnesium carbonate; diagenetically formed concretions

(ii) phosphate; early diagenetic formation

(iii) pyrite; early diagenetic formation

(iv) kerogen; early diagenetic formation

The gross mineralogy of the commoner Kimmeridge Clay lithologies can be expressed in terms of the four components clay minerals, quartz, calcium carbonate and kerogen (Fig. 6). The typical composition* of these common lithologies in Norfolk can be summarized as follows:-

(i) dark grey mudstone - clay minerals 45 to 65%, quartz 10 to 30%, calcium carbonate 5 to 20% depending on shell content, kerogen <2%

(ii) medium grey mudstone - clay minerals 35 to 55%; quartz 10 to 15%; calcium carbonate 20 to 35%; kerogen <1%

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* Yaalon (1962) examined the published analyses from 10,000 shales and found their average composition to be clay minerals .....59%; quartz .....20%; Feldspar .....8%; carbonates .....7%; iron oxides .....3%; organic materials .....1%; other minerals .....2%. With the notable exception of the absence of feldspar in the Kimmeridge Clay, Yaalon's 'average shale' has a similar composition to the dark grey mudstones of the Kimmeridge Clay.

(iii) pale grey mudstone - clay minerals 25 to 45%; quartz 8 to 15%; calcium carbonate 25 to 55%; kerogen <1%

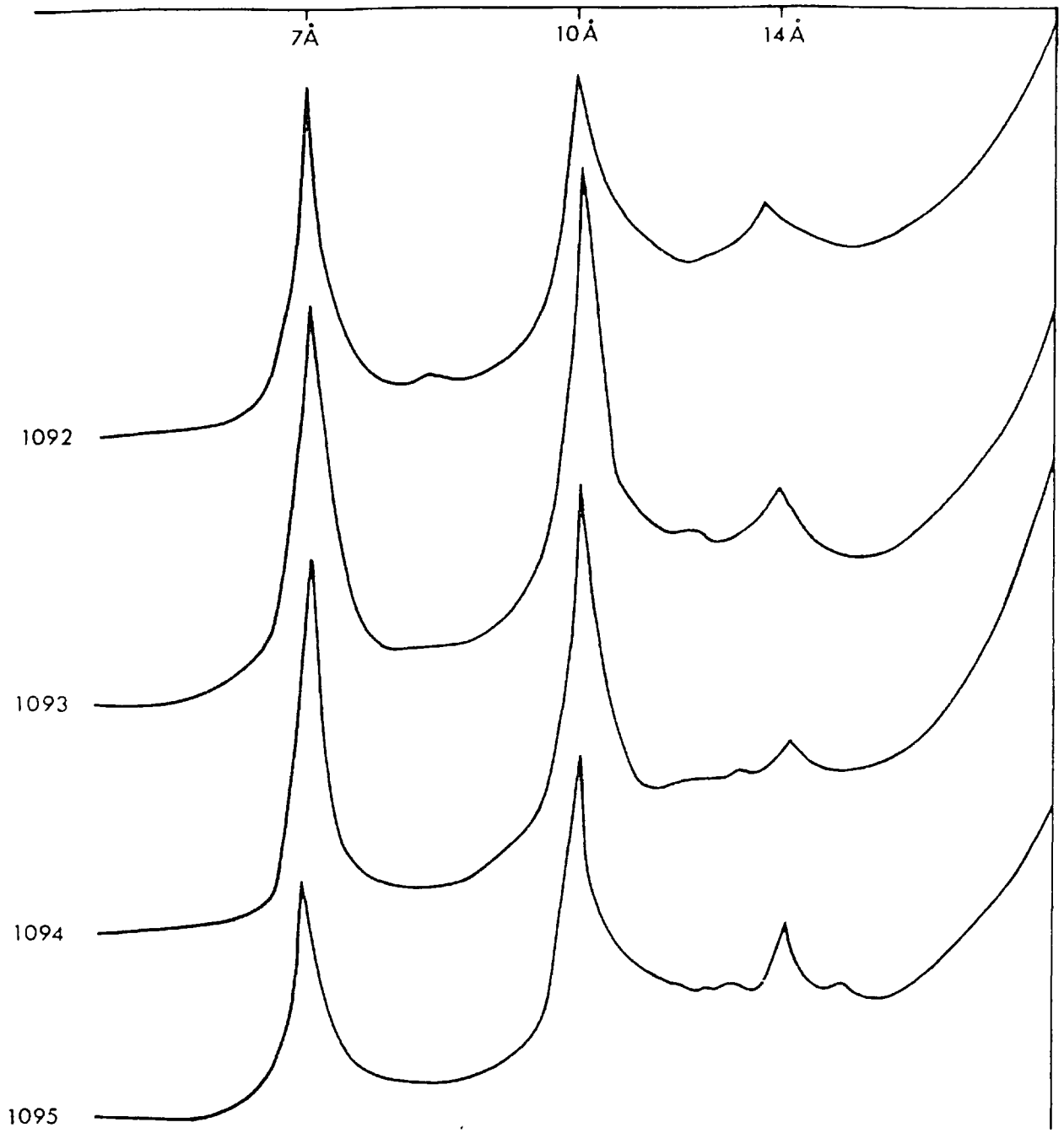
(iv) cementstone - clay minerals 10 to 20%; quartz 2 to 6%; calcium carbonate 60 to 90%; kerogen <1%

(v) oil shale - clay minerals 20 to 40%; quartz 10 to 15%; calcium carbonate 10 to 25%; kerogen 10 to 45%

The compositions of selected Kimmeridge Clay lithologies based on X-ray diffraction and calcimeter analyses are given in Table 3 (after Merriman and Strong in Gallois,1979a) and Table 4 (after Merriman in Gallois 1979b). The XRD method detects only crystalline materials and a small number of additional analyses were therefore made to determine the kerogen contents of selected organic-rich samples (Table 5; after Green in Gallois,1979a).

2.2.1.1 Clay minerals

As with most fine-grained rocks the clay minerals of the Kimmeridge Clay occur in such small particle sizes and in such poorly crystalline forms that they cannot be studied by optical microscopy and yield little data even to the electron microscope. The most convenient method of identifying clay minerals is by X-ray diffraction. Mr R.D. Merriman and Mr G.E. Strong carried out X-ray diffraction and calcimeter analyses of 44 samples selected by the author to be representative of the range of lithologies of the Kimmeridge Clay in Norfolk and Lincolnshire. The X-ray diffraction analyses were carried out on a Philips diffractometer using Ni-filtered Cukα radiation; the calcimeter technique followed was that of Schultz (1964). An additional 155 XRD analyses were subsequently made by Mr Merriman and Dr C.V. Jeans of samples from the oil-shale rich parts of the sequence in various parts of England. Details of the procedures are given by Merriman and Strong (in Gallois,1979a), Merriman



Borehole depth (m)	Sample no.	Kaolinite %	Clay mica %	Expansible minerals	
				Total %	Type
35.50 to 37.50	1092	22	48	30	v, v/m
47.75 to 49.75	1093	22	68	10	v, v/m
52.25 to 54.25	1094	23	62	15	v, v/m
62.50 to 63.00	1095	20	71	9	v, v/m

Abbreviations:

v = vermiculite v/m = irregularly interlayed vermiculite/mica

Figure 7. X-ray diffractograms of untreated Kimmeridge Clay samples from the North Runcton Borehole.

Borehole	Depth m	Clay minerals present	Total clay %	Quartz %	Calcite %	Other minerals detected (j.d.) just detectable	Lithology
Terrington St John	21.13	Clay mica > kaolinite > chlorite, smectite	25	8	47	Aragonite, pyrite, dolomite	Mudstone, pale grey, silty, almost barren
Terrington St John	35.14	Clay mica > kaolinite > chlorite	45	12	18	Gypsum, aragonite, pyrite, (?)dolomite	Mudstone, medium grey, sparsely shelly
Stowbridge	47.40	Clay mica > chlorite	10	2	80	-	Limestone, densely cemented

Table 3. X-ray diffraction analyses of representative Kimmeridge Clay lithologies from boreholes in Norfolk.

Borehole	Depth m	Clay minerals present	Total clay %	Quartz %	Calcite %	Other minerals detected (j.d.) just detectable	Lithology
Denver Sl.	13.06	Clay mica > kaolinite > chlorite	48	30	8	Gypsum, pyrite, feldspar (j.d.), (?)dolomite	Mudstone, dark grey, sparsely shelly
Denver Sl.	22.86	Clay mica ≥ kaolinite, chlorite, smectite	19	3	71	Aragonite, pyrite	Quasi limestone, shelly
Denver Sl.	23.14	Clay mica > kaolinite > chlorite	37	10	32	Aragonite, pyrite, (?)apatite, (?)dolomite	Mudstone, medium and pale grey
Denver Sl.	34.38	Clay mica > kaolinite > chlorite	38	11	27	Gypsum, aragonite, pyrite, (?)dolomite	Mudstone, dark grey, shelly, silty
Denver Sl.	45.61	Clay mica > kaolinite ≥ chlorite	46	14	18	Gypsum, aragonite, pyrite, (?)dolomite	Mudstone, dark grey, sparsely shelly
N. Wootton	31.85	Clay mica > kaolinite ≥ chlorite	23	7	54	Aragonite, pyrite	Mudstone, pale grey, barren, slightly silty
N. Wootton	36.10	Clay mica > kaolinite	20	9	18	Aragonite (15%), gypsum	Oil shale, shelly
N. Wootton	45.70	Clay mica ≥ kaolinite ≥ chlorite	46	20	-	Gypsum, pyrite, feldspar	Oil shale, barren
N. Wootton	47.85	Clay mica > kaolinite > chlorite	18	9	66	Aragonite, pyrite	Limestone, pyritic with oil shale
N. Wootton	64.00	Clay mica ≥ kaolinite	27	12	20	Pyrite, gypsum, aragonite	Oil shale, shelly

Table 3 continued...

Borehole	Depth m	Clay minerals present	Total clay %	Quartz %	Calcite %	Other minerals detected (j.d.) just detectable	Lithology
N. Wootton	68.20	Clay mica > kaolinite ≥ chlorite	35	13	26	Aragonite, pyrite, (?)dolomite	Oil shale/mudstone, interburrowed, shelly
N. Wootton	69.15	Clay mica > kaolinite > chlorite	17	4	61	Aragonite, pyrite	Limestone, muddy, shelly in part
N. Wootton	75.80	Clay mica > kaolinite ≥ chlorite	35	12	32	Gypsum (j.d.), pyrite, aragonite, dolomite	Mudstone, medium grey, silty
N. Wootton	76.10	Clay mica ≥ kaolinite	33	12	13	Pyrite, gypsum, aragonite, (?)dolomite	Oil shale, barren fissile
N. Wootton	98.30	Clay mica > kaolinite, chlorite, smectite	13	5	65	Aragonite	Limestone, weakly cemented, slightly silty
N. Wootton	100.12	Clay mica, smectite, chlorite	7	2	90	-	Limestone, densely cemented with calcite veining
Emorsgate	37.20	Clay mica > kaolinite >chlorite	47	14	-	Gypsum (s), pyrite	Mudstone, dark grey, fissile
Emorsgate	47.14	Clay mica > kaolinite ≥chlorite	50	16	6	Gypsum, aragonite, pyrite, (?)apatite, (?)dolomite	Mudstone, dark grey, sparsely shelly

Table 3 continued...

Depth m	Clay minerals present	Total clay %	Quartz %	Calcite %	Other minerals detected
23.75-25.75	Clay mica > kaolinite > mixed-layer mineral	46	13	24	Aragonite, pyrite feldspar
25.75-27.75	Clay mica > kaolinite > mixed-layer mineral, chlorite	62	23	10	Aragonite, pyrite, feldspar
27.75-29.75	Clay mica > kaolinite > mixed-layer mineral, chlorite	60	23	12	Pyrite, feldspar
29.75-31.75	Clay mica > kaolinite > mixed-layer mineral, chlorite	54	18	23	Aragonite, pyrite
31.75-33.75	Clay mica > kaolinite > mixed-layer mineral, chlorite	70	21	6	Pyrite
33.75-35.75	Clay mica > kaolinite > mixed-layer mineral, chlorite	66	22	7	Pyrite
35.75-37.75	Clay mica > kaolinite > mixed-layer mineral, chlorite	45	15	35	Pyrite
37.75-39.75	Clay mica > kaolinite > mixed-layer mineral, chlorite	60	22	11	Aragonite, pyrite
39.75-41.75	Clay mica > kaolinite > mixed-layer mineral, chlorite	66	20	9	Aragonite, pyrite
41.75-43.75	Clay mica > kaolinite > mixed-layer mineral, chlorite	60	18	20	Aragonite, pyrite
43.75-45.75	Clay mica > kaolinite > mixed-layer mineral, chlorite	62	20	15	Aragonite, pyrite
45.75-47.75	Clay mica > kaolinite > mixed-layer mineral, chlorite	66	22	8	Aragonite, pyrite, feldspar
47.75-49.75	Clay mica > kaolinite > mixed-layer mineral, chlorite	58	19	20	Aragonite, pyrite, feldspar
49.75-51.75	Clay mica > kaolinite > chlorite	60	13	14	Aragonite, pyrite, dolomite, (gypsum)
55.75-57.75	Clay mica > kaolinite > mixed-layer mineral, chlorite	44	10	35	Aragonite, pyrite, dolomite
59.75-61.75	Clay mica > kaolinite > mixed-layer mineral	50	14	21	Aragonite, pyrite, dolomite, (gypsum)

Table 4A. X-ray diffraction analyses of Kimmeridge Clay from North Runcton Borehole A.

Depth m	Clay minerals present	Total clay %	Quartz %	Calcite %	Other minerals detected
24.80-26.80	Clay mica > kaolinite > mixed-layer mineral, chlorite	60	14	16	Aragonite, pyrite
43.05-44.05	Clay mica > kaolinite > mixed-layer mineral, chlorite	45	15	13	Palygorskite, aragonite, pyrite, (gypsum)
45.05-46.05	Clay mica > kaolinite > mixed-layer mineral	54	24	8	Aragonite, pyrite, feldspar, (gypsum)
66.90-68.90	Clay mica > kaolinite > mixed-layer mineral	56	14	12	Aragonite, pyrite, (gypsum)
81.25-83.25	Clay mica > kaolinite > mixed-layer mineral, chlorite	66	17	7	Aragonite, pyrite
91.25-93.25	Clay mica > kaolinite > mixed-layer mineral	56	14	13	Aragonite, pyrite, (gypsum)
99.25-101.25	Clay mica > kaolinite > mixed layer mineral	55	12	21	Aragonite, pyrite, (gypsum)

Table 4B. X-ray diffraction analyses of Kimmeridge Clay from Donington on Bain Borehole B.

Borehole	Depth m	% w/w loss on drying at 100°C	% w/w ash (600°C)	% kerogen (duplicate)		Oil yield on distillation to 450°C		% w/w sulphur in oil	Lithology
						% w/w	gal/ton		
N. Wootton	36.10	5.07	49.7	42.6	40.7	25.6	61.3	7.5	Oil shale, shelly
N. Wootton	64.00	5.08	61.1	30.9	30.5	16.9	40.5	5.7	Oil shale, shelly
N. Wootton	45.70	4.85	79.4	10.2	10.2	2.4	5.8	6.0	Oil shale, shelly
N. Wootton	75.80	3.14	88.4	3.4	3.3	0.2	0.5	not tested	Mudstone, medium grey, silty
N. Wootton	76.10	5.93	79.7	9.4	9.5	6.0	14.4	4.3	Oil shale, shelly
Setchey	outcrop	not tested	not tested	not tested		19.8	47.4	8.4	Oil shale, shelly
Setchey	outcrop	not tested	not tested	not tested		21.3	51.0	8.5	Oil shale, barren

Table 5. Analyses of some typical Kimmeridge Clay lithologies.

(in Gallois,1979b) and Merriman and Jeans (in Gallois, 1979c).

The identification of the clay minerals was based on the spacings of their basal reflections in the XRD charts. Their relative abundances were then estimated from the intensities of the X-ray peaks. No attempt was made to quantify the various clay minerals but their relative order of abundance was determined. All the earlier analyses were carried out on powdered, whole rock samples and the results are therefore only qualitative (Tables 3 and 4). Facilities were not available at that time for the preparation of orientated samples, which would have enabled semi-quantitative estimates to be made of the various components. The later analyses, by Merriman and Jeans, were made on oriented <2 μm fractions and quantitative results were obtained using the method of Griffin (in Carver, 1971). These are reported elsewhere (in Gallois, 1979c).

The most abundant clay mineral in all the samples was a dioctrahedal phyllosilicate with a basal reflection close to 10 Å which was unaffected by heat or treatment with glycerol. These properties characterise a broad class of minerals that is generally referred to as clay mica or 'illite' and which probably includes materials ranging from clastic flakes of muscovite to degraded, poorly crystallized mica polymorphs.

Kaolinite, a class of minerals with a basal reflection near 7 Å, was recorded in all but four of the samples. It is probably significant that three of the barren samples were limestones, and the fourth a highly calcareous mudstone.

The chlorite class of minerals have basal spacings of about 14 Å that are unaffected by either heat or glycerol. Chlorite was recorded as a minor constituent in 32 of 36 samples from Norfolk but in only 3 of 7 samples from Lincolnshire. It is possible therefore that there are marked local variations in the distribution of chlorite in the

Kimmeridge Clay.

Small quantities of the expansible clay mineral smectite, a class characterized by variable basal spacings that expand to about 17.8 Å on treatment with glycerol and collapse on heating to about 10 Å, were recorded in a few of the limestones and more calcareous mudstones. Discrete smectite is probably very rare or absent in the Kimmeridge Clay of Norfolk, all the smectite recorded in Table 3 being interlayed with other clay minerals. Minor amounts of smectite irregularly interlayed within clay mica have been included with the clay mica in this table.

Some clay mica/smectite mixtures are included with the 'mixed-layer mineral' recorded in the North Runcton and Donington on Bain boreholes (Table 4). This material occurs in all but one of the whole-rock samples from these boreholes and, in addition to clay mica/smectite mixtures, probably includes a variety of expanding and non-expanding irregularly interlayed mixtures including clay mica/kaolinite, clay mica/vermiculite and clay mica/chlorite. It may include material recorded elsewhere in the literature as 'vermiculite'.

There are few published clay-mineral analyses of Kimmeridge Clay other than those referred to above. Perrin (1971, pp. 130-33) collected 13 analyses from various stratigraphical levels in the Kimmeridge Clay from localities between Norfolk and Dorset. These are summarized in Table 6; where possible, the zonal position of the sample has been determined by reference to the original source of the data.

Scanning-electron-microscope examination of gold-coated chips of Kimmeridge Clay mudstones show the clay minerals to be poorly crystalline and to consist of irregular sheets and aggregations of sheets, crudely aligned parallel to the bedding, but locally much distorted by differential

Locality	Grid Reference	Exposure type	Clay Minerals: % total					Zone
			Ka	Il	Sm	Ch	Others	
Southery, Norfolk	TL 613 956	excavation	20	70	-	-	Vm 10	wheatleyensis
Sutton, Cambs.	TL 434 790	quarry	15	80	-	-	Vm 5	baylei
Stretham, Cambs.	TL 519 748	quarry	20	70	-	-	Vm 5	mutabilis
Stretham, Cambs.	TL 498 737	excavation	20	70	-	-	Vm 10	mutabilis
Shotover, Oxon	SP 556 064	quarry	10	45	-	-	Sm/Vm 45	mutabilis ?
Culham, Oxon	SU 510 950	quarry	5	20	75	-	Fel	pallasioides
Aylesbury, Bucks.	SP 798 122	old brickpit	10	30	60	-	Qz	pallasioides
Wheatley, Oxon	SP 587 055	quarry	P	P	P	-	-	eudoxus to autissiodorensis
Warlingham Bh., Surrey	TQ 349 571	2286 to 2295 ft	low	high	-	-	-	pallasioides
Gillingham, Dorset	ST 81 26	quarry	25	50	25	-	Qz	cymodoce
Kimmeridge, Dorset	SY 908 791	cliff	15	70	15	-	-	autissiodorensis
Kimmeridge, Dorset	SY 907 792	cliff	31	69	-	-	An; Qz	autissiodorensis
Ringstead, Dorset	SY 755 814	cliff	16	44	35	5	Qz	mutabilis

Abbreviations: P - present; Ka - kaolinite; Il - clay mica ('illite'); Sm - smectite; An - ankerite; Ch - chlorite; Vm - vermiculite; Fel - feldspar; Qz - quartz.

Table 6. Clay-mineral contents of Kimmeridge Clay samples: collated by Perrin (1971, pp. 130-133). Zonal assignments by present author.

compaction around harder materials such as calcitic fossils (Plate 3).

Where sufficiently separate to be distinguishable, all the particles are extremely small. This is not surprising because most of the clay minerals that dominate the Kimmeridge Clay assemblages - clay mica, chlorite, smectite, vermiculite and mixed-layer minerals - are known to usually occur as small, poorly defined flakes. Clay mica, the most abundant clay mineral in the Kimmeridge Clay, has commonly been recorded elsewhere as flakes only 0.1 to 0.3 μm in diameter, the thinnest flakes being approximately 30 Å (only a few molecules) thick (Grim, 1968, p. 177). Smectite, vermiculite and mixed-layer minerals generally occur as even smaller particles than clay mica (Grim, 1968, pp. 174 and 183). Kaolinite can occur as well-crystallized six-sided flakes up to 4 µm across, but only when well ordered. Disordered kaolinite, such as that indicated by the broad nature of the 7 Å peaks in the Kimmeridge Clay samples, generally occurs as much smaller particles, some of which have poorly developed hexagonal outlines (Grim, 1968, p. 171).

No clay-mineral particle larger than about 0.3 µm diameter was observed in the Kimmeridge Clay. Aggregates of clay minerals commonly form irregular sheets up to 2 µm across in most samples but these can be seen to consist of numerous, much smaller, irregular particles (Plate 3). Poorly crystalline kaolinite was observed in a few samples and possible smectite sheets in others. Individual particles of clay mica, chlorite and vermiculite could not be identified. Small amounts of the fibrous clay mineral palygorskite were recorded in a few of the XRD analyses, but this mineral was not seen in the electron micrographs.

SEM studies of replica films (which avoid the problem of damage

Plate 3. Electron micrographs of mudstone textures. All specimens gold-coated.

A. Dark grey mudstone, fracture surface viewed parallel to bedding. XRD analysis shows composition to be clay minerals (48%), quartz (30%) and calcite (8%). Specimen no. GS 108, photo. no. SEM 18091. Denver Sluice Borehole, 13.06 m, Bed 34. Magnification 120x.

B. As A, dark grey mudstone; fracture surface viewed parallel to bedding and showing clay minerals draped and compacted around shell debris. Specimen no. GS 108, photo. no. SEM 18096. Magnification 1,150x.

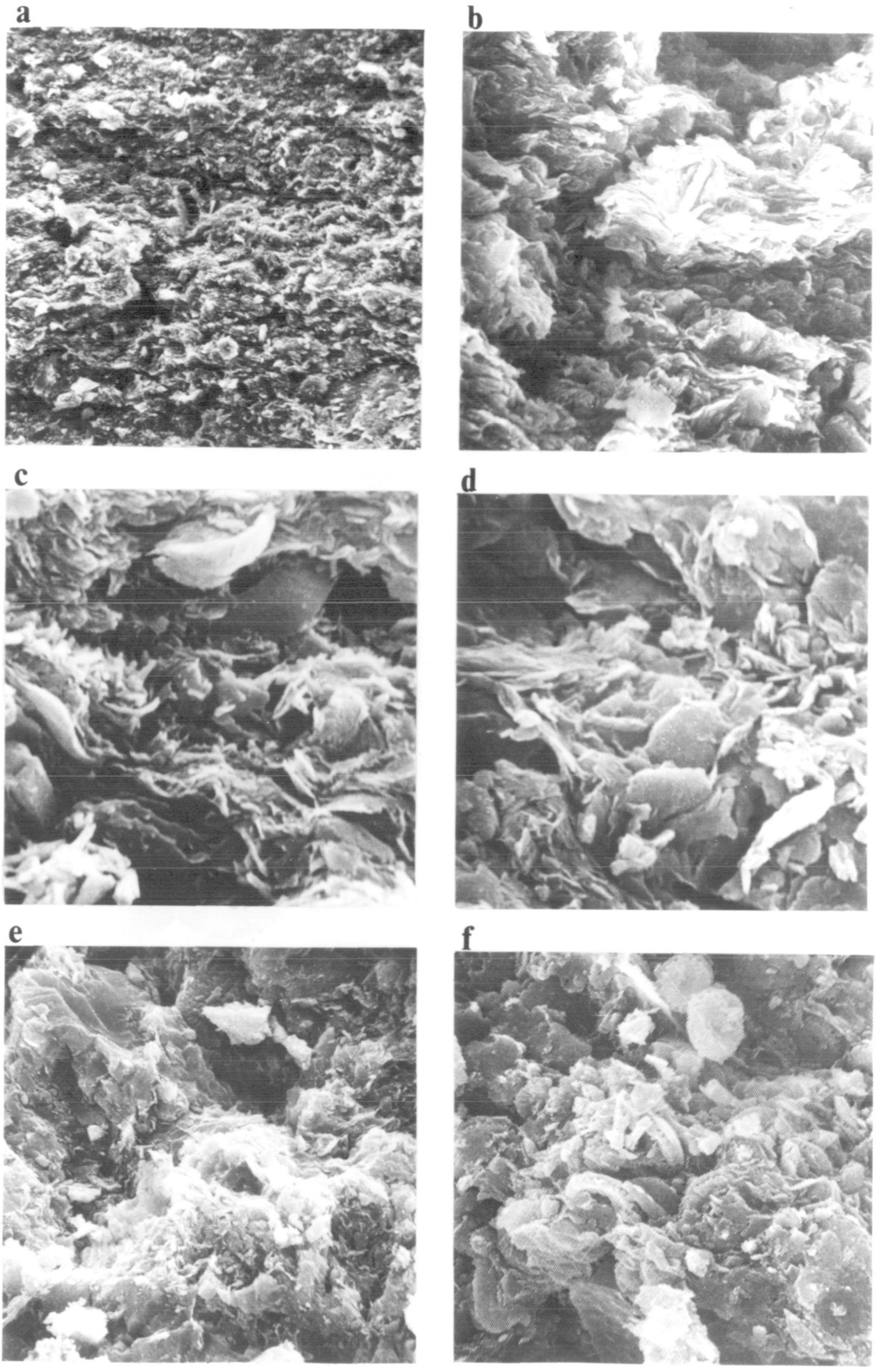
C. Shelly oil shale, fracture surface viewed parallel to bedding; composed of clay minerals (27%), quartz (12%) and calcite (20%). Specimen no. GS 123, photo. no. SEM 18314. North Wootton Borehole, 64.00 m, Bed 32. Magnification 3,000x.

D. Quasi cementstone, fracture surface showing clay-mineral concentration; whole rock composition clay minerals (19%), quartz (3%) and calcite (71%). Specimen no. GS 144, photo. no. SEM 18285. Denver Sluice Borehole, 22.86 m, Bed 30. Magnification 3,000x.

E. Quasi cementstone, fracture surface of D. showing finely crystalline calcite with clay-mineral-rich wisps. Photo. no. SEM 18231. Magnification 600x.

F. Coccolith-rich concentration within pale grey mudstone. Skegness Borehole, 401 ft 6 in., Bed 44. Photo. no. SEM 18117. Magnification 1,200x.

Plate 3



and possible alteration of the clay minerals by the electron beam), combined with transmission electron microscope studies, could yield more information on the crystalline nature of the clay minerals in the Kimmeridge Clay, but their small particle sizes suggest that this would entail considerable effort and might provide little additional data.

2.2.1.2 Quartz

X-ray diffraction analyses of untreated and unorientated samples of typical Kimmeridge Clay lithologies show from 2 to 30% of crystalline quartz. None of this is visible on fracture surfaces with either the naked eye or a binocular microscope at magnifications up to 50X. With the exception of the silty mudstones in the Type A rhythms, the largest amounts of crystalline quartz occur in the smoothest textured dark grey mudstones. This feature has not previously been discussed with respect to British Jurassic mudstones and there are few descriptions of quartz in other mudstones despite the fact that it makes up 20% of Yaalon's (1962) 'average shale'.

Subsequent XRD analyses of the clay fractions (< 2 μm) of selected Kimmeridge Clay mudstones showed them to be almost quartz-free (Merriman and Jeans in Gallois 1979c). In these analyses the clay minerals were basally orientated to give the strongest possible diffraction peaks and it is possible that up to 1% of quartz could have gone undetected due to the masking effect of the strong clay-mineral reflections. Almost all the crystalline quartz recorded in the whole-rock XRD analyses probably occurs as silt-grade particles.

Quartz concentrates were made by removing the carbonate (with acetic acid), kerogen (with hydrogen peroxide and/or ignition) and clay minerals (by ultrasonic disaggregation and decanting) from

typical mudstone lithologies of known composition. The concentrates were then examined optically and with the SEM. They contain very large numbers of grains that vary greatly in size and degree of roundness (Plate 4). The following generalisations are true of the small number of samples examined:

(i) in the most quartz-rich lithologies, some of the dark grey mudstones, the vast majority of the grains are in the range 5 μm to 35 μm (Plate 4); grains between 2 μm and 5 μm and between 35 μm and 55 μm are common, and grains between 55 μm and 70 μm (coarse silt and very fine-grained sand) are rare. Grains less than about 2 μm were probably lost during the preparation of the concentrates, but are assumed from the XRD analyses to be rare.

(ii) in the quartz-poor lithologies, the more calcareous mudstones, grains coarser than about 35 μm are rare; the distribution of grain sizes in lithologies having intermediate quartz contents suggests that there is a decrease in the percentage of larger grains with decreasing quartz content

(iii) the grains vary from very angular to subrounded and have low to moderately high sphericities, but there is no obvious correlation between grain size and shape in the range 10 μm to 70 μm. Many of the smallest grains, <5 μm, have recognisable crystal faces or are relatively unabraded crystals (Plate 4). Arrowhead-shaped flakes, presumably chips from sand grains, are common throughout the size range

(iv) almost all the grains are clear, very pale brown or yellow

Plate 4. Phosphate, pyrite and quartz.

A. Myid bivalves in growth position, infilled with pale brown phosphate. Specimen no. BDU 7749, Ongar Hill Borehole, 76.92 m, within burrows in the top of Bed 7 (2 cm below the base of Bed 8). Natural size.

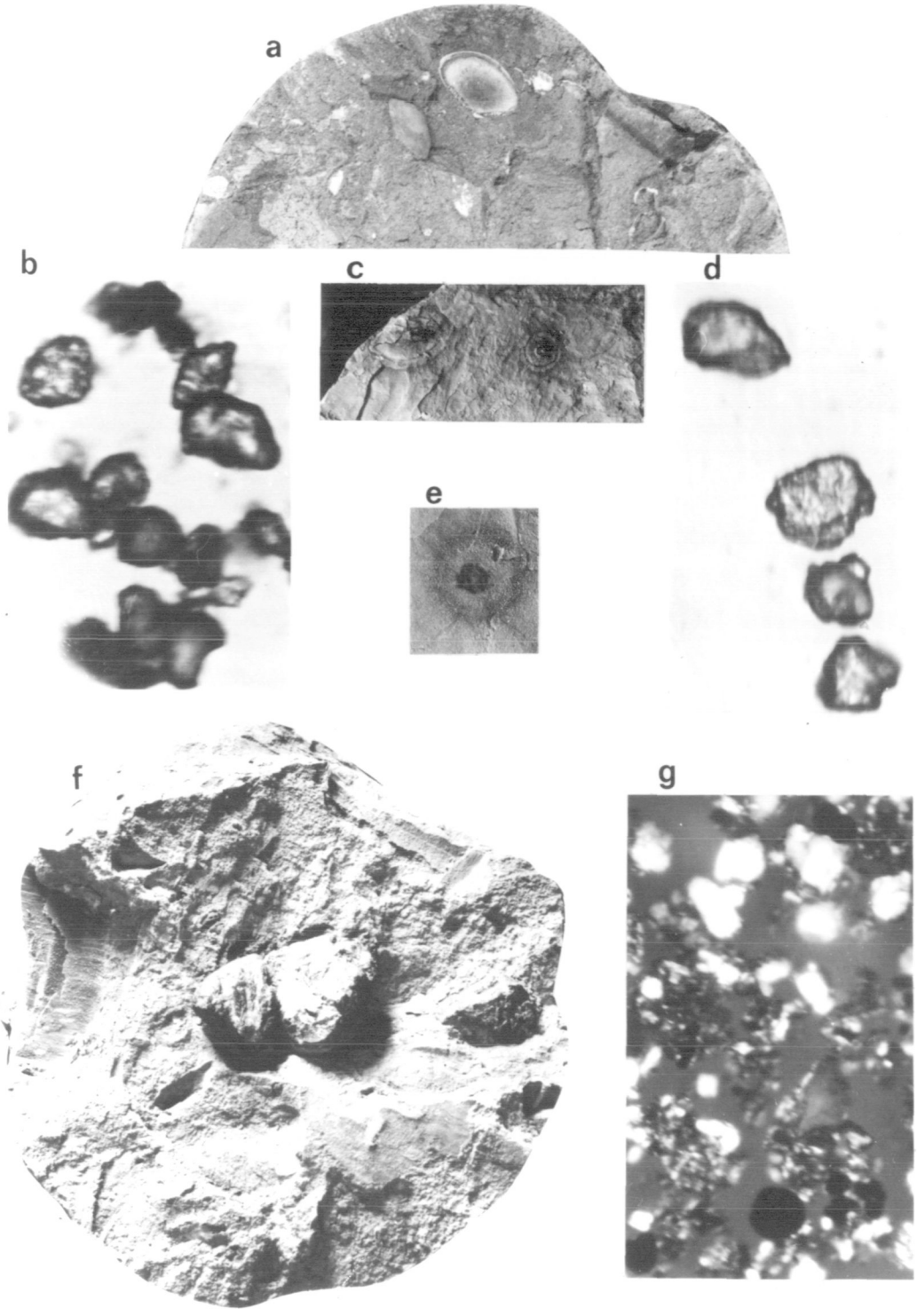
B., D. Silt-grade quartz grains; coarse fraction of dark grey sparsely shelly mudstone (total quartz content 30%) after removal of carbonates with acid, kerogen by oxidation and clay and fine silt by decanting. Specimen GS 108, Denver Sluice Borehole, 13.06 to 13.38 m, Bed 34. Magnification 300x.

C., E. Vertical small-diameter pyritized burrows viewed normal to bedding; partially oxidised with halos of limonite. C, Tisbury Borehole, 79.90 m; E, Tisbury Borehole, 92.90 m. Natural size.

F. Rounded pebbles of hard black phosphate in bioturbated silty mudstone. Specimen no. BDU 7753, Ongar Hill Borehole, 78.10 m, Bed 5. Natural size.

G. Pyrite framboids (black), quartz grains (white) and kerogen particles (grey); unsorted fraction of dark grey sparsely shelly clay after removal of carbonates and clay-grade particles. Specimen GS 108, as B, D. Magnification 300x.

Plate 4



monocrystalline quartz; staining and/or inclusions are common in the larger grains.

The origin of this quartz is discussed in Section 2.4. Quartz of obvious clastic origin occurs as angular, coarse (visible to the naked eye) silt-grade particles in high concentrations in the silty mudstones and siltstones at the bases of the Type A rhythms of Figure 5.

2.2.1.3 Calcium carbonate

Calcium carbonate of obvious biogenic origin occurs throughout the Kimmeridge Clay in the form of macroscopic and microscope calcareous fossils. Differences in the nature of preservation of the fossils in the Kimmeridge Clay commonly reflect original differences in the shell composition, calcitic shells being generally better preserved than aragonitic shells. In the least permeable mudstones, aragonitic shells such as ammonites commonly retain their iridescence whereas in the more permeable lithologies they have inverted to a soft white calcite. In the more permeable mudstones only calcitic fossils such as oysters, brachiopods and belemnites have retained their original structure. At some levels aragonitic fossils are preserved as 'ghosts', clay casts with a film of calcite, and the dissolved calcium carbonate has provided the cement for calcitic concretions. The original composition of the shell structure of the more common fossils in the Kimmeridge Clay can be summarised as follows:

Aragonite	Aragonite/Calcite	Calcite
ammonites	some bivalves	brachiopods
scaphopods	(e.g. Pinna)	echinoids
most burrowing bivalves		crinoids
		coccoliths
		foraminifera
		most bysally attached bivalves
		oysters

Calcimeter analyses have shown that the palest coloured mudstones in the Kimmeridge Clay contain up to 55% of calcium carbonate (Tables 3 and 4). Other lithologies contain lesser amounts, some of the darkest coloured mudstones having as little as 5%. X-ray diffraction analyses have shown that the bulk of the calcium carbonate in the matrix occurs as finely crystalline calcite. Aragonite is present only as an accessory mineral.

With the exception of the shelly fauna described above, none of the calcite is sufficiently coarsely crystalline to be satisfactorily resolved with an optical microscope. SEM studies show this fine-grained calcite to consist of a number of components, prominent among which are fragments of coccoliths, calcispheres (Plate 5), foraminifera and probably bivalves. Coccoliths and their disarticulated plates may constitute up to 15% of the micrite in some of the more calcareous lithologies. Small patches of almost any lithology can appear to be almost wholly composed of coccoliths under the SEM and these are probably collapsed coccospheres. Undamaged coccospheres are rare in the Kimmeridge Clay except in the coccolith-rich limestone bands described in Section 2.2.1.7.

Much of the remaining micrite occurs in the form of crystals and aggregates of crystals in a clay-mineral matrix. Small patches of

Plate 5. Electron micrographs of calcispheres.

A. Complete calcisphere. Specimen no. GS 144, Denver Sluice Borehole, 22.86 m, Bed 29. Photo. no. SEM 18275. Magnification 1,200x.

B. Detail of outer layer of A. showing radially orientated prismatic calcite crystals with some dissolution. Photo. no. SEM 18273. Magnification 6,000x.

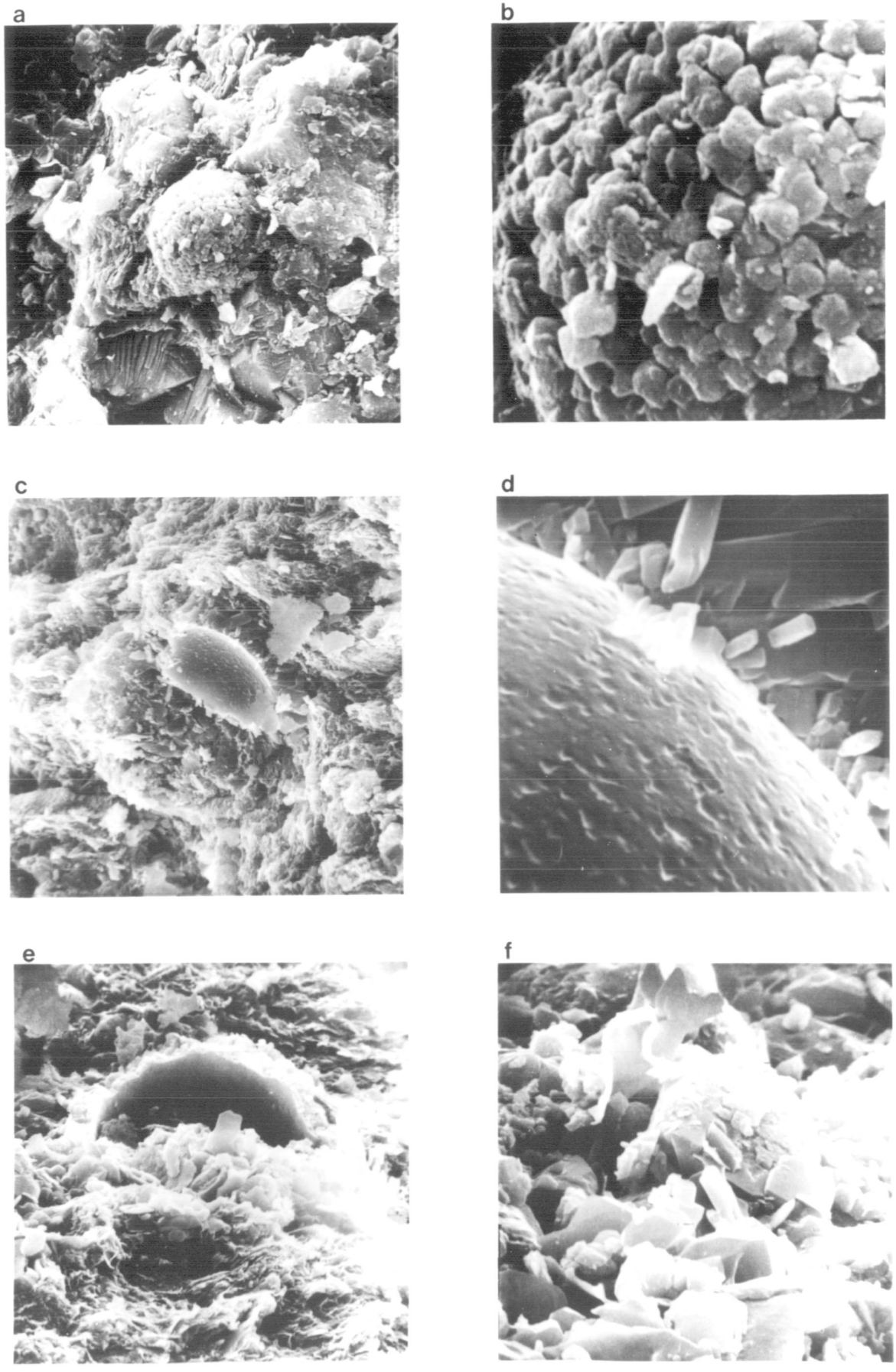
C. Broken calcisphere partially infilled with sediment. Specimen no. GS 123, North Wootton Borehole, 64.00 m, Bed 32. Photo. no. SEM 18324. Magnification 600x.

D. Detail of calcisphere in C. showing junction of outer prismatic layer and smooth, pitted inner layer. Photo. no. SEM 18321. Magnification 6,000x.

E. Broken calcisphere partially infilled with micritic cement. Specimen no. GS 123. Photo. no. SEM 18316. Magnification 1,200x.

F. Detail of calcite crystals in E. Photo. no. SEM 18319. Magnification 3,000x.

Plate 5



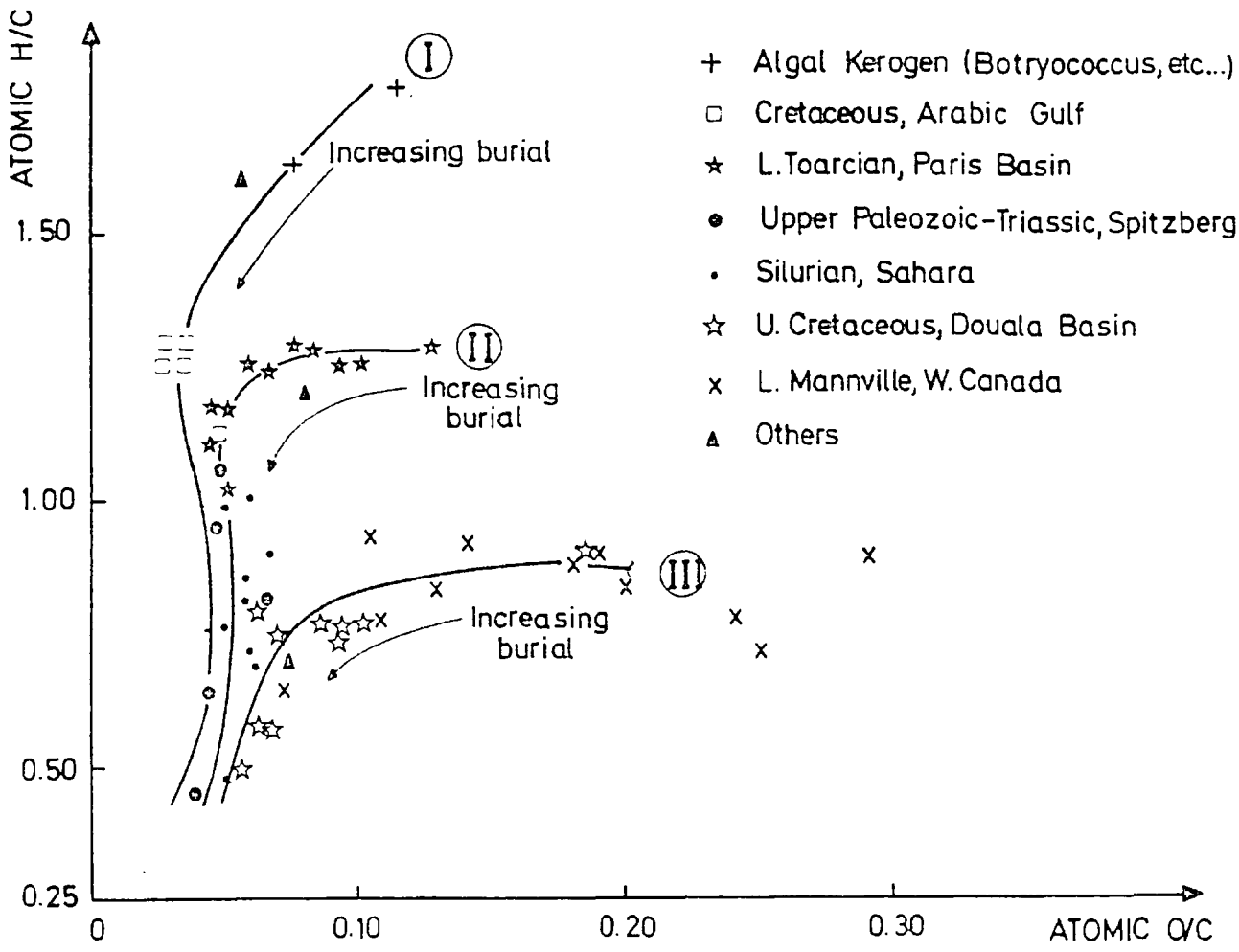
recrystallized calcite spar occur in what were formerly free spaces in the rock, notably inside foraminifera tests and calcispheres (Plate 5). Most of these crystals are prismatic and 2 to 3 μm in length, a form described by Folk (1974) as typical of calcite precipitation in a magnesium-rich environment (cf. sea-water).

The occurrence of diagenetic calcite, in the form of calcitic doggers and septaria, is discussed in Section 2.2.1.7.

2.2.1.4 Kerogen

The term kerogen was introduced by Crum-Brown (1927) to describe that part of the organic fraction of a sediment which is insoluble in normal organic solvents at ambient temperature and pressure and which on thermal-decomposition gives rise to shale oil. In practice this definition covers a large group of enormously complex organic compounds with molecular weights in the range of thousands to tens of thousands. It excludes the soluble organic fraction, generally referred to as 'bitumen', which in modern sediments consists largely of biolipids and in ancient sediments of free oil.

In ancient sediments, kerogen is generally believed to have formed by low-temperature diagenesis and polymerisation of biolipids soon after deposition. The composition of the kerogen in any particular sediment will therefore clearly depend upon a number of factors. The most important of these are thought to be the nature of the source material (Fig. 8), its weathering history, its transport history and the chemical conditions present just below the sediment-water interface. After formation, the kerogen continues to mature slowly, almost wholly under the action of temperature. The rate at which this process proceeds is therefore largely governed by depth of burial and the local geothermal gradient. Given sufficiently high temperatures and a sufficiently long period of time all kerogens will degenerate, by loss of carbon dioxide,



Types of kerogen: I.....Algal II.....Mixed I and III
III.....Higher plants.

Figure 8. Van Krevelen diagram showing variation of atomic H/C and O/C ratios with diagenesis for kerogens of differing origins (after Tissot et al., 1974).

methane and water, to graphite (Fig. 8).

In recent years kerogen has been used to describe all insoluble complex organic materials in sediments. Using this broader definition the Kimmeridge Clay contains two distinct types of kerogen, coalified debris of terrestrial plants, and amorphous kerogen derived largely from marine organisms. The origin of the first type is obvious and is not discussed here. Kerogen in the strict Crum-Brown sense is a minor constituent of most Kimmeridge Clay mudstones and is a major constituent of the oil shales. These shales yield substantial quantities of oil when pyrolysed in an inert atmosphere at temperatures over about 400°C due to thermal breakdown of the kerogen. They yield oils rather than hydrocarbon gases because the atomic hydrogen to carbon ratios of their kerogens is more conducive to the formation of long-chain organic compounds than it is to short-chain gaseous compounds. Other kerogens, notably those formed from higher plants, tend to yield hydrocarbon gases (Fig. 8).

Because of its amorphous nature (no reflection with XRD) and the difficulty of separating it from other mineral constituents, kerogen contents are difficult to measure. Potential oil yields are, however, readily determinable and these can give indirect approximations of kerogen contents. In the Kimmeridge Clay, 1 wt% kerogen yields about 1.5 gal. oil/ton shale (Section 2.2.1.8). The relationship of potential oil yield to the composition of the crystalline minerals in bulk samples from the oil-shale-rich part of the North Runcton Borehole is shown graphically in Figure 9.

In thin section in transmitted light the bulk of the kerogen in untreated oil shales or mudstones in the Kimmeridge Clay appears as yellow to pale brown translucent laths or irregular sheets aligned

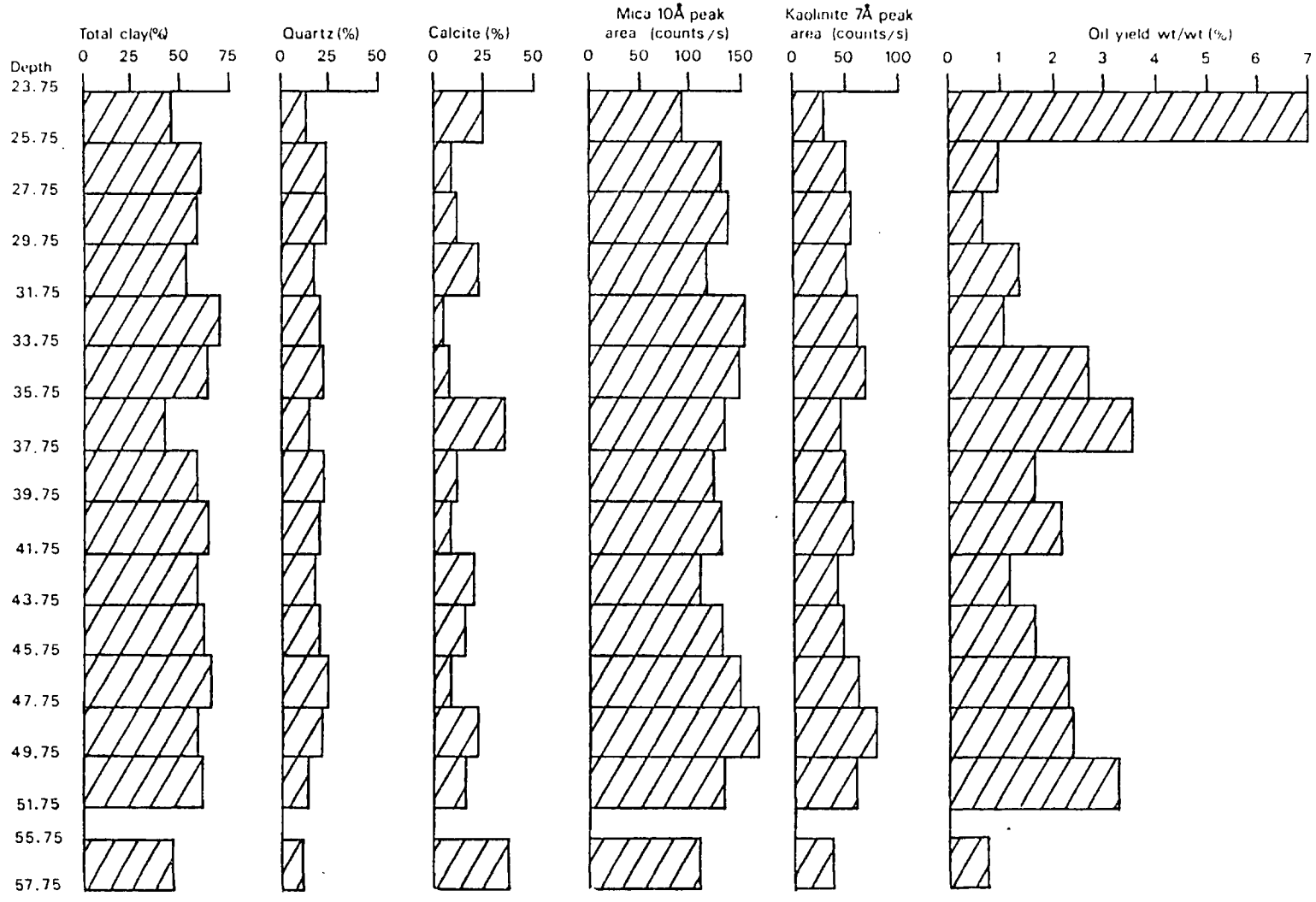


Figure 9. Relationship of mineralogy to potential oil yield for part of the North Runcton Borehole.

roughly parallel to the bedding. Recognisable organic remains are rare although land-derived plant spores, dinoflagellates, the algal body Tasmanites and parts of the chitinous films of foraminifera are present. Pure kerogen concentrates can be prepared by successive treatment of the rock with weak acid (to remove the $CaCO_3$), hydroflouric acid (to remove quartz and clay minerals) and controlled oxidation with lithium aluminium hydride (to remove pyrite) following the method described by Saxby (1976). A quicker and simpler method of concentration, but one which can retain appreciable quantities of inorganic contaminants, consists of crushing followed by acid treatment and flotation to separate out the low density kerogen.

Strew slides of kerogen concentrates made by this latter method consist largely of pale yellow amorphous organic matter (Plate 6) composed mostly of exinite. This indicates that the organic matter has suffered little thermal maturation. Vitrinite and inertinite, both of which components are probably derived from older rocks or carbonised wood in the case of the Norfolk Kimmeridge Clay, are comparatively rare.

2.2.1.5 Pyrite, phosphate and other minerals

Pyrite (FeS_2) is common in the Kimmeridge Clay, occurring mostly as a coating or replacement of fossils, trails and burrows. Less commonly, it occurs as thin, impersistent tabular beds or as part of the cementing matrix of a calcareous concretion or a silty mudstone. The thickest band of pyrite recorded in the Kimmeridge Clay in boreholes in Norfolk is 2 cm thick, but slabs up to 10 cm thick occur in the Kimmeridge Clay spoil from the Flood Relief Channel between Downham Market and Stowbridge.

The commonest forms of pyrite in the Kimmeridge Clay are the burrowfills (burrow infillings) known as 'pins' and 'knots'. These

Plate 6. Selected kerogen components from the Kimmeridge Clay. All photographs are of + 20μ fractions sieved from kerogen concentrates, at 300x magnification.

A. Foraminiferal sheaths in a concentrate rich in amorphous sapropel; custers of well-developed pyrite framboids (arrowed) are common within the kerogen. Specimen no. KOS 930, Kimmeridge Bay Borehole, 54.88 m, eudoxus Zone.

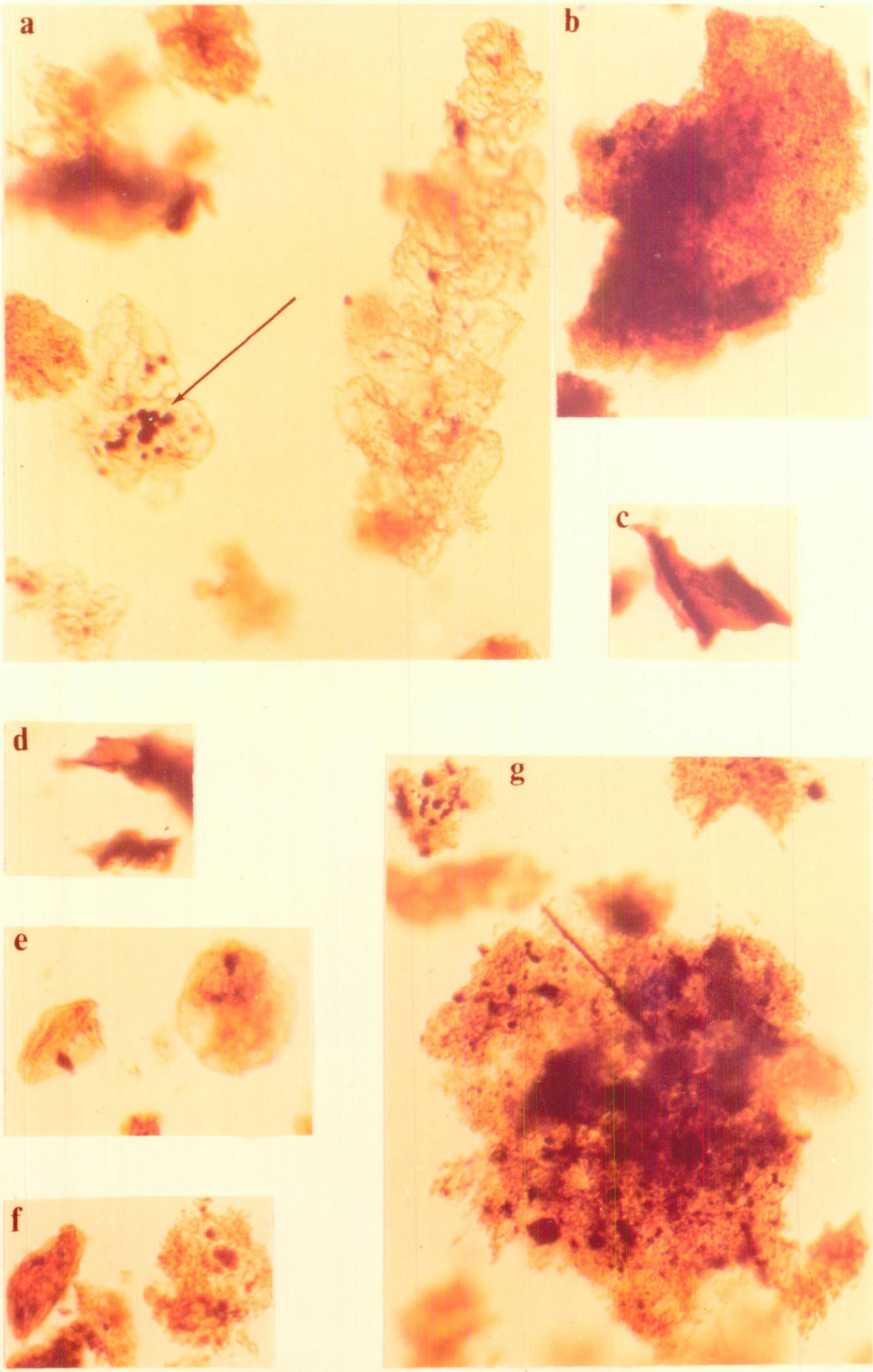
B. Amorphous sapropel showing the characteristic 'kerogen grumuleuse' texture or French authors. Specimen no. KOS 933, Donington on Bain Borehole, 46.43 m, Bed 42.

C, D. Vitrinite, a rare constituent of the English Kimmeridge Clay, from the vitrinite-rich Kimmeridge Clay of Lothbeg Bay, Helmsdale, Sutherland. Specimen no. KOS 908, Lower Kimmeridge Clay.

E, F. Spores and some amorphous sapropel from the Kimmeridge Clay of Ethie, Cromarty, a sequence much richer in land-derived organic constituents than any in the English Kimmeridge Clay. Specimen no. KOS 907, mutabilis Zone.

G. Amorphous sapropel with 'grumuleuse' texture and scattered concentrations of pyrite framboids (e.g. top left). Specimen no. KOS 930, as A.

Plate 6



are particularly common in the paler mudstones where many are preserved as hollow pyritized tubes. In some of the larger examples the pyrite crystals have free faces on the inside of the tube indicating that crystal growth progressed from the burrow-wall towards the axis of the burrow whilst it was still empty of sediment. Further evidence of the early diagenetic origin of much of the pyrite is provided by the selective pyritisation of some trails and Chondrites burrows. This must have occurred whilst the burrows were still open because the infillings of both pyrite and mud are now preserved in an impermeable mudstone matrix. Pyrite also occurs as minute framboidal spheres (1 to 5 μm diameter), aggregates of spheres (5 to 30 μm across) and small rounded concretions (30 to 50 μm across) that have probably grown from framboids. Because of their size the smaller spheres can only be satisfactorily observed with the SEM. They are common (Plate 4) in the unoxidised quartz concentrates made from all the Kimmeridge Clay mudstones but appear to be most common in the kerogen-rich horizons. Kerogen concentrates commonly show clusters of framboids trapped within amorphous kerogen laths. Similar pyritic spheres have been described from a number of other 'Black shales' including the Lias (Love, 1964) and modern sediments in the Black Sea (Degens et al., 1978). Their origin is discussed in Section 2.4.

A completely gradational process of increasing phosphatisation can be observed in the Kimmeridge Clay in which patches of soft, partially phosphatised mudstone pass into dense phosphatic pebbles. Four main stages of phosphatisation can be recognised (Plate 4):

(i) formation of pale brown patches of soft, partially phosphatised mudstone with diffuse edges. Such patches are especially common in the most calcareous mudstones and are

often penetrated by burrows, such as Chondrites, that are infilled with darker, unphosphatised, mudstone indicating that the phosphatic patch must have been formed, but still have been soft, prior to the burrowing.

(ii) increasing phosphatisation produces medium brown, hard areas in the centres of some of the partially phosphatised patches; similar medium brown phosphate also occurs as infillings of deep burrowing bivalves, such as myids and Thracia, in growth position and within ammonite, gastropod and serpulid body chambers.

(iii) with increasing phosphatisation, dense dark brown phosphate occurs as nodules with well defined edges, as infillings of shells and, sparingly, as replacement of shells.

(iv) reworking and further phosphatisation produces dense, almost black phosphatic pebbles, many of which are casts of bivalves or ammonite body chambers.

Phosphate is also common in the oil shales in the Kimmeridge Clay as phosphatized vertebrate remains such as fish scales, teeth and bones, and faecal pellets.

The XRD analyses show that small amounts of dolomite and feldspar occur at a number of levels in the Kimmeridge Clay of Norfolk. The hydrated sulphate gypsum is almost ubiquitous in dried-out cores of Kimmeridge Clay and in weathered sections; lesser amounts of jarosite and its sodium equivalent natrojarosite are also commonly present.

Feldspar has only been recorded in the oil shales, but it is rare and there are too few analyses to determine its distribution. A few small grains of possible feldspar were noted in the quartz concentrates.

Dolomite occurs as a minor constituent in a large number of the

Norfolk samples. In Dorset most of the tabular limestones of the Kimmeridge Bay cliff sections (the various named 'stone bands' of Arkell, 1933) have been described by Downie (1957) as dolomites and as ferroan dolomites and ankerites by Irwin et al. (1977). Dolomite appears to be confined to dark grey mudstones in Norfolk and to be absent from the limestones. Irwin et al.(1977) have suggested from a study of their chemistry (including C and O isotopes) that the formation of diagenetic dolomites in the Dorset Kimmeridge Clay is dependent upon a rapid rate of sedimentation. They have argued that Fe- and Mg-rich solutions can be protected from oxidation and leaching if they pass through the zone of bacterial action within the sediment sufficiently quickly. Slow sedimentation, and thereby longer exposure to this bacterial action, might be expected to produce calcite-rich limestones such as those observed in Norfolk. The Irwin model has yet to be tested outside Dorset but work currently in hand at IGS and Sheffield University includes similar chemical and isotopic analyses of limestones and calcareous mudstones from Norfolk.

It has long been recognised (see Russell and Parker,1979 for review) that the most obvious weathering feature of Mesozoic pyritic clays is that produced by the oxidation of pyrite and the consequent interaction of its decay products with calcium carbonate and clay minerals to produce the hydrated sulphates gypsum ($CaSO_4.2\ H_2O$), jarosite $K\ Fe_3\ (SO_4)_2\ (OH)_6$ and natrojarosite $Na\ Fe_3\ (SO_4)_2\ (OH)_6$. The more important reactions can be summarised as follows:

$$2\ FeS_2 + 7\ O_2 + 2\ H_2O \longrightarrow 2\ Fe^{2+} + 4\ SO_4^{2-} + 4\ H^+$$

$$CaCO_3 + 2\ H^+ + SO_4^{2-} + H_2O \longrightarrow Ca\ SO_4.2\ H_2O + CO_2$$

Oxidation of the ferrous iron, combined with the extraction of potassium from clay mica by acidic porewater in the presence of

sulphate irons, enables jarosite to form. A supply of sodium from the caustic soda used in many drilling muds or, at outcrop, from sea-spray enables natrojarosite to form. If left untreated (one common treatment is to paint specimens with a polyvinyl acetate-solution to exclude moisture) calcareous fossils preserved in pyritic clays become incrusted with 'pyrite mould', a yellow and white powdered or finely crystalline mixture of these hydrated sulphates. Pyritic fossils are usually totally destroyed.

The Kimmeridge Clay of Norfolk is a lightly over-consolidated mudstone with a relatively high natural porosity and has moisture contents generally in the range 18 to 30 wt %. If core samples of such a material are prevented from drying out (e.g. by the common engineering practice of loosely wrapping the cores in polythene) the calcitic fauna and flora can be destroyed by the odixation reactions described above. Even when the core has dried out rapidly in a warm, well ventilated room, some sulphates form at the expense of the calcite.

Gypsum therefore appears as a ubiquitous accessory mineral in XRD analyses of the pyritic parts of the Kimmeridge Clay. In hand specimen it appears as silt or sand grade aggregates of minute crystals regularly spaced on bedding planes and shells (Plate 7) and on the edges the core as concentrations along selected bedding planes. With the SEM these aggregates can be seen to be 'flowers' of well formed platy, prismatic and acicular crystals of gypsum (Plate 7). In addition to these visible aggregates, gypsum also occurs as single acicular crystals and interwoven clusters of crystals, mostly 1 to 2 μm in length, within the pore spaces of the rock (Plate 7). In many cases these small crystals occur adjacent

Plate 7. Secondary gypsum in Kimmeridge Clay cores.

A. Expansion cracks formed in mudstone core by the growth of gypsum crystals in damp core stored in polythene bags in a heated store. North Runcton Borehole, Upper Kimmeridge Clay. Natural size.

B., E. Electron micrographs of gypsum flowers growing on a bivalve shell at the expense of the underlying calcite. Skegness Borehole, 401 ft 6 in.; B., photo. no. SEM 18132, Magnification 560x. E. photo. no. SEM 18130, Magnification 60x.

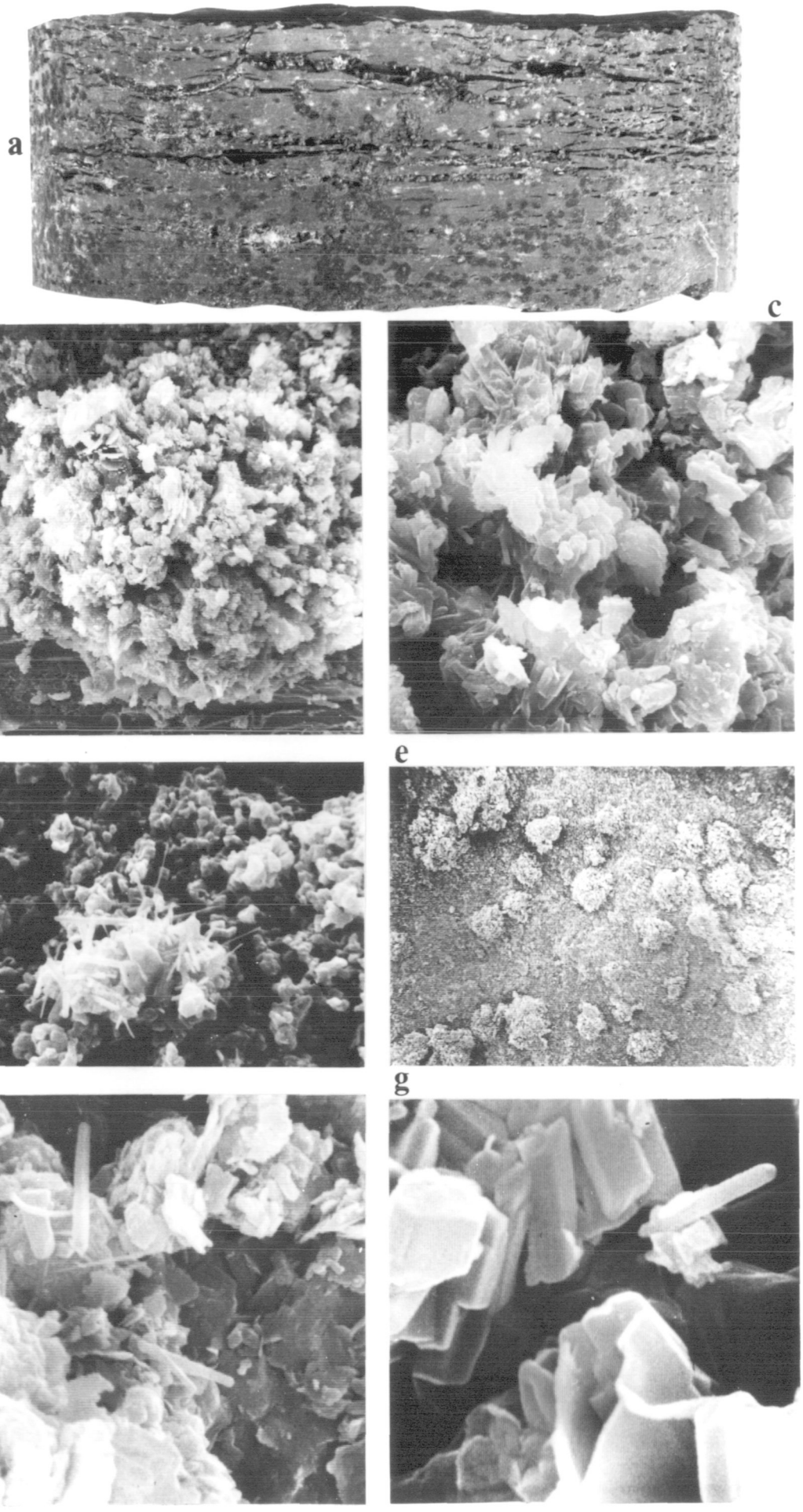
C. Detail of swallow-tail twinning in gypsum crystals (detail of B.). Photo. no. SEM 18139, Magnification 2,200x.

D. Small rose of acicular gypsum crystals growing on a partially dissolved shell fragment. North Wootton Borehole, 64.00 m. Photo no. SEM 18309. Magnification 5,600x.

F. Gypsum needles within the pore space of a calcareous mudstone. Locality as B., photo. no. SEM 18127. Magnification 6,800x.

G. Prismatic and acicular gypsum crystals growing into a pore space in dried-out mudstone. Locality as B. Photo. no. SEM 18134. Magnification 12,400x.

Plate 7



to undamaged coccoliths and must have formed from a gypsum-rich solution that had formed elsewhere. They could be mistaken for aragonite needles (Plate 7); they are, however, readily soluble in water. Larger gypsum crystals and crystal aggregates can be rapidly identified in the field by heating the rock to about 250°C (Shearman, 1979). At this temperature the gypsum partially dehydrates to form a brilliant white powder of amorphous hemihydrate.

A small number of minerals occur in the quartz concentrates, mostly in the range 10 to 40 μm, that were not recorded in the XRD analyses. These include relatively common glauconite, and apatite biotite, sericite and possible rutile.

2.2.1.6 Mudstones

The stratigraphical distribution of the main lithologies in the Kimmeridge Clay in Norfolk is summarized in Figure 10; the bed numbers are explained in Section 2.3.

More than 98% by volume of the sequence is composed of soft mudstones. The most obvious lithological variation in these mudstones is their colour. This ranges from very dark grey to very pale grey; five shades can readily be recognised in hand specimen - very dark, dark, medium, pale and very pale. With practice, these shades can be recognised in either wet or dry samples. In the present work all the cores were examined dry because it is difficult to make clean fractures in wet Kimmeridge Clay cores and impossible to collect undamaged fossils before the cores have dried out. Furthermore, colours are a transient feature in the wet mudstones, the shades becoming darker with increasing moisture content, and only dry cores give repeatable results. The mudstones cannot be re-wetted once dry because of changes in their fabric that occur during drying due to the formation of sulphates etc. Examples of dry mudstone are shown in Plate 8.

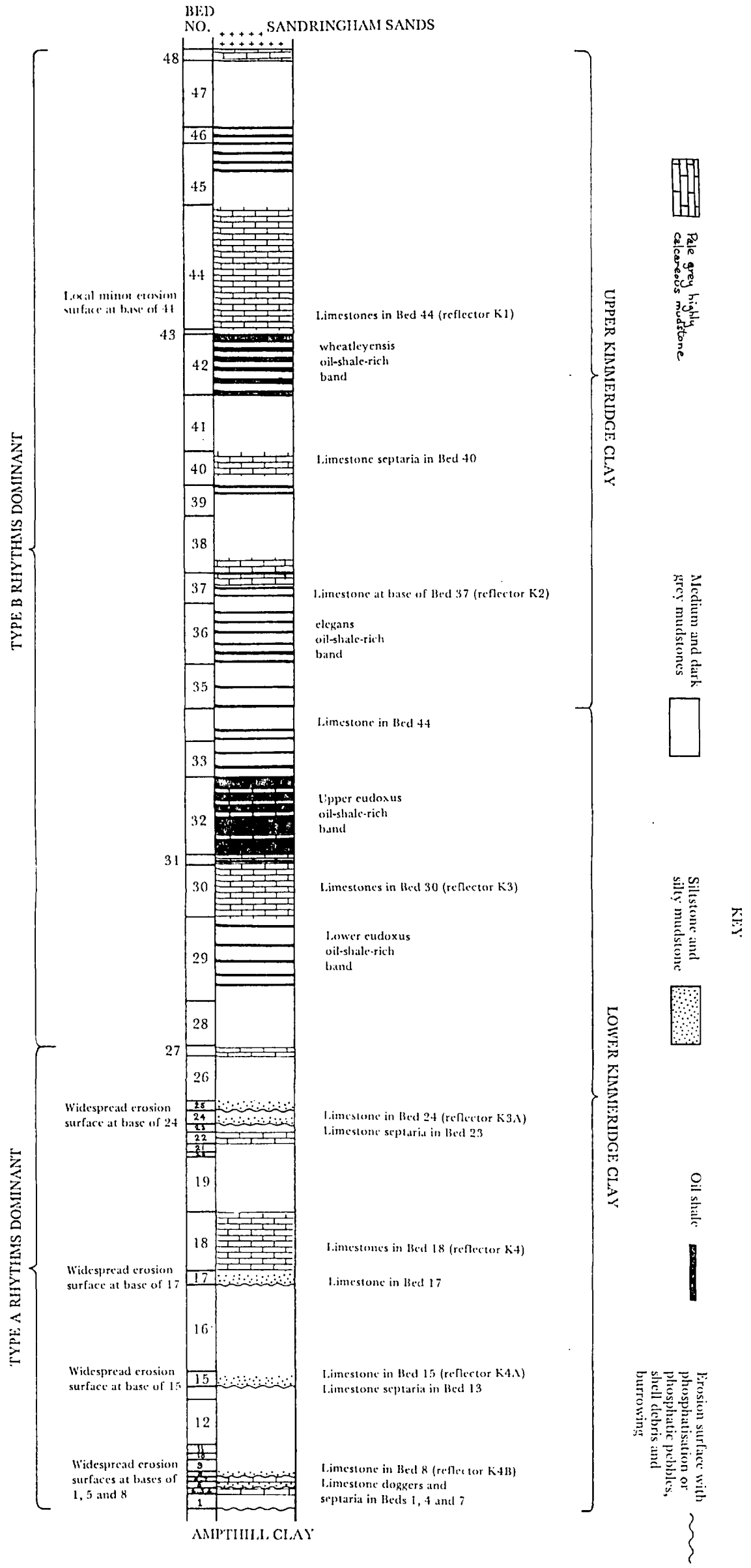


Figure 10. Generalized vertical section of the Kimmeridge Clay of Norfolk showing the distribution of lithologies.

At many levels in the Kimmeridge Clay shades intermediate between the five listed above can be recognised. This is especially easy where burrowing causes slightly different shades to be juxtaposed. None of these shades can be closely matched with those of the Geological Society of America Rock-Color Chart (1970), partly because of the difficulty of comparing irregular, unevenly coloured rock surfaces with uniformly printed colours. Olive gray (5Y4/1) and Medium dark gray (N4) in the Chart are near to some of the dark greys of the present classification; no other shade was found to be particularly close.

The colours of the Kimmeridge Clay mudstones are largely related to their calcium carbonate contents, the palest mudstones having the highest carbonate contents. It is commonly suggested that the colours of Mesozoic clays are mostly controlled by the amounts of carbonized plant debris that they contain. Whilst it is true that the colour of the darkest Kimmeridge Clay mudstones is due to large amounts of this material, it does not appear to be true in the other mudstones.

Lithological variations in the Kimmeridge Clay mudstones can also be detected by means of the two related features of texture and the nature of their fracture. In the absence of shells, plant debris or silt, the dark grey mudstones generally have a smooth texture and a straight, blocky fracture. With increase in calcium carbonate this fracture becomes more curved until a sub-conchoidal fracture is characteristic of the most calcareous mudstones. At outcrop, these latter commonly develop a distinctive reticulate pattern of shrinkage cracks that Blake (1875) graphically described as "dicey" (Plate 2). The addition of silt or the presence of bioturbation produces an irregular, rough fracture in all the mudstones. The presence of

Plate 8. Mudstone textures; photographs at natural size.

A. Pale to medium grey mudstone with smooth texture, subconcoidal fracture and few fossils other than small oysters and thin trails. Specimen no. BDK 8537, North Wootton Borehole, 119.60 m, basal Kimmeridge Clay.

B. Dark grey mudstone, barren except for fish debris, with no obvious trace of bedding; finely irregular to smooth fracture. Specimen no. BDU 8778, North Wootton Borehole, 58.17 m, Bed 33.

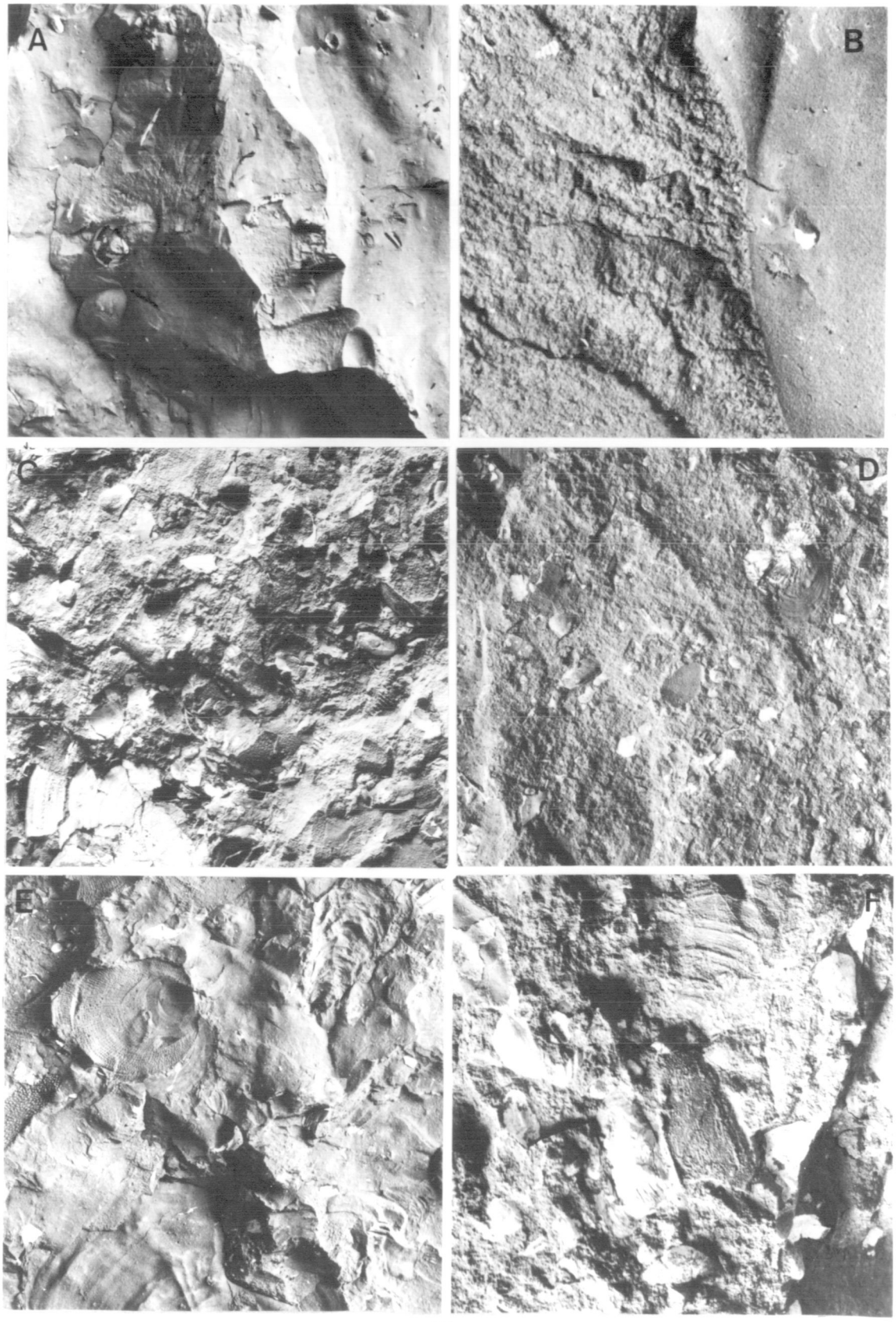
C. Shelly, medium grey mudstone with much bioturbation and many shell fragments including bivalves and Aulacostephanus; irregular fracture. Specimen no. BDK 8201, North Wootton Borehole, 101.06 m, Bed 17.

D. Bioturbated mixture of brown oil shale and medium grey mudstone with a few shelly fossils (including Amoebites) and an irregular fracture. Specimen no. BDK 7770, North Wootton Borehole, 74.89 m, Bed 29.

E. Oyster-rich pale grey mudstone with irregular fracture due to shell (mostly oysters) concentration. Specimen no. BDK 7969, North Wootton Borehole, 86.26 m, Bed 26.

F. Silty, shelly mudstone, bioturbated and with scattered phosphatic pebbles, giving rise to very irregular fracture. Specimen no. BDU 8664, Symington Farm Borehole, 63.55 m, Bed 15.

Plate 8



concentrations of shelly material, plant or other organic material along bedding planes gives rise to fissility on drying out or weathering. The oil shales are noticeably resistant to weathering and form hard ribs at outcrop (Plate 2).

2.2.1.7 Limestones

One of the prime aims of the stratigraphical work for the Wash Water Storage Feasibility Study was to identify the levels at which persistent limestones occur and impersistent limestones were likely to occur in the Kimmeridge Clay. At the time of the study the most economical type of aqueduct construction available was that of standard 100-in (2.54-m) diameter tunnels, bored by a soft-ground shield and lined with expanded concrete rings (Tattersall segments). Such a system could cope with only a small amount of limestone if it were to remain cost effective.

The following six types of limestone were identified in the study; in the past, the term 'cementstone' has been used to describe several of these:

(i) Muddy limestone - the most common type; present at several levels

(ii) Silty limestone - the second most common type; prominent bands occur in the Lower Kimmeridge Clay

(iii) Bituminous limestone - restricted to two bands

(iv) Septarian nodules - present at many levels; mostly laterally widely-spaced

(v) Shelly limestone - rare

(vi) Coccolith limestone - present as very thin (1 to 50 mm thick) bands at 10 levels.

The stratigraphical distribution of limestones recorded in the

cored boreholes in the Kimmeridge Clay in Norfolk is summarized in Table 7. It should be noted that the reliability of the information is uneven because some stratigraphical horizons were cored as many as twelve times, whereas others were cored only twice. Widely spaced doggers are likely to have been missed where they occur at stratigraphically horizons that were sampled only a few times.

A continuous tabular calcareous sandstone at the base of the overlying Sandringham Sands is included in Table 7 for completeness because it forms an important seismic reflector which marks the top of the Kimmeridge Clay beneath The Wash. The coccolith limestones have been omitted because of their thinness; they are discussed separately below. Those limestones which formed persistent reflectors in the seismic (sparker) traverses carried out in The Wash are thought to be continuous tabular beds or lines of closely-spaced doggers that strongly influence the sub-glacial topography in that area (Fig. 11). These are numbered in Table 7 (K1 = first Kimmeridge reflection signal) in accordance with the geological interpretations of the sparker traverses (Wingfield et al., 1979). The strongest reflectors, K1 to K4, are sufficiently persistent for their outcrops, and subcrops beneath drift deposits, to be plotted on the geological map (Gallois et al. 1978).

Fifteen limestone horizons have been identified in the Kimmeridge Clay. Nine of these were recorded as single occurrences (mostly widely-spaced doggers); the remaining six are probably persistent tabular beds or closely spaced doggers. Three of the single occurrences (those in Beds 8, 17 and 24) occur at outcrop elsewhere in England and are persistent horizons, but made up of widely spaced concretions. The fifteen horizons can be divided into muddy limestones (5 horizons),

Stratigraphical horizon	No. of times stratigraphical horizon penetrated in boreholes	Total no. of limestones recorded	Maximum no. of limestone bands in any one borehole	Seismic reflector	Lithology
Base of Sandringham Sands	6	6	1	K0	calcareous sandstone
Bed 44	6	6	1	K1	muddy
Bed 40	5	1	1		septarian
Bed 37	2	2	1	K2	bituminous
Bed 34	4	1	1		bituminous
Bed 30	3	3	2	K3	muddy
Bed 24	9	1	1	K3A	silty
Bed 23	9	1	1		septarian
Bed 18	10	8	2	K4	muddy
Bed 17	10	1	1		silty
Bed 15	10	3	1	K4A	silty
Bed 13	9	1	1		septarian
Bed 8	12	1	1	K4B	silty
Bed 7	12	1	1		septarian
Bed 4	11	3	1		muddy
Bed 1	12	1	1		muddy

Source of data: Wash feasibility study cored boreholes (1972) and IGS cored boreholes 71/65; 71/66; Skegness, Hunstanton, Gayton and Marham. Coccolith-rich bands omitted.

Table 7. Distribution of limestones in the Kimmeridge Clay in Norfolk.

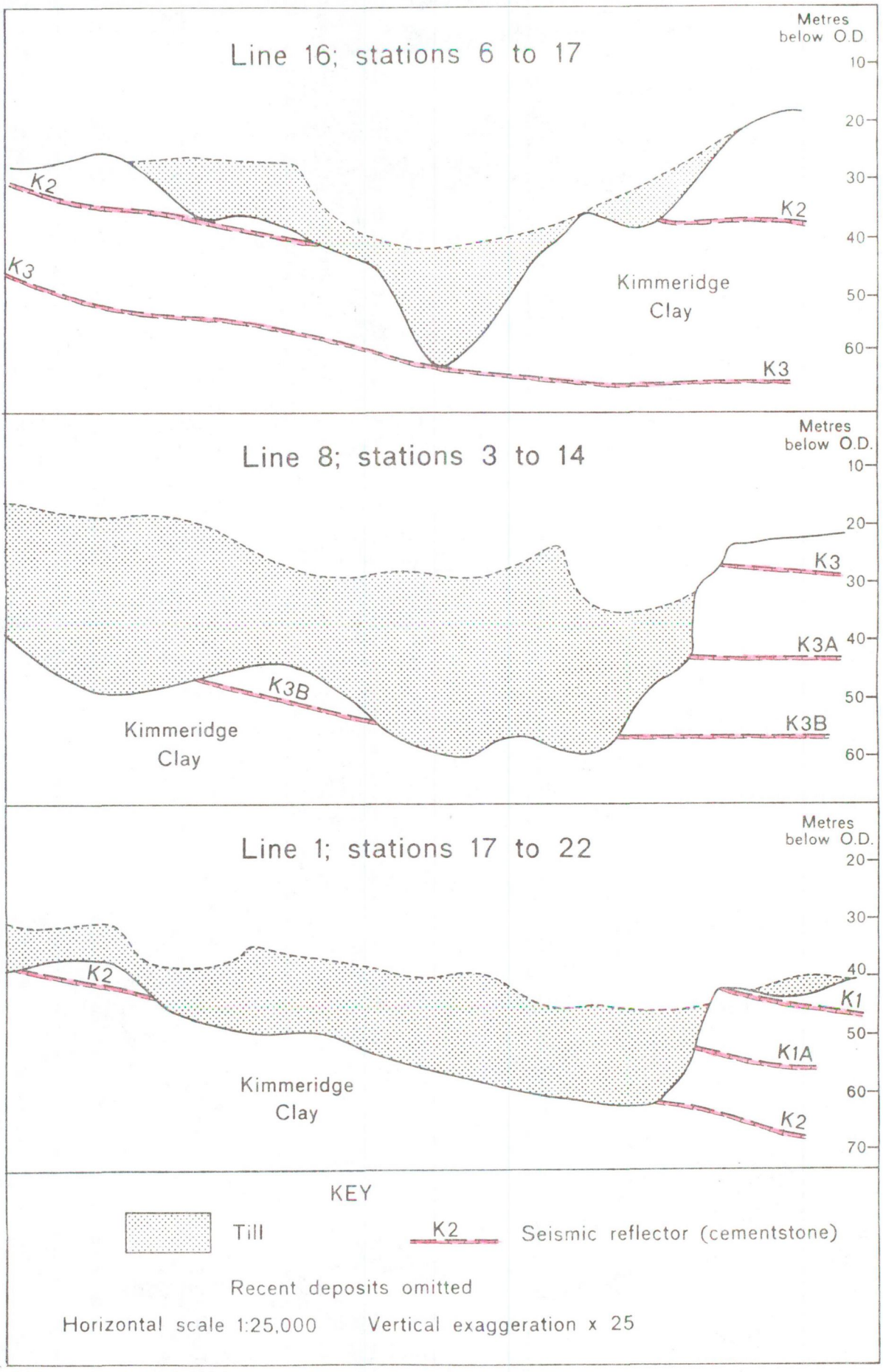


Figure 11. Glacially-filled valleys beneath The Wash in which the subglacial topography appears to be controlled by limestones in the Kimmeridge Clay. (See Wingfield et al., 1979 for lines of sections).

silty limestones (4 horizons), septarian limestones (4 horizons) and bituminous limestones (2 horizons). In cored boreholes, it is often difficult to be certain of the nature of a particular limestone because some of the larger muddy limestone doggers contain densely cemented patches with septarian cracks lined with calcite crystals. Details of the lithologies and distributions of the main types of limestone are given below:

(i) Muddy limestones may occur either as continuous tabular beds or as closely-spaced flattened ovoids (doggers) following a bedding plane. They are usually moderately densely cemented (up to 70% calcium carbonate content) and always occur in association with pale grey calcareous mudstones (up to 55% calcium carbonate content). Their stratigraphical positions have been closely defined in the present work. Evidence from the offshore sparker profiles together with correlations based on total gamma-ray logging in Norfolk and Lincolnshire and outcrop evidence from elsewhere in southern England, indicates that this type of limestone is laterally persistent and maintains its stratigraphical level over very large areas. SEM studies show them to consist largely of micrite in the form of interlocking, prismatic crystals 2 to 3 μm in length, irregularly intermixed with lenticular concentrations of clay minerals (Plate 9).

Little can be said from the borehole evidence alone about the size, shape and spacing of the doggers at any particular level. Seismic reflectors K1, K3, K4, (all muddy limestones) were recorded in the boreholes almost

Plate 9. Cementstones in the Kimmeridge Clay.

A. Closely spaced large cementstone doggers in pale grey, highly calcareous mudstones, Roslyn Hole, Ely, Bed 30.

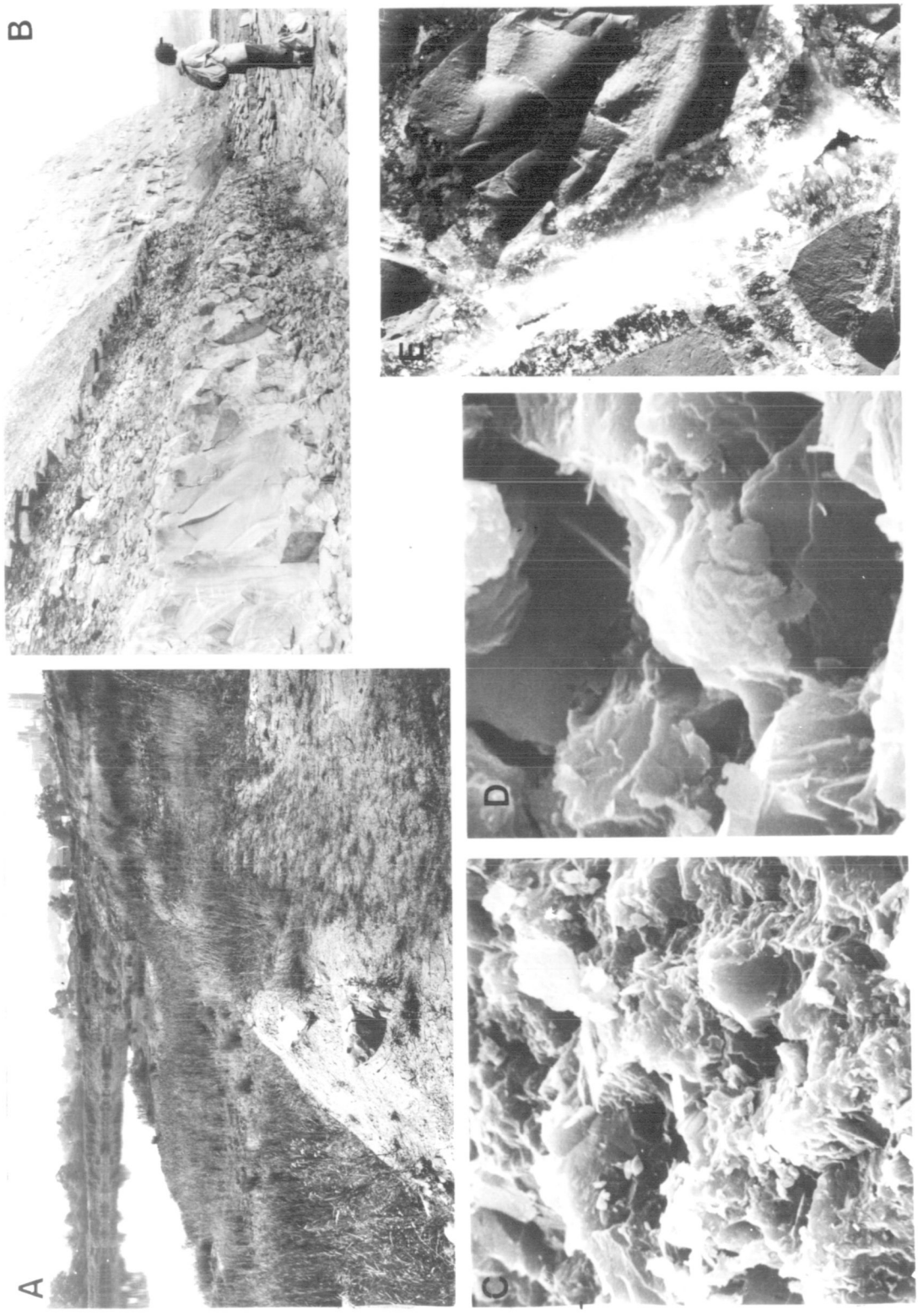
B. Almost continuous tabular cementstone in pale grey, highly calcareous mudstone, Cattle Ledge Stone Band, Kimmeridge cliffs, Dorset.

C. Electron micrograph of interlocking calcite crystals in fracture surface (gold-coated) of cementstone composed of calcite (90%), quartz (2%) and clay minerals (7%). Specimen no. GS 141, North Wootton Borehole, 100.12 m, Bed 17. Photo. no. SEM 18300. Magnification 1,200x.

D. Electron micrograph showing detail of calcite crystals in cementstone shown in C. Photo. no. SEM 18295. Magnification 3,000x.

E. Detail of secondary calcite infilling septarian crack in cementstone. Specimen no. BDU 9212, Vinegar Middle Borehole, 78.78 m, Bed 15. Natural size.

Plate 9



every time the relevant stratigraphical horizon was penetrated, suggesting that each band is a continuous tabular bed or a layer of very closely spaced doggers.

The only exposures of limestone in Norfolk at present occur in the banks of the Flood Relief Channel at Downham Market Bridge [TF 601 003] and the Cut-Off Channel near Fordham [TL 607 996]. The fauna and lithology of the adjacent beds show the limestone at both localities to be Bed 44 (reflector K1 of Table 7) (see Appendix A for details of section). The limestone is continuously exposed for some 200m northwards from Downham Bridge; the doggers vary considerably in their horizontal spacing and they occupy rather less than half the total length of the outcrop. The spacing there is probably wider than that in the Marham to Skegness area where all six boreholes that penetrated this level proved a tabular bed. Most of the doggers at Downham Market are flattened ovoids (when small) or tabular masses with rounded edges (when large). Almost all the doggers, whether large or small, appear to be 0.30 to 0.35m thick. The maximum visible length of dogger is 2.05m; the maximum visible width (measured into the bank) is about 0.8m. Doggers of a similar size and at the same stratigraphical level are present at Fordham but are more widely spaced than those at Downham Market. It therefore seems likely that the density of spacing of this band of doggers increases northwards in Norfolk. Loose doggers of cementstone from the same horizon occur in the spoil of old pits at Stowbridge [TF 614 073] and Setchey [TF 6268 1452].

The limestones in Beds 30 and 18 (reflectors K3 and K4 respectively) are also likely to be persistent throughout Norfolk and to consist of closely-spaced doggers or, locally, continuous tabular beds. Both horizons contain more than one limestone band; for practical purposes these are sufficiently close together to be regarded as a single thick bed. Doggers of the Bed 30 limestone, up to 2m across, have been recorded at outcrop near Southery [TL 6128 9318] and at Ely (Plate 9), and both the Bed 30 and Bed 18 limestones can be traced via boreholes at Swindon and West Lavington, Wiltshire to the Dorset coast. The only other muddy limestone horizon likely to be persistent in the Lower Kimmeridge Clay of Norfolk is that in Bed 4. This bed was recorded in three adjacent boreholes (Feasibility Study boreholes 29, 30 and 31) in the Terrington Marsh area; it is possible that it is only developed in that area and northwards from there beneath The Wash.

(ii) Silty limestones occur at four horizons in the Kimmeridge Clay (Beds 8, 15, 17 and 24). They are typically silty, shelly beds in which part of the shell material has been leached and re-precipitated as a patchy calcite cement. In some cases small discrete septaria are formed, but more commonly the cement occurs irregularly throughout the rock. Each of these four beds maintains its lithological character in boreholes throughout southern England. Calcareously cemented siltstones occur as marker beds at these stratigraphical levels in the Dorset coastal sections. The lowest has been named the Black Head Siltstone (Cox and Gallois, 1981).

(iii) Bituminous limestones were recorded at two horizons in Norfolk, one in the Upper and one in the Lower Kimmeridge Clay. Both are calcareously cemented oil shales which have probably formed in a manner similar to that of the silty limestones. The Upper Kimmeridge Clay occurrence (reflector K2) is almost certainly a very persistent horizon and may be continuous from The Wash to Dorset (where it correlates with the Yellow Ledge Stone Band). It was penetrated in two boreholes in Norfolk (North Wootton and IGS 71/65) and was encountered in a sewer tunnel beneath the River Gt Ouse, north of King's Lynn |TF 604 227|. At this last locality, the bed was mostly densely cemented and tabular, but in places passed into uncemented oil shale and shelly clay. The Lower Kimmeridge Clay horizon (Bed 34) has only been recorded in the Denver Sluice Borehole.

(iv) Septarian nodules have been recorded only as single occurrences in boreholes; these are listed in Table 7. Many of those cored have curved lower and upper surfaces or were only partly projected into the core, suggesting that they are small in relation to the borehole diameter (mostly c100 mm). It seems likely that the septaria are mostly less than 0.3 m in diameter and spheroidal in shape. Although having a very densely cemented matrix, most contain septarian cracks which are partially infilled with coarsely crystalline sparry calcite (Plate 9). Several stages of calcite precipitation are present in most cases. These septaria were too infrequent in the borehole cores for any stratigraphical pattern or their

relationship to any particular mudstone lithology to be determined. Several were recorded within dark grey mudstones. Electron micrographs show the matrix of the septarian nodules to consist of densely interlocking micritic calcite crystals (Plate 9).

(v) Shelly limestones (cemented shell coquinas) were recorded at several levels in the Kimmeridge Clay, but they appear to be of restricted extent and to pass laterally into shelly mudstones. In the Lower Kimmeridge Clay the best example of this type of limestone occurs in the Nanogyra virgula-rich horizons of Bed 30. These very shelly mudstones are locally calcite-cemented to form soft limestone concretions or tabular beds. Although these beds are individually of small extent, similar soft limestones occur at this stratigraphical level throughout the Kimmeridge Clay outcrop south of the River Humber.

(vi) Coccolith limestones have been recorded at ten levels in the Kimmeridge Clay of Norfolk. Thin beds of pale coloured limestone composed largely of coccoliths were first noted in the Kimmeridge Clay by Downie (1957). He identified five levels in the cliff sections near Kimmeridge Bay, Dorset - the Rope Lake Head, White, Middle White and Freshwater Steps stone bands and a thin limestone close to the Rope Lake Head Stone Band. One of these beds, the White Stone Band, was subsequently recorded in the Warlingham Borehole, Surrey, in boreholes in Hampshire and Sussex (Downie in Worssam and Ivimey-Cook, 1971, pp. 38-9) and in Norfolk (Gallois and Cox, 1974).

The recognition of coccolith-rich bands* in boreholes in Norfolk, Lincolnshire, Surrey and Wiltshire in the present work indicates that they occur more frequently and over much wider areas in the Kimmeridge Clay than had previously been supposed. Eleven bands have been recognised in England (Fig. 12), of which 10 have been recorded in Norfolk (see Appendix B for details). The coccolith-rich bands are readily recognised in borehole cores by their pale colour and low density, and at outcrop by their almost white weathering patina. The thickest band recorded, the White Stone Band in Dorset, is about 0.9 m thick and composed over 100 laminae; in Norfolk these bands are generally less than 0.1 m thick and may occur as a single lamina only a few mm thick.

The coccolith contents of the calcite fractions of the bands have been determined by Dr A.W. Medd by examination of ultrasonically disaggregated samples both optically and electron-optically. The total calcium-carbonate content of selected samples was measured to enable coccolith/whole rock percentages to be determined. In many cases, however, representative samples were difficult to obtain for calcite determination because of the thinness of the bands and their disturbance by burrowing. Calcite-rich laminae that can be seen under the microscope to be crowded with coccoliths, cannot always be sufficiently well separated to allow a coccolith/whole rock percentage to be determined.

The coccolith component of the bands varies from 30 to 90% of the calcium carbonate content; this is a minimum value because, in addition to the recognisable coccolith debris present, most bands

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* The term 'band' is used here because it is equally applicable to the coccolith-rich limestones of the Dorset coast and the very thin beds of coccolith-rich mud that occur in Norfolk.

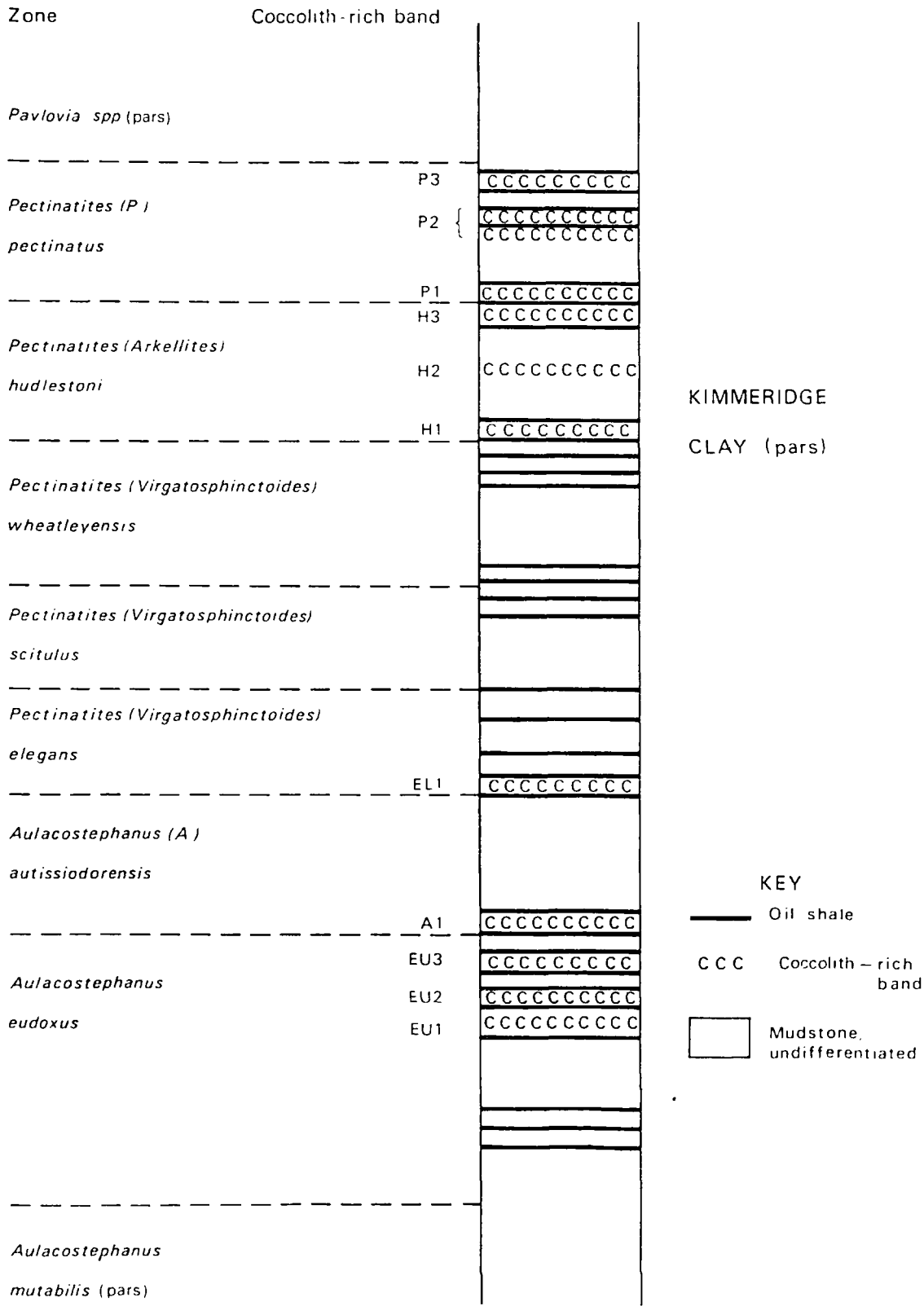


Figure 12. Distribution of coccolith-rich bands on the Kimmeridge Clay.

contain minute calcite fragments and recrystallized calcite which could be of coccolithic origin. In the limited number of samples determined coccolith/whole rock percentages vary from 15 to more than 50% (Table 8). Other Kimmeridge Clay lithologies generally contain less than 5% coccoliths/whole rock although up to 12% have been recorded in some of the very calcareous clays (high calcium-carbonate content combined with moderate coccolith content). The term coccolith-rich band is therefore defined here as a band which can be seen to contain more than 30% of recognisable coccoliths in the calcite fraction within a rock that has more than 50% calcium carbonate (determined either by analysis or visual examination). A few instances have been recorded in which abundant coccoliths are present in oil shales that have a low overall calcium carbonate content.

The floras of the coccolith-rich bands were identified by Dr Medd and are given in Gallois and Medd (1979, Appendix A) together with a discussion of their stratigraphical significance and taxonomy. The coccolith contents of the bands vary between 2 and 27 species (Table 9), but most are dominated by a single species; in the Upper Kimmeridge Clay this is usually Ellipsagelosphaera britannica (Stradner). Most of the coccoliths are well preserved and with the scanning electron microscope many of the coccolith-rich bands appear to be composed exclusively of coccoliths with little or no clay or inorganic calcite (Plate 10). Coccospheres and disarticulated coccospheres of some species are common and Dr Medd recorded minute pellets composed almost entirely of the plates of a single coccolith species that may be faecal debris of a coccolith-ingesting organism.

The stratigraphical positions of the 11 coccolith-rich bands are

Lithology	Borehole	Depth down borehole m	Carbonate %	Approximate coccolith of carbonate fraction %	Approximate coccolith of total rock %
Oil shale, shelly	Hunstanton	106.8	51.02	1	0.5
Oil shale, sparsely shelly	Hunstanton	106.4	18.06	2	0.4
Mudstone, dark grey, fissile, shelly	Hunstanton	105.4	26.30	10	2.6
Mudstone, dark grey, almost barren	Hunstanton	104.3	16.55	5	0.8
Mudstone, medium grey, almost barren	Hunstanton	105.2	26.67	25 + bits	6.8+
Mudstone, pale grey, almost barren	Hunstanton	105.1	50.63	25 + bits	12.5+
Muddy limestone	Hunstanton	115.4	93.45	nil	nil
'White Stone Band' lithology	Hunstanton	105.0	75.59	60 + bits	45.6+
	Skegness	120.6	57.86	90+	52.2+
	Skegness	121.9	34.21	90+	31.6+

Table 8. Carbonate and coccolith contents of some typical Upper Kimmeridge Clay lithologies.

Plate 10. Examples of coccolith-rich bands.

A. Electron micrograph of coccosphere, Ellipsagelosphaera britannica (Stradner). White Stone Band, Kimmeridge cliffs, photo. no. SEM 12664. Magnification 15,000x.

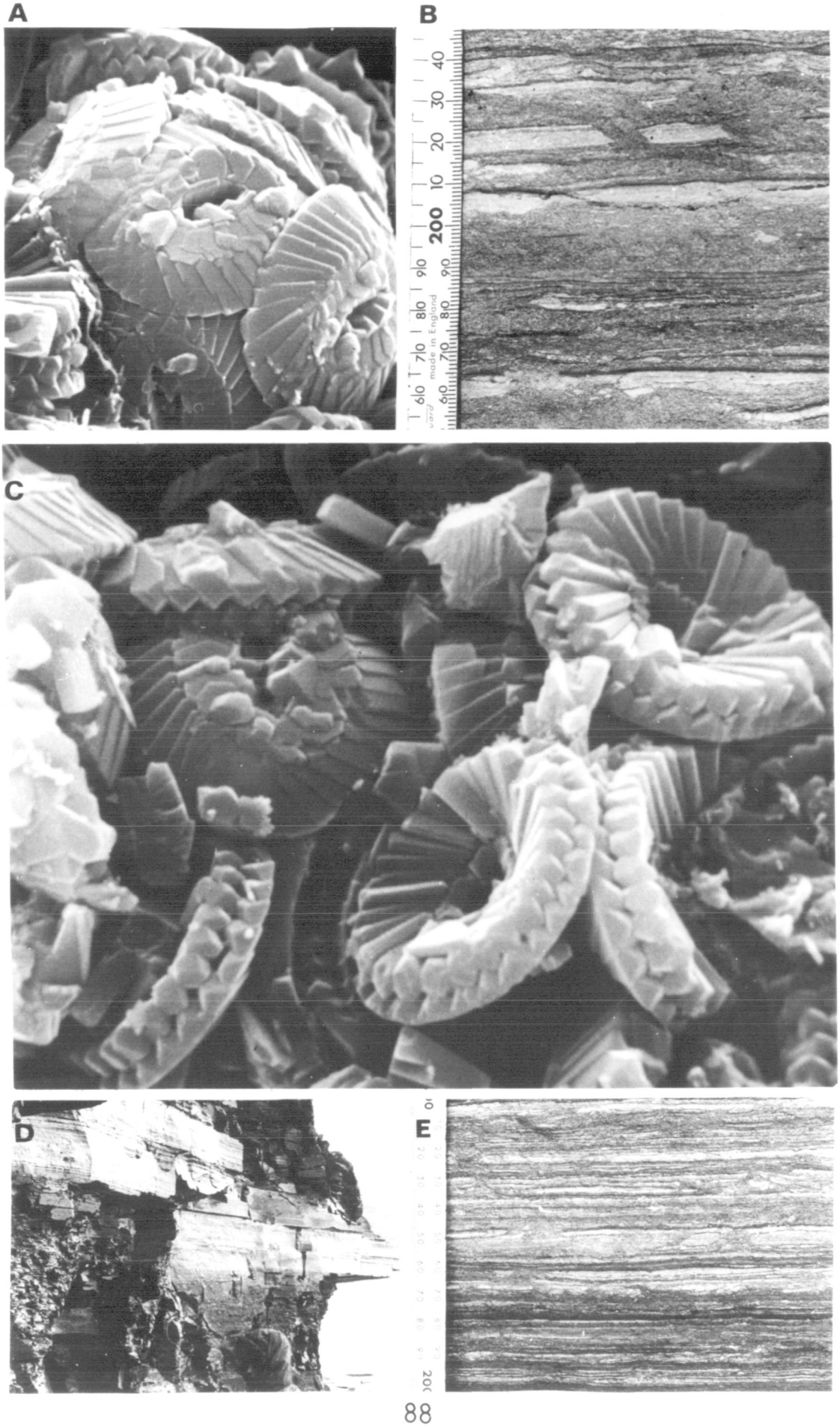
B. Laminated coccolith-rich (pale) and kerogen-rich mudstone with disruption of laminae by bioturbation. White Stone Band, Kimmeridge cliffs, Dorset. Centimetre scale.

C. Electron micrograph showing detail of disaggregated plates of E. britannica. White Stone Band, Kimmeridge cliffs, photo no. SEM 12663. Magnification 25,000x.

D. Outcrop of the Freshwater Steps Stone Band, Kimmeridge cliffs.

E. Detail of lamination and bioturbation in Freshwater Steps Stone Band, Kimmeridge cliffs. Centimetre scale.

Plate 10



shown in Fig. 12. For ease of reference each band has been given a code letter or letters based on the ammonite zone in which it occurs. At several localities and levels, two or more bands, usually with a similar flora, occur close together and have been coded as a single band (e.g. Band P 2). Outside the Dorset type section most of the coccolith-rich bands are less than 10 mm thick and it is unlikely that ammonite or other faunal evidence will ever be sufficiently refined to prove that such thin beds occur at precisely the same stratigraphical levels in widely separated boreholes. However, in the case of coccolith-rich Bands EU1, EU2, EU3 and A1, a combination of lithological and faunal features, in particular the narrow stratigraphical range of the ammonites Sutneria rebholzi Berckmeyer and Propectinatites? and a flood occurrence of the free-swimming crinoid Saccocoma, provide sufficient stratigraphical control to suggest that several of these bands are at precisely the same levels in the West Lavington, Swindon, North Wootton and Donington on Bain boreholes (Fig. 13). Similarly, the close association of Bands H3 and P1 with the upward replacement of Pectinatites (Virgatosphinctoides) spp. by Pectinatites (Pectinatites) spp., including P. (P.) eastlecottensis (Salfeld), is sufficiently well-documented in the borehole cores to suggest that these two bands occur at the same levels in the Donington on Bain, North Wootton and Warlingham boreholes and that the higher band (the White Stone Band of the Kimmeridge cliffs) is present as far north as the Vale of Pickering, North Yorkshire (Golden Hill Brickpit, Marton; Bed 16 of Cope 1974a, p. 216).

In every occurrence except one (Band H2), the coccolith-rich bands are interlaminated with oil shales and it is suggested (see Section 2.4.4.3) that this association may be the key to their origin.

Coccolith-rich Band	Donington on Bain Bh.	North Wootton Bh.	Swindon Bh.	West Lavington Bh.	Warlingham Bh.	Kimmeridge Bay cliffs
P3	2	A	S	S	2	3
P2	4	A	S	S	2	2
P1	16	6	S	S	2	3
H3	4	5	S	S	N.R.	N.R.
H2	N.R.	18	S	S	N.R.	N.R.
H1	4?	7?	S	S	N.R.	5?
EL1	4	N.R.	S	S	N.R.	N.R.
A1	N.R.	11	S	8	N.R.	N.R.
EU3	3	10	N.R.	N.R.	N.R.	3?
EU2	7	17	27	13	4	N.R.
EU1	6	16	10	9	N.R.	N.R.

? = high coccolith/$CaCO_3$ percentage but $CaCO_3$/whole rock percentage $< 50\%$.

A = absent through erosion.

N.R. = not recorded.

S = absent through replacement by sands.

Table 9. Maximum number of species recorded in each of the coccolith-rich bands at some selected localities.

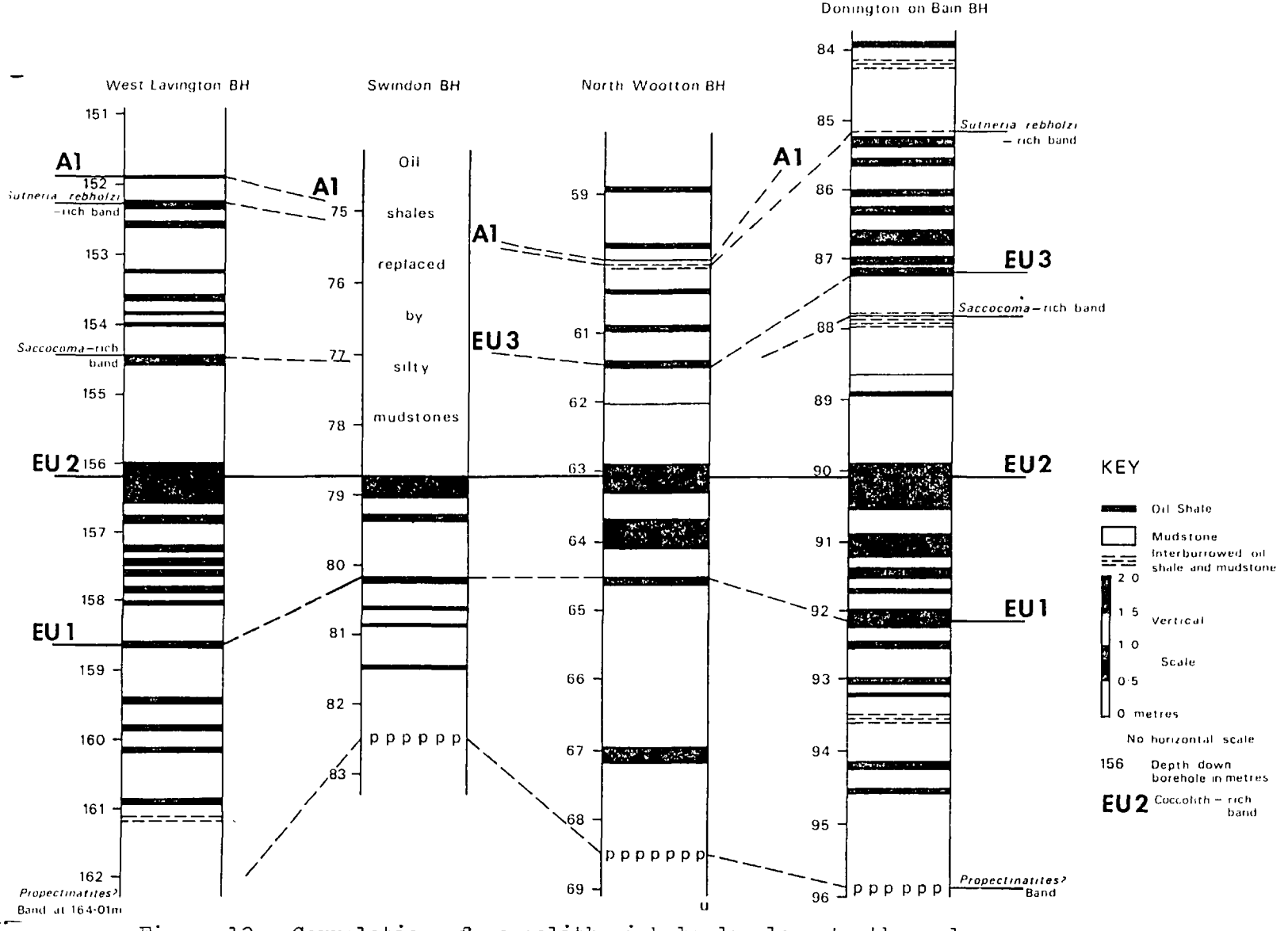


Figure 13. Correlation of coccolith-rich bands close to the eudoxus-autissiodorensis zonal boundary.

Lamination is particularly distinct in the Freshwater Steps (Band P3) and White (Band P1) stone bands in Dorset, in the Warlingham Borehole and at Marton. It is present to some degree in all the Norfolk occurrences, although commonly masked by burrowing.

2.2.1.8 Oil shale

Seams of oil shale occur throughout much of the Kimmeridge Clay where they form the basal part of the Type B rhythms of Figure 5. Concentrations of seams occur at five levels. Commercial exploration in the past has been almost exclusively confined to only one of these oil-shale-rich bands, that which includes the Blackstone. During the IGS Pilot Study of the occurrence of oil shale in the Kimmeridge Clay four continuously cored boreholes were drilled to provide samples for stratigraphical and chemical analyses. Part of the study was designed to examine the overall distribution, nature and origin of oil shales within the formation and each borehole was sited on Volgian sands or limestones in order to obtain a complete, unweathered Kimmeridge Clay sequence. Boreholes were drilled at Donington-on-Bain, North Runcton, Swindon, and West Lavington; additional boreholes were drilled in Dorset, Wiltshire, Berkshire, Buckinghamshire and North Yorkshire for the subsequent Department of Energy project (Fig. 14).

In Norfolk, in addition to the cored borehole at North Runcton, the outcrop of the main group of oil-shale seams was mapped out and archival material and specimens from about 50 boreholes associated with the 1916-1923 Norfolk oil-shale industry were examined (Appendix A). Excavations were made at the former oil-shale opencast workings at Setchey and samples of the seams were obtained for analysis. Stratigraphical information from these excavations enabled a detailed correlation to be made with both the North Runcton Borehole and the

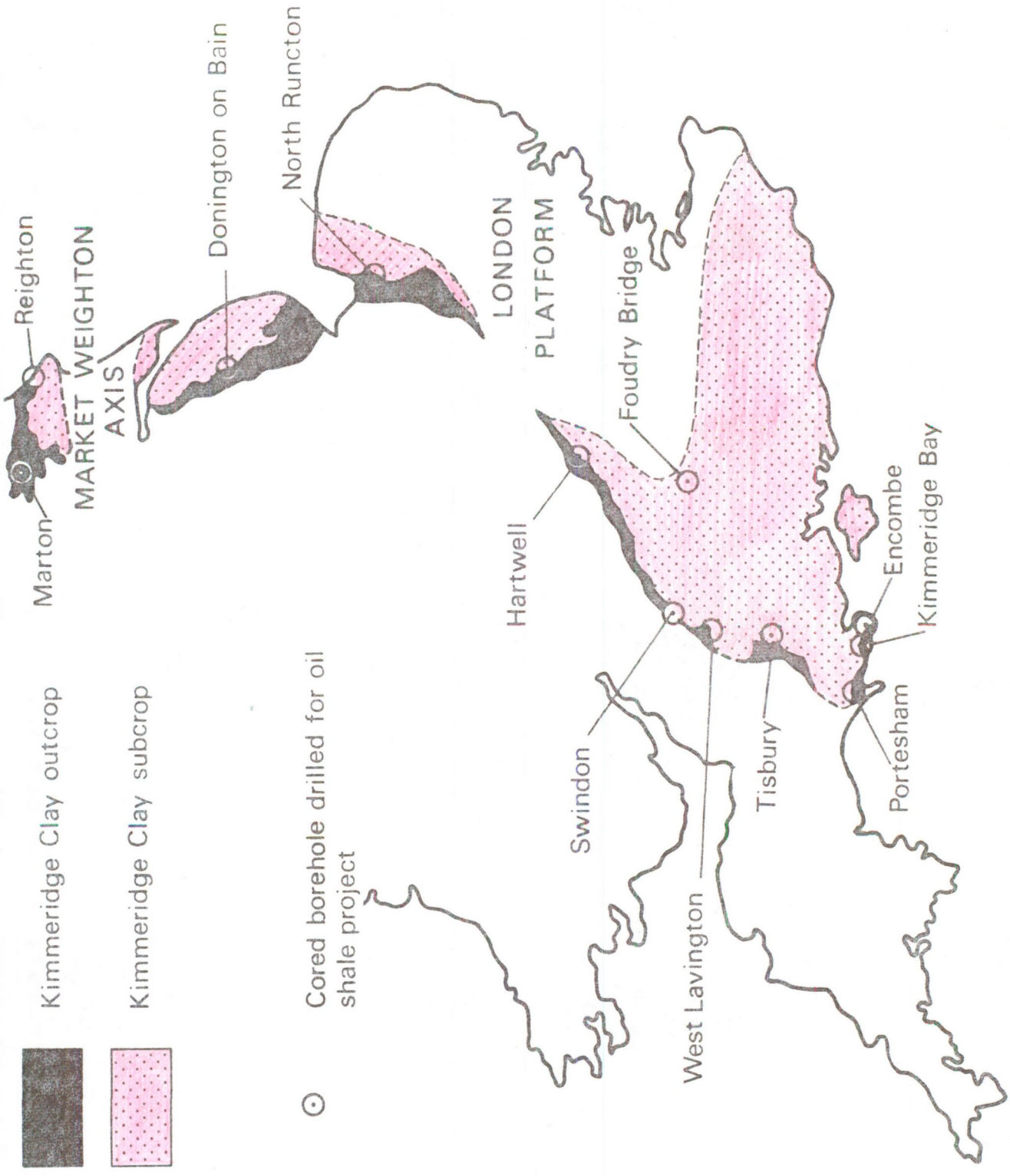


Figure 14. Sites of the continuously cored boreholes drilled for the oil-shale projects.

Dorset succession.

The continuously cored boreholes drilled through parts of the Kimmeridge Clay for The Wash Water Storage Scheme feasibility study proved a large number of oil-shale seams, but all were less than 0.5 m thick and were separated by barren mudstones. The North Runcton Borehole was therefore sited close to the Kimmeridge Clay outcrop, about 1.5 km down-dip from the old workings at Setchey. The borehole proved a total of 7.17 m of oil shale in 80 seams ranging from 1 to 47 cm in thickness. The average seam thickness is 9.0 cm; 82% of the seams are <20 cm thick and 60% of the total volume of oil shale occurs in seams <20 cm thick (Fig. 15).

On pyrolysis at 500°C, individual oil-shale seams in Norfolk yield up to 25 wt oil/wt dry shale % (≈ 60 U.S. gals oil/short ton of shale*). When bulked with the intervening non-productive mudstones the overall yield, as proved by continuously sampling 2-metre runs of bulked core in the North Runcton Borehole, varies from about 0.2 gal/ton in the more calcareous parts of the sequence to about 16.8 gal/ton in the best oil-shale rich band (Fig. 16). A similar relationship between seam thickness and potential yield was proved in the other pilot study boreholes (Gallois 1979b, Figs 5, 6 and 7).

The main concentrations of the better quality seams in Norfolk occur at five levels: (i) in the lower part of the eudoxus Zone, (ii) the upper part of the eudoxus Zone and the lower part of

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* All assay methods for potential yield of oil shale measure the weight of oil produced by the pyrolysis of a known weight of shale. Results are expressed in the laboratory as wt oil/wt shale (%) but are usually quoted in U.S. gal oil/short (2000 lb) ton of shale when published. For an oil of specific gravity 1.00 (Kimmeridgian shale oil varies from 0.95 to 1.05) 1 wt/wt % is approximately 2.4 U.S. gal/short ton.

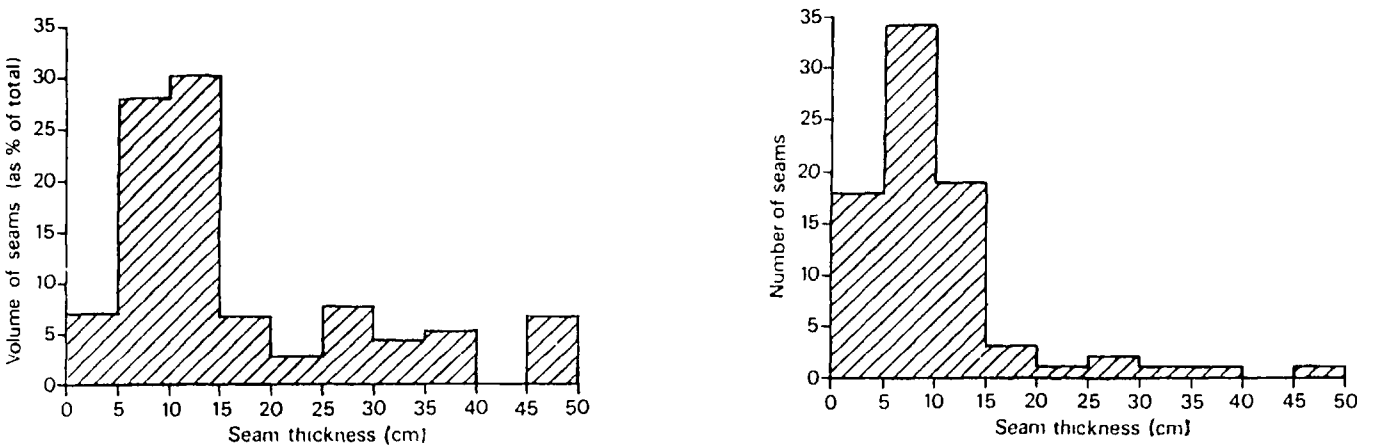


Figure 15. Distribution and thickness of oil-shale seams in the North Runcton Borehole.

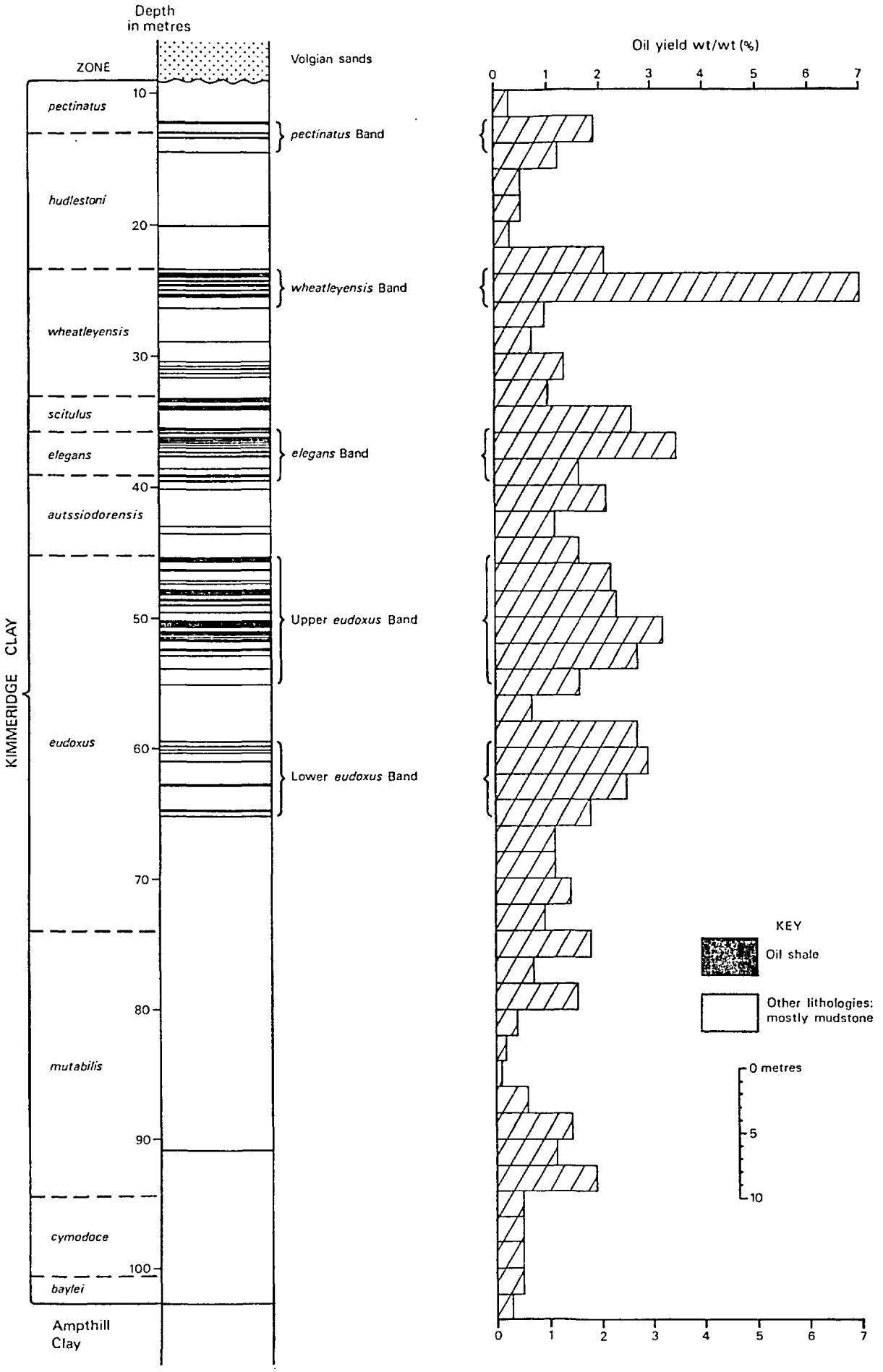


Figure 16. Relationship of oil-shale seams to potential oil yield in the North Runcton Borehole.

autissiodorensis Zone, (iii) the elegans Zone, (iv) the upper part of the wheatleyensis Zone and the basal part of the hudlestoni Zone and (v) the upper part of hudlestoni Zone and the lower part of the pectinatus Zone (Fig. 16). Lesser concentrations of oil shale of generally inferior quality occur in the upper part of the mutabilis Zone, the middle part of the eudoxus Zone and in the scitulus Zone.

The five main oil-shale-rich bands were named, for ease of reference, after the ammonite zones in which they occur or largely occur. The bands being referred to, in ascending stratigraphical order, as the Lower eudoxus Band, Upper eudoxus Band, elegans Band, wheatleyensis Band and pectinatus Band.

Comparison of the North Runcton sequence with that proved in the cored boreholes drilled for the pilot and Department of Energy studies, and with the sequence outcropping in the cliffs at Kimmeridge Bay, has shown that the five oil-shale-rich bands are present in the Kimmeridge Clay of much of southern England (Figs. 17 and 18).

The oil shales have lower densities than other Kimmeridge Clay lithologies, the density decreasing with increasing kerogen (Sp. Gr. ≈ 1.0) content. Potential oil yield is directly related to kerogen content and hence the density of an oil shale, or of oil shale/mudstone mixture, has a roughly linear relationship to its potential oil yield (Fig. 19).

The oil shales are mostly brown or brownish grey (some darker specimens are close to Dusky yellowish brown (10 YR 2/2) of the American Geol. Soc. Rock-Color Chart) and they are the only Kimmeridge Clay lithology with a brown streak. They commonly have a faint bituminous smell when freshly broken because a small part, usually <5%, of their organic content is present as solvent-

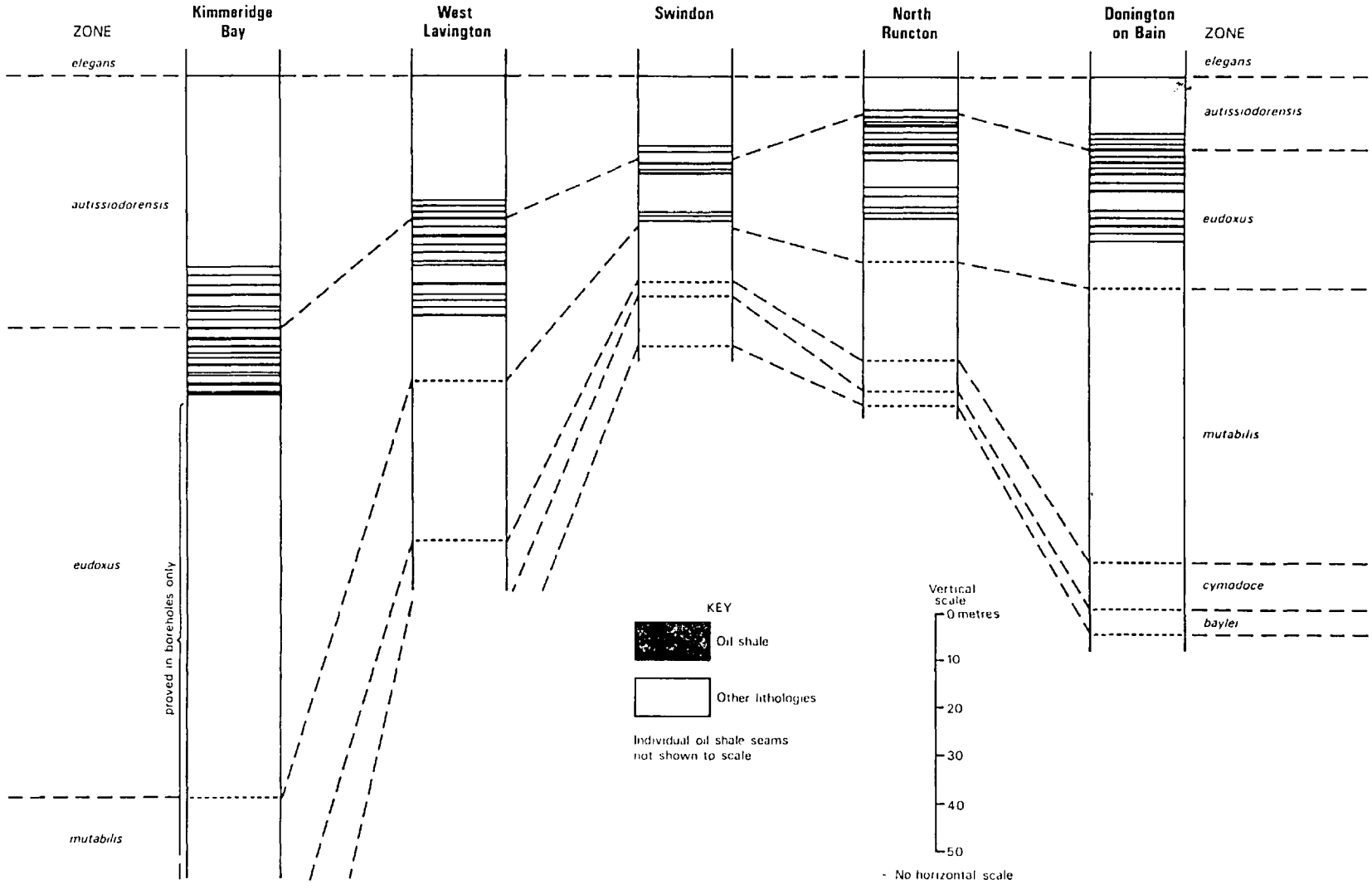


Figure 17a. Correlation of the oil-shale-rich bands in the Lower Kimmeridge Clay of the pilot-study boreholes with those in the Dorset type section.

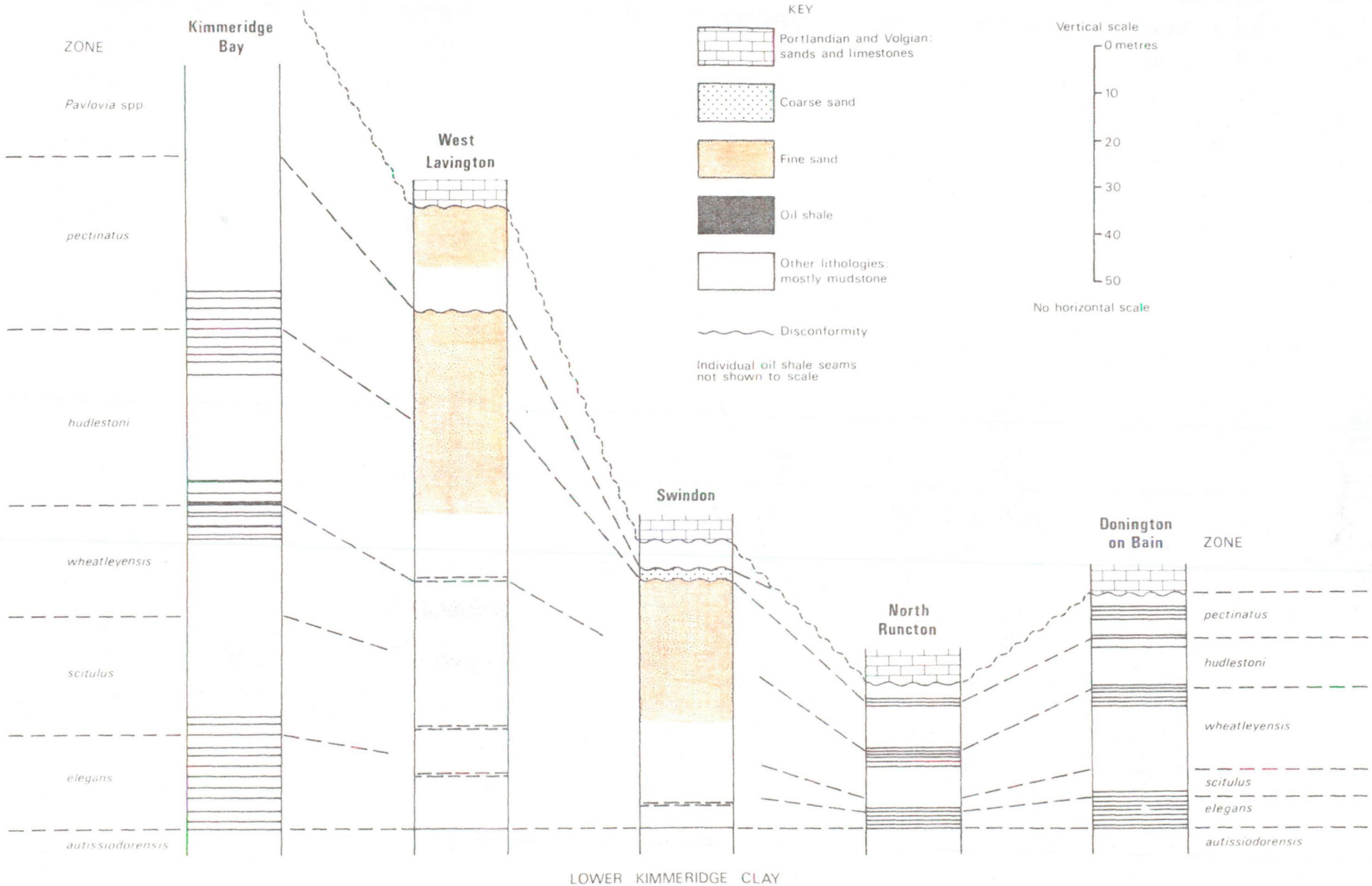


Figure 17b. Correlation of the oil-shale-rich bands in the Upper Kimmeridge Clay of the pilot-study boreholes with those in the Dorset type section.

extractable oil ('bitumen'). Analyses of samples from Norfolk (Table 5) suggest that mudstones containing >10% kerogen can be recognised in hand specimen by their distinctive density, colour and smell. This was confirmed for the North Runcton Borehole by comparing the volume of oil shale recorded in the field log of the cores with the oil yields obtained by pyrolysis of samples representative of 2 m-runs of core made up of a mixture of oil shale and mudstone (Fig. 20). The scatter of results partly reflects variations in the potential yields of the kerogens at different stratigraphical levels, but it is mostly caused by variable amounts of other minerals, such as layers of shells and burrow concentrations of clay minerals, within the oil-shale seams. These variations are especially large in the Lower Kimmeridge Clay where many of the seams have high shell contents.

The fauna of the oil shales is generally richer and more varied than that of other Kimmeridge Clay lithologies at the same stratigraphical level. They are characterised by bedding planes crowded with one or two species of small bivalve or ammonite preserved in either calcite or pyrite, and by small gastropods, phosphatised fish debris and faecal pellets, and abundant foraminifera. At five levels in the oil shales, pyritized plates of the free-swimming crinoid Saccocoma occur in large numbers. The association of coccolith-rich bands with oil shales has already been noted.

2.2.2 Palaeontology

2.2.2.1 Introduction

During the latter part of the Jurassic period world-wide earth movements caused the areas of marine deposition to become contracted and, in some cases, isolated from one another. In Europe the constric-

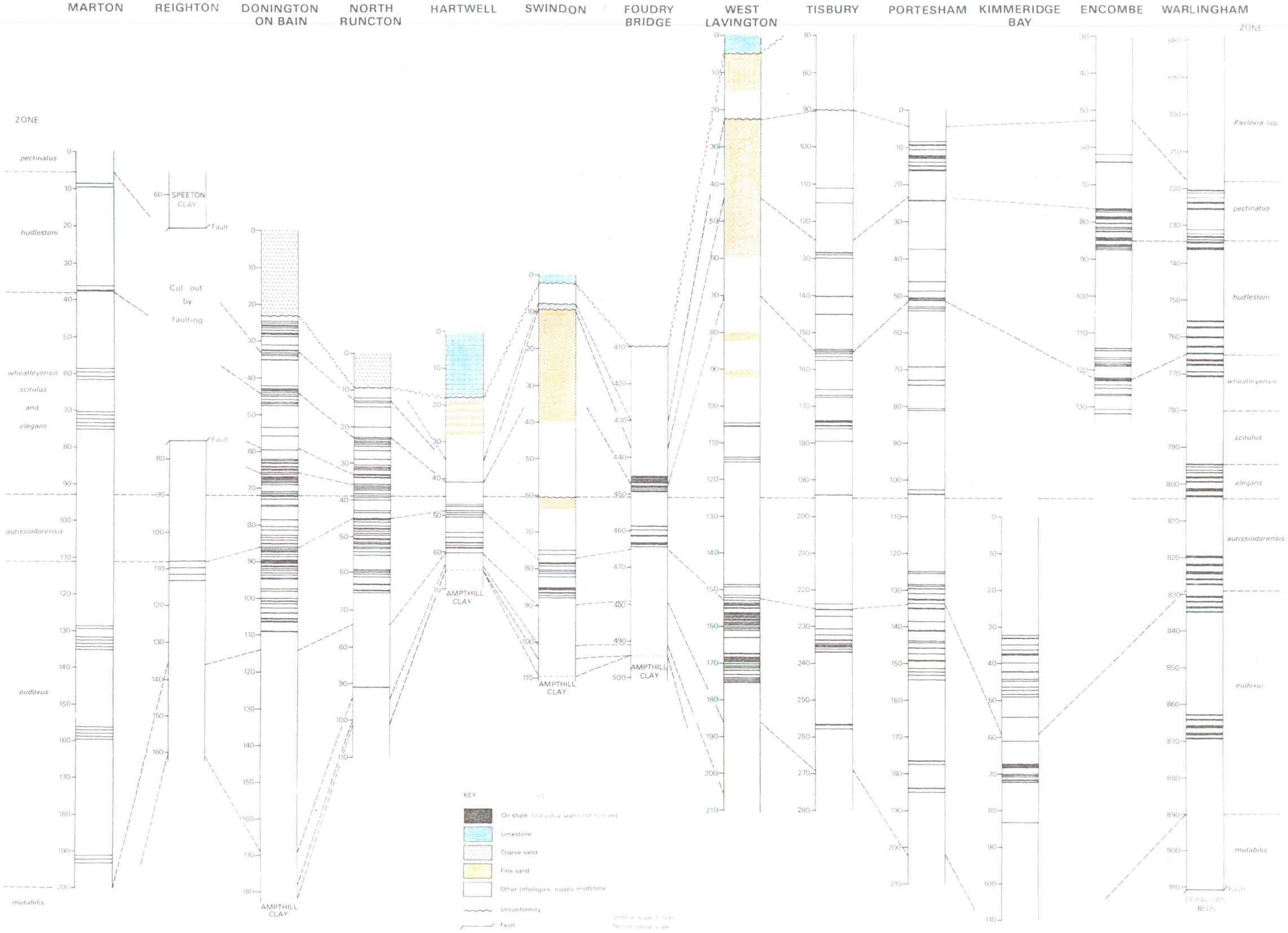


Figure 18. Correlations between the oil shales in the boreholes drilled for the oil-shale projects.

tion or disappearance of former seaways resulted in a segregation of the marine faunas into two main provinces, the Boreal region in the north and the Tethyan region in the south. By the end of the Jurassic many of the former marine areas had contracted to the point where they had become local marine or freshwater embayments with their own distinctive lithologies and faunas.

In Kimmeridgian times this process had not yet advanced sufficiently for any part of the Boreal province, covering most of north-west Europe, to have become geographically isolated, but the steady segregation of faunas with time may be reflected in the Kimmeridge Clay by a gradual upward decrease in diversity in the fauna.

The macrofauna of the Kimmeridge Clay is dominated by bivalves and ammonites. Other groups make up an important part of the fauna at certain levels but most of these are related to particular lithologies; only the bivalves and ammonites are sufficiently abundant throughout the formation for comment to be made on changes in their diversity with time. Even the bivalves are of limited use for this purpose because they include forms which are facies-dependent and their distribution varies from area to area at the same stratigraphical level in response to local environmental changes. The ammonites therefore provide the best indicator of regional changes in faunal diversity.

The observed stratigraphical distribution of fossil groups in borehole cores can be biased by a number of factors. The three most important of these in the present work are:

(i) the size of the fossil (or that portion of it which is diagnostic) in relation to the core diameter (mostly c 100 mm)

(ii) the frequency of occurrence of the fossil

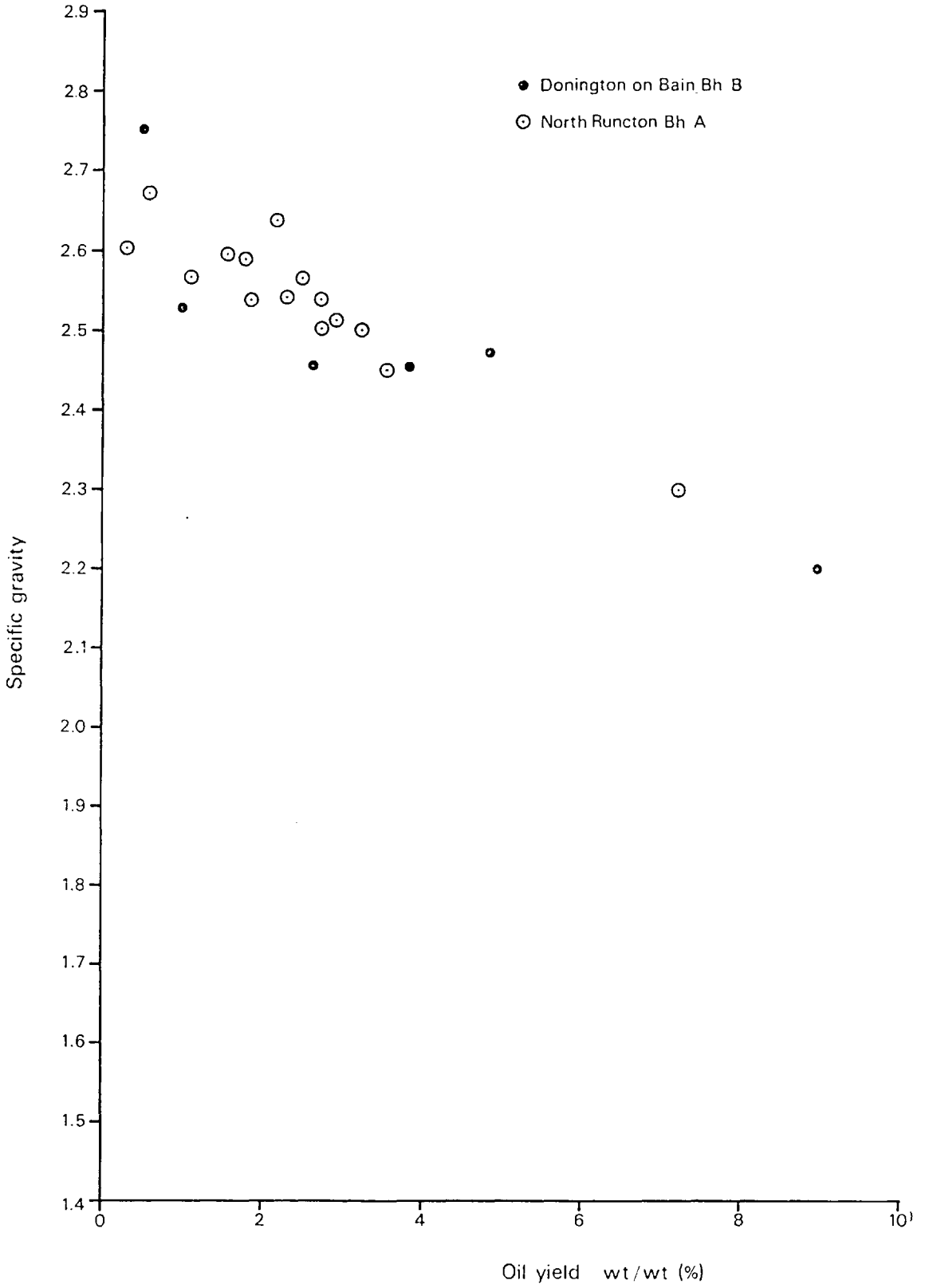


Figure 19. Relationship of density of sample to potential oil yield for oil shale/mudstone mixtures from the North Runcton and Donington on Bain boreholes.

(iii) the chemical composition of that part of the original animal or plant which is likely to be fossilized and its susceptibility to subsequent alteration.

The ammonites of the Kimmeridge Clay are subjected to this bias to differing degrees at different stratigraphical levels (Plate 11). In the Lower Kimmeridge Clay, borehole cores commonly contain large numbers of specimens of distinctively ornamented, small species preserved as aragonitic shells that have undergone little alteration. The ranges of species and genera can, therefore, be accurately determined from a small number of boreholes. The macroconchs of some forms, such as Aspidoceras and some species of Aulacostephanus, are large in relation to the core diameters, but they can be identified from only part of the shell; furthermore, microconchs are commonly present. Most of the remaining Lower Kimmeridge Clay genera, including Amoeboceras (Amoebites), Amoeboceras (Nannocardioceras), Rasenia and Sutneria, are both small and distinctively ornamented. The outstanding exceptions to this generalisation are Pictonia and Propectinatites, both of which are large and have nondescript perisphinctid ornaments that require large parts of the shell to be preserved for species identification. Furthermore, they are common at only a few horizons and their full stratigraphical ranges are therefore poorly known.

In the Upper Kimmeridge Clay identification of species of the long-ranging genera Pavlovia and Pectinatites requires mature (usually large), well-preserved specimens. These are rare in borehole cores and are commonly damaged by epizoic oysters. For example, the Pectinatites (P.) pectinatus Zone of the Warlingham Borehole (17.7 m of 15-cm diameter core) yielded no specifically determinable ammonite (Callomon and Cope, 1971, p. 151). Even in the Dorset cliff sections,

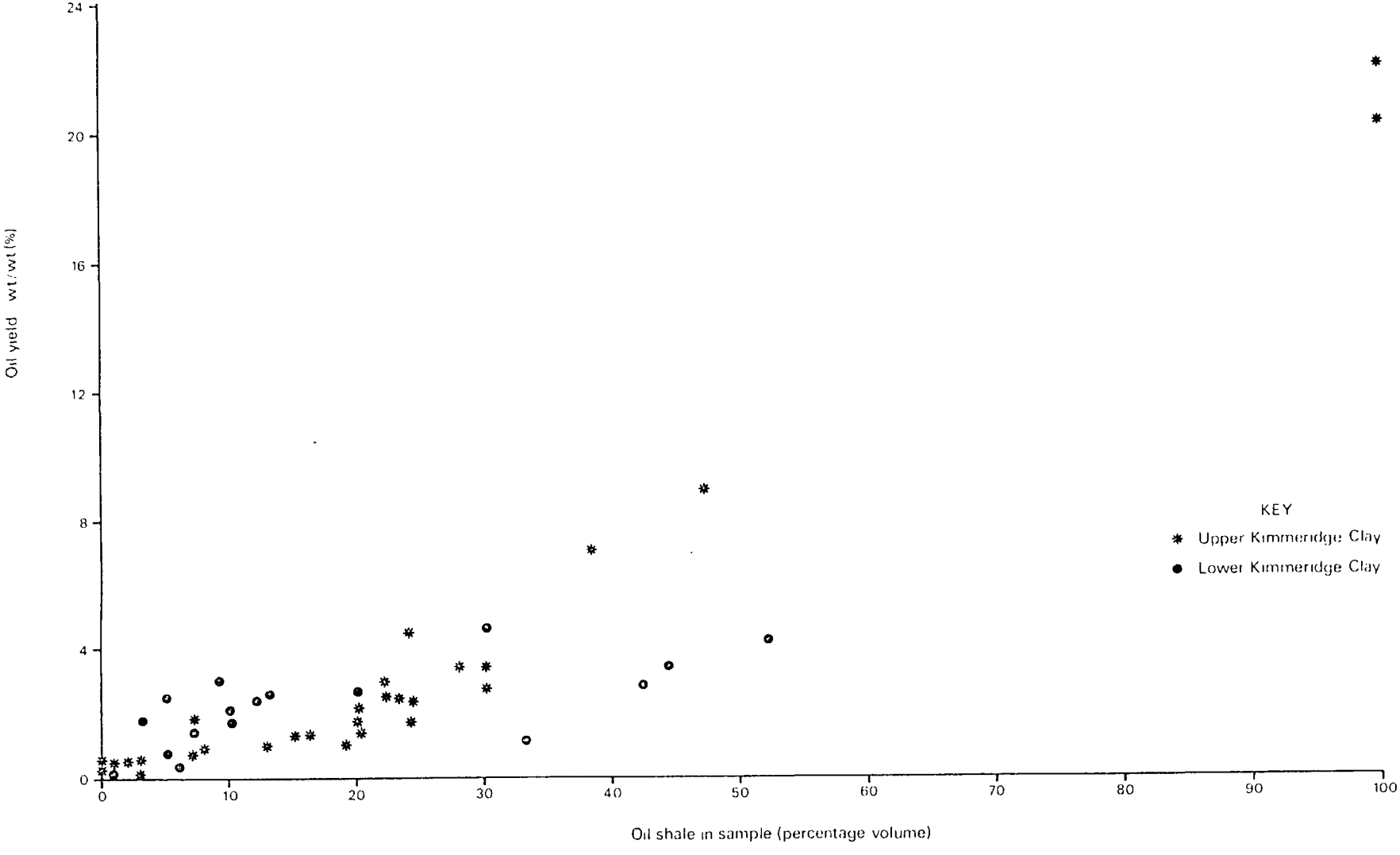


Figure 20. Relationship of volume of oil shale recorded in borehole cores to potential oil yield.

Plate 11. Comparative sizes of selected fossils in the Kimmeridge Clay in relation to typical borehole-core diameters. All photographs at natural size.

A. Part of an ammonite, Pachypictonia or Rasenia, much larger in diameter than the core, without diagnostic ornament, and therefore not generically determinable. Specimen no. BDU 8401, Terrington St John Borehole, 41.20 m, Bed 8.

B. Broken spines (arrowed) of Aspidoceras. No similar structure has been recorded from the Kimmeridge Clay and a fragment of a single spine is therefore diagnostic of the genus. The listric surface in the background has formed on the smooth shell of the ammonite; it is characteristic of this genus, but not diagnostic because it can be confused with similar surfaces that form on some smooth-shelled large bivalves. Specimen no. BDK 7844, North Wootton Borehole, 78.45 m, Bed 29.

C. Mature specimens of Amoeboceras (Nannocardioceras) of the smooth-shelled species A. (N.) krausei (Salfeld). Specimen no. BDK 7581, North Wootton Borehole, 63.20 m, Bed 32.

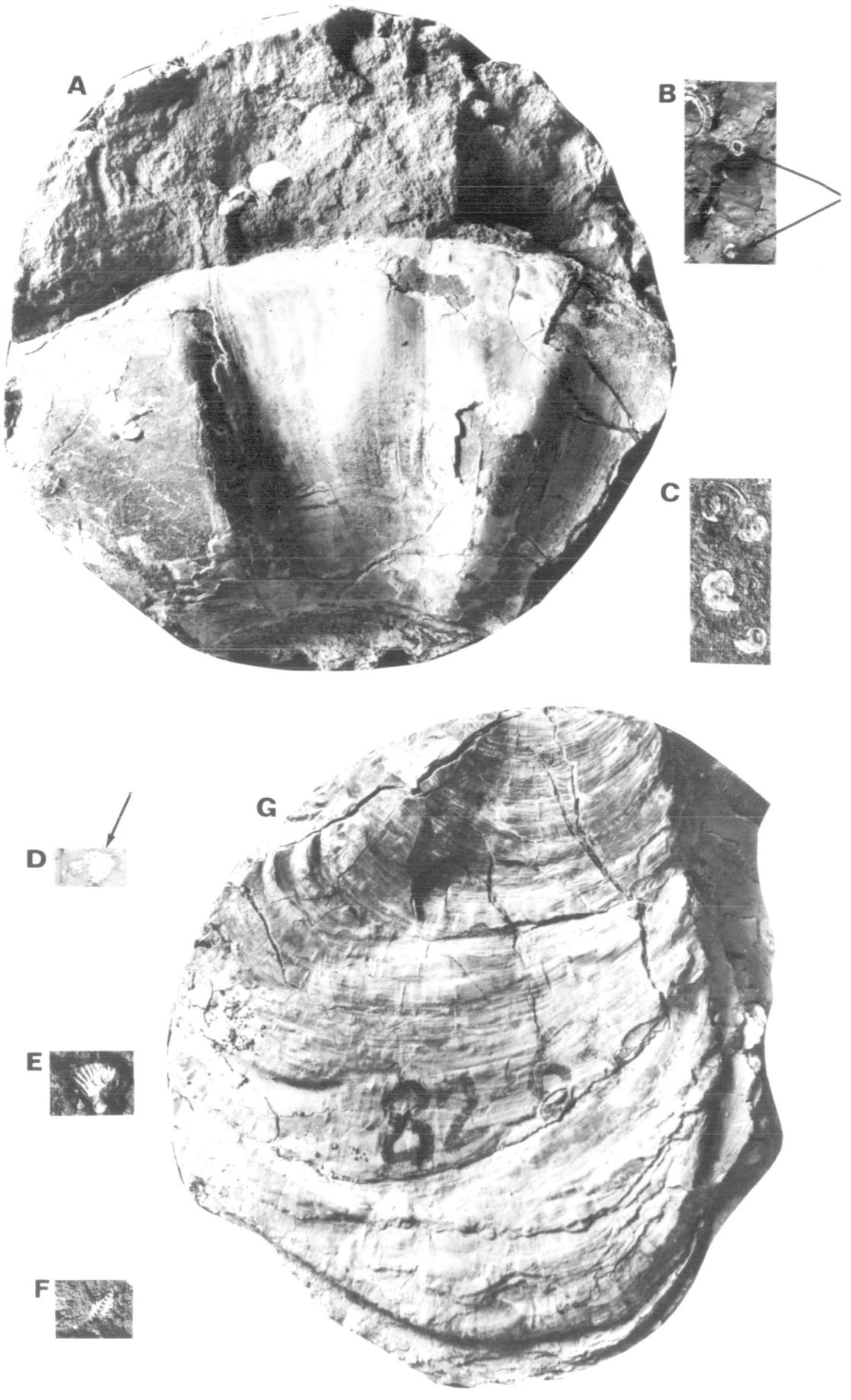
D. Fragment of a small Aulacostephanus showing its diagnostic smooth ventral band. Very small fragments of the venters of this genus can be used to accurately define its upper stratigraphical limit, and hence the upper limit of the Lower Kimmeridge Clay. Specimen no. BDU 0346, Donington on Bain Borehole, 72.76 m, Bed 35.

E. Fragment of a mature microconch of Sutneria showing the characteristic kink in the primary ribs close to the dorsal margin, a feature known from no other Kimmeridge Clay ammonite. Specimen no. BDK 7772, North Wootton Borehole, 74.95 m, Bed 29.

F. Fragment of the venter of a small Amoeboceras showing the characteristic corded keel and some of the faint ridges that join it to the ribbing. Even tiny fragments cannot be confused with any other Kimmeridge Clay genus. Specimen no. BDK 7555, North Wootton Borehole, 61.62 m, Bed 32.

G. Large, crushed, flat oyster, probably Deltoideum delta (Wm Smith); absence of the umbo from core makes specific determination impossible. Specimen no. BDU 2385, Pierrepont Farm, 82.63 m, Bed 2.

Plate 11



where bed by bed collecting can be carried out over large areas, the ranges of some species of Pectinatites are imperfectly known (e.g. see Cope's (1974b, p. 31) discussion of the base of the Pectinatites (Arkellites) hudlestoni Zone in the Dorset type section). The remaining Upper Kimmeridge Clay genus, Gravesia, is small, usually well preserved and readily recognisable, but it is extremely rare and its stratigraphically range can only be estimated by combining all the known (probably <10) outcrop and borehole specimens.

Bivalves are the only other macrofossil group in the Kimmeridge Clay which are sufficiently abundant to be of possible stratigraphical use. Most forms are small in relation to the core diameters but few are sufficiently distinctive, well preserved and well documented to be identified specifically. Many are facies dependent. None of the twenty-five recorded Kimmeridgian bivalve genera is restricted to that stage and most of their species are long ranging in comparison with the ammonites.

Some bivalves, particularly those such as the oysters that had thick, calcitic shells in life, have their original shells well preserved. Others, such as the aragonitic, thin-shelled, deep-burrowing myids occur only as calcite films coating clay casts. Intermediate between these extremes are the shallow-burrowing Astarte, 'Lucina' and nuculids. Because of these original differences oysters are common throughout the sequence, especially as shell debris in the more condensed parts, Astarte, 'Lucina' and nuculids occur in life position and as disarticulated valves in shelly layers, but myids occur only in life position or as derived steinkerns which were phosphatized whilst the bivalve was in life position.

Other macrofossil groups in the Kimmeridge Clay include gastropods,

belemnites, brachiopods, echinoderms, serpulids, and fish, crustacean and plant debris. None of these is sufficiently common or has a sufficiently short range to be stratigraphically useful. A few can, however, be used to define marker beds where they make a sudden appearance or where they occur in great abundance in a single bed.

2.2.2.2 Ammonites

In the early Kimmeridgian the perisphinctid stock, which had been a minor element in the ammonite faunas of the Oxfordian (where the cardioceratids were dominant), diversified to produce the genera Pictonia, Rasenia and Aulacostephanus; species of these form the basis of the zonation of the Lower Kimmeridgian (Table 10). The cardioceratids continued to be represented at this time by Amoeboceras and, in the upper part of the Lower Kimmeridgian, the Tethyan genera Aspidoceras and Sutneria were also present.

In the Upper Kimmeridgian Aulacostephanus was replaced by Pectinatites, a derivative from the same perisphinctid stock. Except for the brief appearance of rare examples of another perisphinctid, Gravesia, in the earliest Upper Kimmeridgian, Pectinatites remained the sole ammonite genus until it was replaced by Pavlovia in the upper part of the stage.

The stratigraphical ranges of the ammonite genera proved in Norfolk are summarized in Fig. 21. They are based on The Wash Feasibility Study and IGS boreholes in the area (Cope 1974b, Gallois and Cox 1974, 1976). Because they form the basis of the zonal scheme, the distribution of the ammonite genera and species in the Kimmeridge Clay has been discussed by numerous authors. The ammonite distribution and zonation of the Lower Kimmeridgian in Dorset has recently been summarized by Cox and Gallois (1981); that of the Upper Kimmeridgian has been

Salfeld, 1913	Arkell, 1933	Present scheme; Callomon and Cope 1971; Cope 1978; Ziegler 1962
not zoned	not zoned	Virgatopavlovia fittoni
	Pavlovia pallasiodes	Pavlovia rotunda
	Pavlovia rotunda	Pavlovia pallasiodes
	Pectinatites pectinatus	Pectinatites (P.) pectinatus
Virgatites spp.	Virgatosphinctoides nodiferus	Pectinatites (Arkellites) hudlestoni
	Virgatosphinctoides wheatleyensis	Pectinatites (Virgatosphinctoides) wheatleyensis
Gravesia spp.	Subplanites spp.	Pectinatites (V.) scitulus
	Gravesia irus	Pectinatites (V.) elegans
	Gravesia gravesiana	Aulacostephanus autissiodorensis
Aulacostephanus pseudomutabilis	Aulacostephanus pseudomutabilis	
Aulacostephanus yo	Aulacostephanus yo	Aulacostephanus eudoxus
Rasenia mutabilis	Pararasenia mutabilis	Aulacostephanus mutabilis
Rasenia cymodoce	Rasenia cymodoce	Rasenia cymodoce
Pictonia baylei	Pictonia baylei	Pictonia baylei

Table 10. Selected stages in the evolution of the zonal scheme for the Kimmeridge Clay of the Dorset type area. Horizontal lines do not imply precise correlation of zonal boundaries.

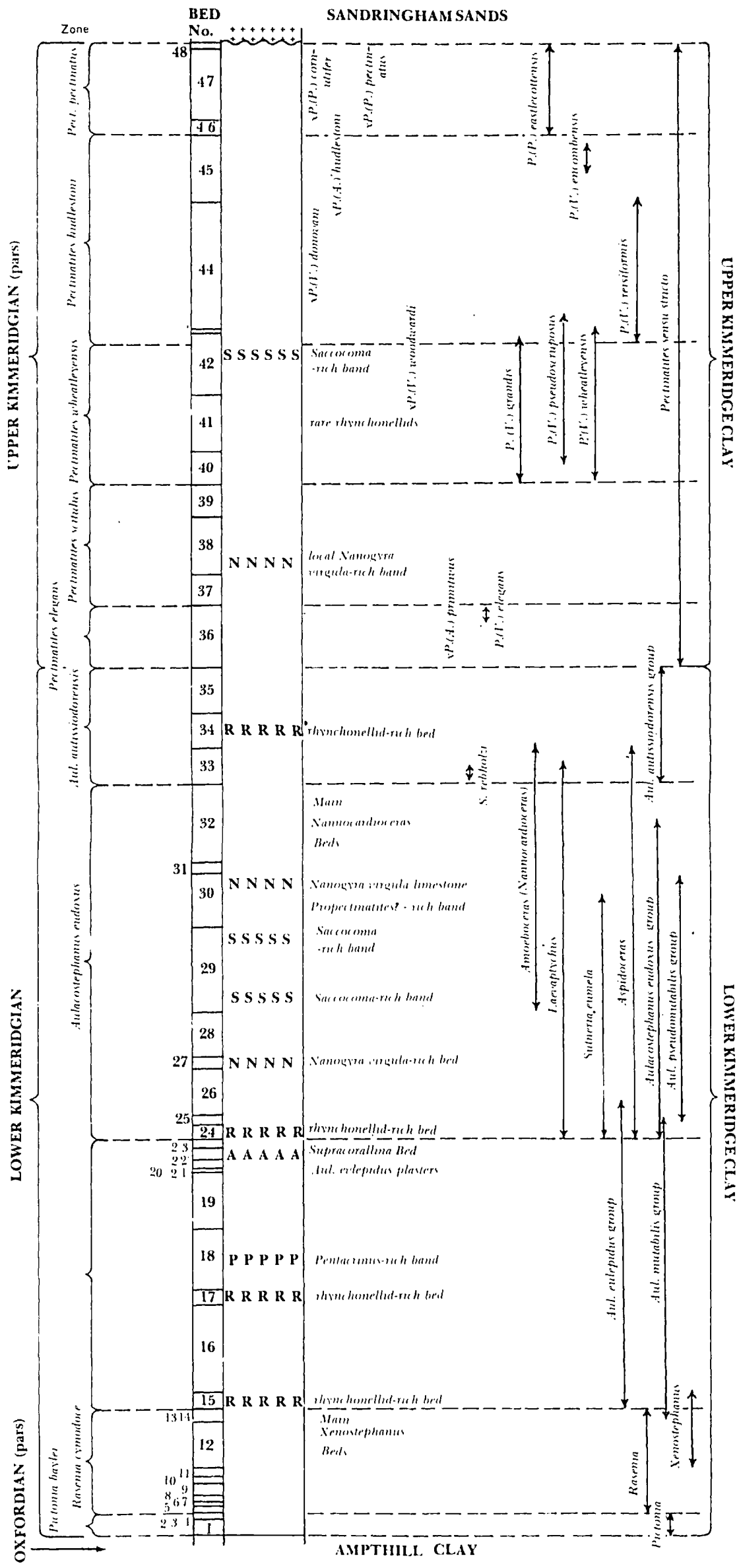


Fig.21. Generalized vertical section of the Kimmeridge Clay of Norfolk and The Wash showing ammonite ranges and selected faunal marker bands. See text for sources of data.

described by Cope (1967, 1978). The present state of knowledge concerning the stratigraphical ranges of the genera and the zonal boundaries can be summarized as follows. The zonal indices are discussed in ascending stratigraphical order, other ammonites alphabetically.

(i) Pictonia

Pictonia is confined to the lowest zone of the Kimmeridge Clay, that of Pictonia baylei as defined by Salfeld (1913). In southern England, from Norfolk to Dorset, ammonites are rare at this level except in the lowest part of the formation. Salfeld (1913) recorded specimens from Wiltshire, Lincolnshire and North Yorkshire. In Norfolk, partially phosphatized Pictonia are extremely common in the phosphatic nodule bed which marks the base of the Kimmeridge Clay (Bed 1, Fig. 21). The very high frequency with which they have been recorded in boreholes at this level suggests that they form an almost continuous sheet. Salfeld (1913) and Arkell (1935) noted that Pictonia was common in the basal Kimmeridge Clay in Dorset and that its range was distinct from that of the related Oxfordian genus Ringsteadia. The base of the Kimmeridgian Stage and the Pictonia baylei Zone were therefore taken at the incoming of Pictonia. Throughout southern England, including Dorset and Norfolk, this horizon is marked by a widespread erosion surface that also marks the base of the Kimmeridge Clay; the relationship of Pictonia to Ringsteadia has yet to be demonstrated in an unbroken sequence. The upper limit of Pictonia and its relationship to Rasenia is also poorly understood at present.

(ii) Rasenia

The stratigraphical range of Rasenia was taken by Ziegler (1962) to define the limits of the Rasenia cymodoce Zone. In Dorset and

Norfolk, the base of the zone is marked by a minor erosion surface with phosphatic pebbles, interburrowing* and a sudden influx of large numbers of raseniids. Birkelund et al. (1978) recognised a succession of four Rasenia faunas in Britain, the oldest of which is characteristic of the Wyke Siltstone in Dorset (= Bed 5 in Norfolk). Ziegler (1962) concluded that the boundary between Rasenia and Aulacostephanus was transitional (progressive weakening of the ribs across the venter in the raseniids to produce a smooth ventral band in the aulacostephanids). This is difficult to verify in Norfolk because an erosion surface at the top of the cymodoce Zone largely separates the two forms. A well preserved (Plate 12), prolific and varied raseniid fauna is present in the cymodoce Zone (Beds 5 to 14, Fig. 21) in Norfolk (Gallois and Cox, 1976), in which Dr Cox has identified Rasenia anglica Geyer, R. cymodoce (d'Orbigny), R. erinus (d'Orbigny), R. (Eurasenia) trifurcata (Reinecke), R. (Involuticeras) sp., R. (Raseniodes) lepidula (Oppel), R. (Raseniodes) paralepida Schneid, R. (Semirasenia) askepta Ziegler and R. (S.) moeschi (Oppel).

(iii) Aulacostephanus

In his monograph of the genus Ziegler (1962) used assemblages of species of Aulacostephanus to define the A. mutabilis, A. eudoxus and A. autissiodorensis zones. Aulocostephanus is abundant at this stratigraphical level in Norfolk. In the mutabilis Zone finely ribbed varieties of the A. eulepidus (Schneid) and A. mutabilis (J. Sowerby) groups predominate (Plate 13). These are replaced in the eudoxus Zone by more coarsely ribbed forms of the A. eudoxus (d'Orbigny) group, and in the

* In soft sediments that have not been hardened by calcitisation, phosphatisation or other secondary mineralisation, erosion surfaces are commonly represented by thin bands of complexly burrowed sediment composed of material from immediately below and above the erosion surface. Such bands are referred to here as 'interburrowed'.

Plate 12. Rasenia; all photographs at natural size.

A, B. Coarsely ribbed Rasenia with ribs becoming weakened, but still continuous, across the venter. Specimen no. BDK 8416, North Wootton Borehole, 113.48 m, Bed 8.

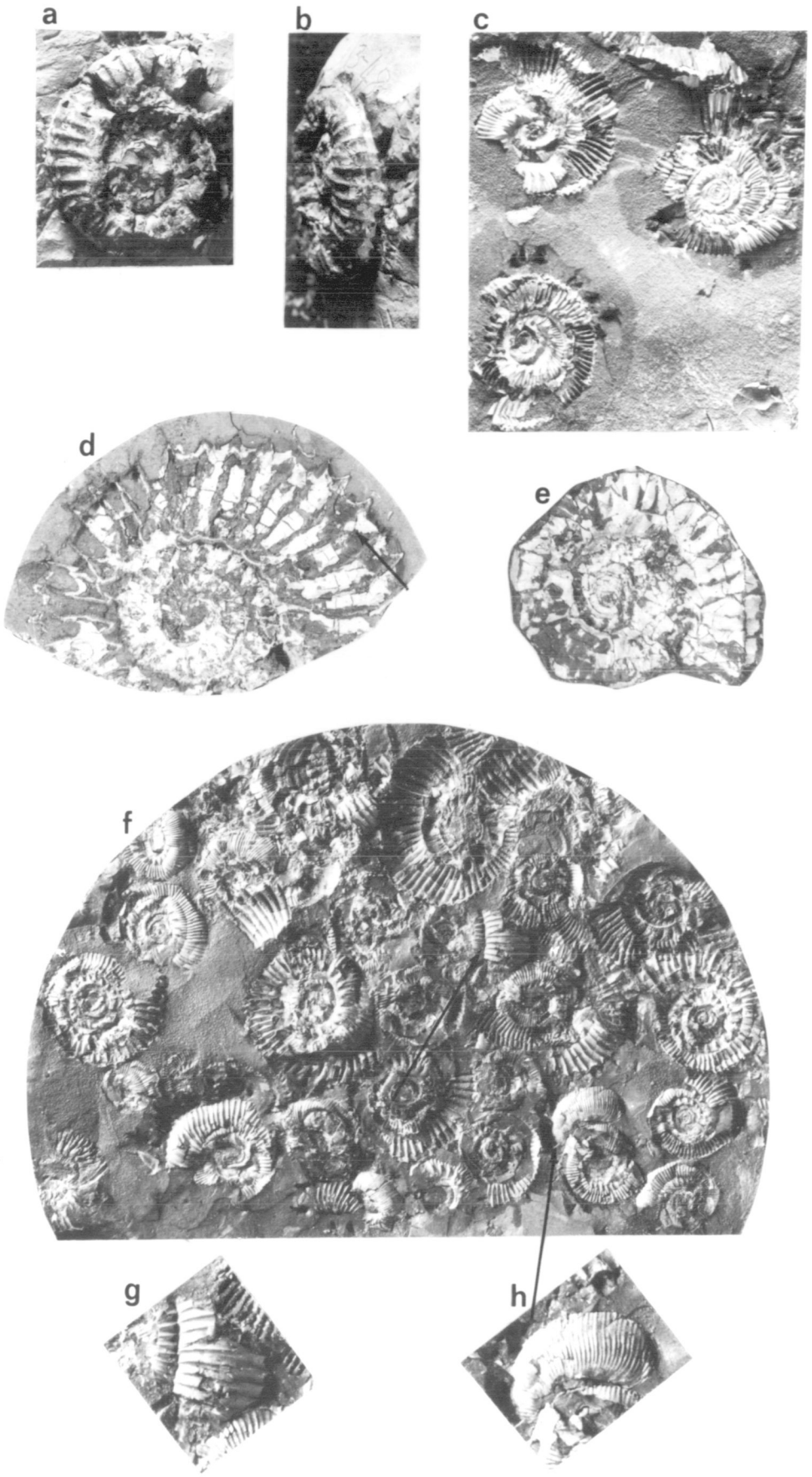
C. Crushed Rasenia or Aulacostephanus, in which the ventral band is too damaged for generic determination to be made. These three specimens have their body chamber openings facing in the same direction and may have been orientated by a current moving from right to left. Specimen no. BDU 8264, North Wootton Borehole, 104.75 m, Bed 16.

D. Crushed, coarsely ribbed Rasenia in which the ribs can be seen to weaken slightly, but continue unbroken across the venter (arrowed). Specimen no. BDU 7709, Ongar Hill Borehole, 69.58 m, Bed 12.

E. Rasenia or Xenostephanus in crushed preservation typical of that of much of Kimmeridge Clay, and in which the venter and ribbing style is far from clear. Specimen no. BDK 8429, North Wootton Borehole, 113.90 m, Bed 12.

F, G, H. A rich Rasenia fauna in which finely-ribbed R. (Raseniodes) lepidula (Oppel) is common, close to the upper range of the genus. Some specimens (for example G) have strong ribs passing without diminution across the venter, whereas others (for example H) show a marked weakening of the ribs across the venter; this line of weakening is commonly the site of a fracture during compaction. Specimen no. BDK 8407, North Wootton Borehole, 102.98 m, Bed 12.

Plate 12



autissiodorensis Zone by an assemblage dominated by large A. autissiodorensis (Cotteau).

In Norfolk, there is probably a small overlap between Rasenia and Aulacostephanus and a larger, proven overlap of Aulacostephanus of the eulepidus and mutabilis groups with those of the eudoxus group. The bases of the mutabilis and eudoxus zones have therefore been taken in the present work at minor, but widespread, erosion surfaces (bases of Beds 15 and 24) that mark the incoming of Aulacostephanus and the A. eudoxus group respectively. The younger of these also marks the incoming of the ammonites Aspidoceras and Sutneria. The same erosion surfaces have been taken to mark the bases of these zones in Dorset (Cox and Gallois, 1981) and, because they are the bases of Type A rhythms (Fig. 5), they are likely to be persistent throughout southern England.

The base of the autissiodorensis Zone has been determined in the cliff sections at Kimmeridge Bay, Dorset by bed by bed collecting. Even there, the boundary has not been precisely identified because of the scarcity of well preserved ammonites close to the boundary. In the borehole cores in Norfolk, the position is even more difficult because there is an unbroken sequence of mudstones at this level in which specifically determinable Aulacostephanus are rare. However, in the Warlingham Borehole, Callomon and Cope (1971, p. 161) recorded a thin bed rich in the distinctive finely ribbed ammonite Sutneria rebholzi Berckhemer close above the base of the autissiodorensis Zone. The same species is also present over a narrow stratigraphical range just above the base of the zone at Kimmeridge Bay (Cox and Gallois, 1981). This band has been recognised in boreholes in Lincolnshire and Norfolk and its base, taken in conjunction with the ranges of

Plate 13. Aulacostephanus, all photographs at natural size.

A. Aulacostephanus of the eudoxus group. Specimen no. BDK 7555, North Wootton Borehole, 61.62 m, Bed 32.

B. Large evolute Aulacostephanus or possible Rasenia from the zone of overlap of the two genera. Specimen no. BDU 8660, Symington Farm Borehole, 60.90 m.

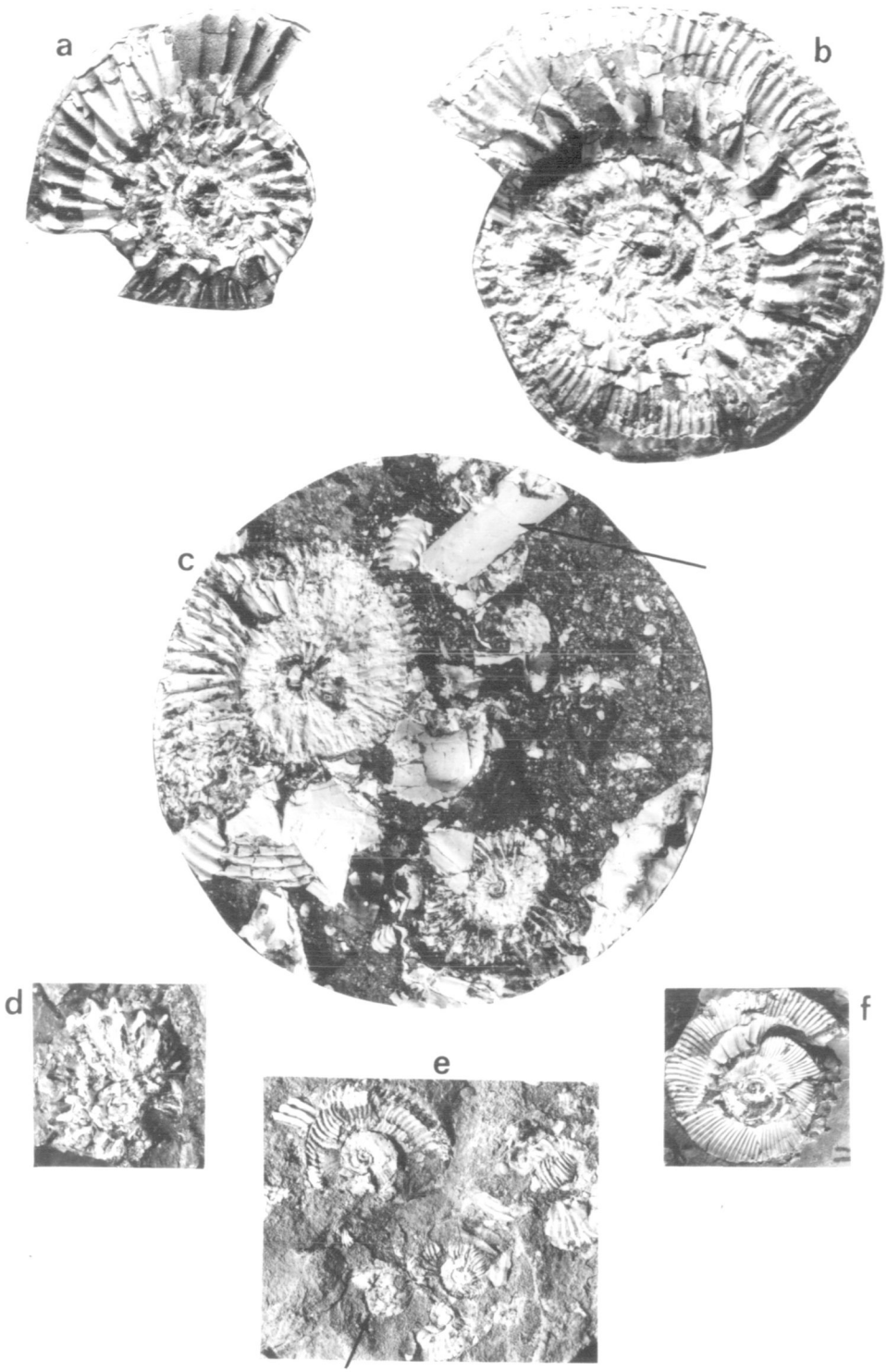
C. Rich Aulacostephanus fauna, comprising loose lappets (arrowed) and several species including a small, smooth variety (either a juvenile or a new species) together with common Pectinatites or Propectinatites. Specimen no. BDU 0346, Donington on Bain Borehole, 72.76 m, Bed 35.

D. Very coarsely ribbed Aulacostephanus showing marked ventral trough. Specimen no. BDK 7826. North Wootton Borehole, 77.60 m, Bed 29.

E. Small, smooth Aulacostephanus (arrowed, as C.) are common close to the upper stratigraphical limit of the genus. Specimen no. BDK 7418, North Wootton Borehole, 53.00 m, Bed 35.

F. Finely ribbed crushed Rasenia or Aulacostephanus from the zone of overlap of the two genera. Specimen number BDK 8475, North Wootton Borehole, 116.22 m.

Plate 13



A. eudoxus and A. autissiodorensis, forms a useful approximation to the eudoxus-autissiodorensis zonal boundary.

The junction of the autissiodorensis Zone with the overlying Zone of Pectinatites (Virgatosphinctoides) elegans, which is also taken to be the junction of the Lower and Upper Kimmeridge clays, has been defined by Cope (1967) on the incoming of Pectinatites. This definition is impracticable for use in borehole cores because the distinction between the Upper Kimmeridgian Pectinatites and the Lower Kimmeridgian Propectinatites (Cope, 1968) is based on the recognition of a ventral horn in the microconch of Pectinatites, a feature that is rarely preserved even among the large number of specimens that can be observed in the Kimmeridge Bay sections. The base of the elegans Zone has therefore been taken in Norfolk at a lithological change just above the highest recorded Aulacostephanus.

Recent discoveries of specimens of the Upper Kimmeridgian ammonite Gravesia in the upper part of the autissiodorensis Zone in Dorset and Lincolnshire have led to the suggestion (Cox and Gallois, 1981) that the Gravesia Zone of Salfeld (1913), which was abandoned by Cope (1967), might usefully be reintroduced because of the importance of Gravesia for international correlation at this level. This would place the upper part of the stratigraphical range of Aulacostephanus in the Upper Kimmeridgian, but the range of common A. autissiodorensis would remain within the zone for which it is the index fossil. Gravesia (see below) has not been recorded in Norfolk and the usefulness of a Gravesia Zone would be dependent upon its being linked to other faunal and lithological features.

(iv) Xenostephanus

Ziegler (1962) described Xenostephanus, a coarsely ribbed, evolute

subgenus of Aulacostephanus, from erratic sandstone blocks in the boulder clay of Lincolnshire. Arkell and Callomon (1963) subsequently provided detailed descriptions of the Lincolnshire material and Kent and Casey (1963) recorded Xenostephanus in situ in the Elsham Sandstone in Lincolnshire and from Dover and Culgower, Sutherland in association with Aulacostephanus indicative of a mutabilis Zone age. Xenostephanus is common in Norfolk over a restricted stratigraphical range in the upper part of the cymodoce Zone and occurs more sparingly in the lowest part of the mutabilis Zone (Fig. 21). It occurs at a similar stratigraphical level in Dorset. The main range of Xenostephanus lies below that of Aulacostephanus and it has been proposed (Cox in Cox and Gallois, 1981) that they should be regarded as separate genera. This is in accord with Kent and Casey's suggestion (1963, p. 61) that Xenostephanus might be misplaced as a subgenus of Aulacostephanus.

(v) Pectinatites

Species of Pectinatites have been used by Cope (1967) to define the elegans, scitilus, wheatleyensis, hudlestoni and pectinatus zones of the Upper Kimmeridgian. He concluded from a study of the ammonite sequence at this stratigraphical level in the Dorset coast sections that these perisphinctids, which first appear in large numbers a little below the upper limit of Aulacostephanus, form a single, evolving group. He therefore placed forms which had previously been attributed to a large number of genera, including Lithacoceras, Pectinatites, Subplanites and Virgatosphinctoides, in the single genus Pectinatites.

Pectinatites is the only ammonite genus recorded to date from the elegans to pectinatus zones in Norfolk (Plate 14). Identification of the various subgenera and species is based largely on the ribbing style and number ribs per whorl. Well preserved, adult specimens showing an

Plate 14. Pectinatites and Propectinatites; all photographs at natural size.

A. Large Pectinatites with epizoic oysters obscuring ribbing, a typical Kimmeridge Clay form of preservation. Specimen no. BDC 1331, Marham Borehole, 297 ft 2 in., Bed 37.

B. Crushed, but readily diagnostic, very finely ribbed Pectinatites (Pectinatites) eastlecottensis Salfeld. Specimen no. BDD 3493, Hunstanton Borehole, 344 ft 0 in., Bed 46.

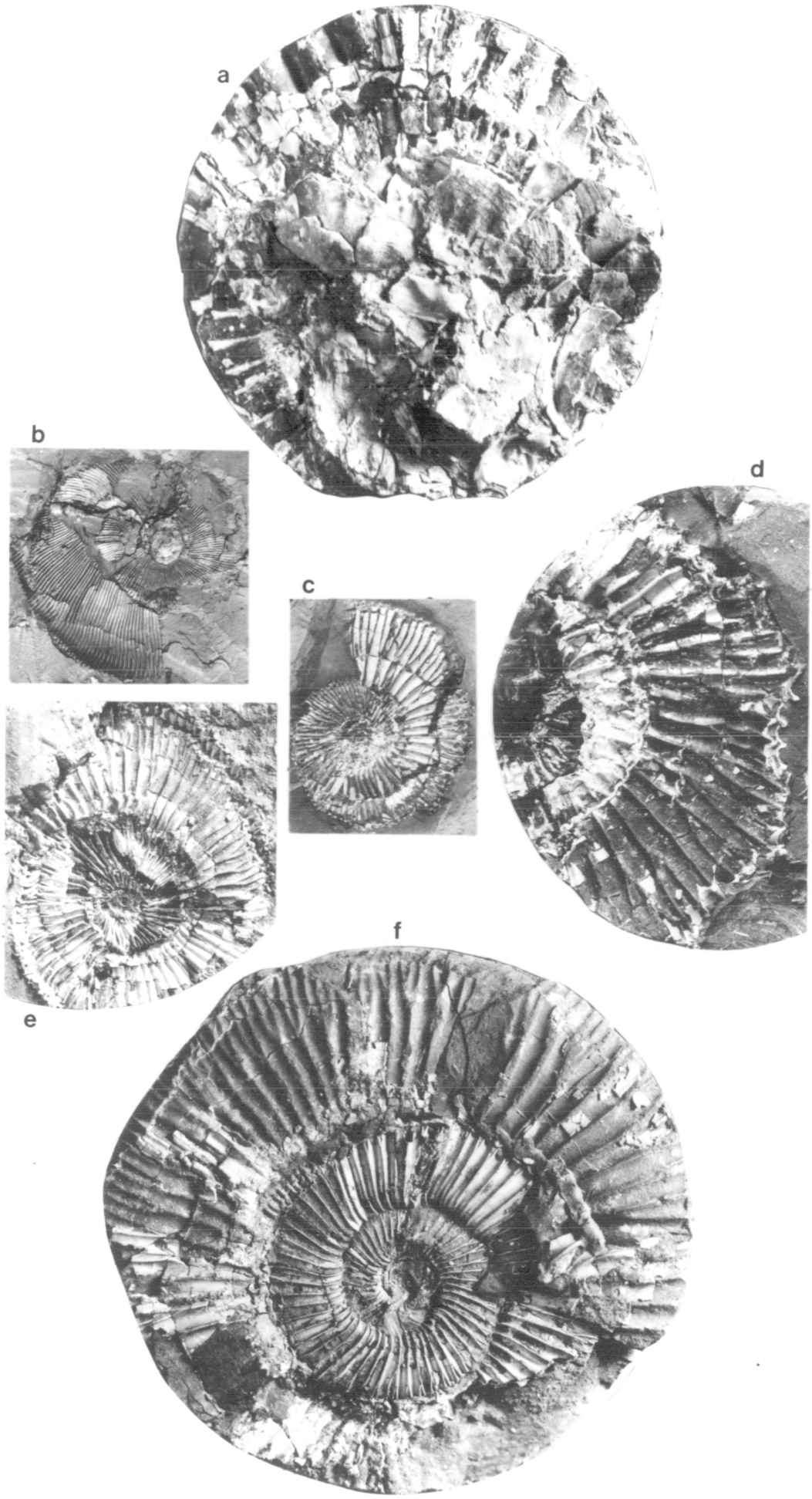
C. Pectinatites (Virgatosphinctoides) of the reisiformis group. Specimen no. BDU 0145, Donington on Bain Borehole, 39.80 m, Bed 44.

D. Crushed Propectinatites from close to the Lower/Upper Kimmeridge Clay boundary. This specimen occurs with a rich Aulacostephanus fauna. Specimen no. BDU 0385, Donington on Bain Borehole, 74.77 m, Bed 35.

E. Crushed Pectinatites (Virgatosphinctoides). Specimen no. BDC 1239, Marham Borehole, 276 ft 10 in., Bed 41.

F. A well preserved and accurately cored Pectinatites (Virgatosphinctoides) wheatleyensis (Neaverson), showing characteristic virgatatome ribbing in its outer whorl. Specimen no. BDU 0198, Donington on Bain Borehole, 47.15 m, Bed 41.

Plate 14



almost complete outer whorl are necessary for species identification and such material is rare in borehole cores even though pectinatitids are common throughout much of the sequence. The boundaries of the zones of the Upper Kimmeridgian in Norfolk (Fig. 21) have therefore been placed on the basis of lithological features that can be matched with the Dorset type section, within the broad framework provided by the ammonites. The stratigraphical ranges of the species recorded in Norfolk are summarised in Fig. 21, in which the ammonite determinations are taken from Cope (1974b). Because of the rarity of identifiable specimens none of these ranges is likely to be complete; some species are represented by a single specimen.

(iv) Pavlovia

Detailed discussion of the stratigraphy of the Pavlovia zones falls outside the scope of the present thesis because any beds of this age which were deposited in Norfolk were subsequently removed by erosion in the late Jurassic. Pavlovia is common in phosphatic pebbles at the base of the Sandringham Sands in Norfolk and it is relevant to the discussion of the late Jurassic earth movements that affected the area (Chapter 3).

Neaverson (1924, 1925) divided the highest part of the Kimmeridge Clay in Wiltshire and Buckinghamshire into two zones, characterised by Pavlovia rotunda (Sowerby) below and P. pallasiodes (Neaverson) above; Casey (1967) subsequently showed these to be stratigraphically inverted. This has recently been confirmed in a study of the Dorset cliff sections by Cope (1978) who recognised three zones. The index species are, in ascending order, Pavlovia pallasiodes, Pavlovia rotunda and Virgatopavlovia fittoni Cope. The fittoni Zone has yet to be recognised outside Dorset.

(v) Amoeboceras

Species of Amoeboceras form the zonal indices for the argillaceous facies of the Upper Oxfordian (Sykes and Surlyk, 1976) and the genus occurs sporadically throughout the Lower Kimmeridgian. Salfeld (1913), Spath (1935), Morris (1968) and the Callomon and Cope (1971) have described various species of Amoeboceras from the British Kimmeridgian. Most of these have been assigned to the subgenus Amoebites. In Norfolk, species of Amoeboceras (Amoebites) are locally common in the lower part of the cymodoce Zone and at several levels in the middle part of the eudoxus Zone. The upper part of the eudoxus Zone and the lowest part of the autissiodorensis Zone contain enormous numbers of the tiny subgenus Nannocardioceras, some beds consisting almost entirely of interlaminated oil shales and crushed Nannocardioceras shells (Plate 15). Callomon and Cope (1971, p. 158) introduced the name Nannocardioceras Beds for similar beds in the eudoxus Zone in the Warlingham Borehole. However, it was not appreciated at that time that these shell plasters occur in both the eudoxus and autissiodorensis zones in Dorset (Cox and Gallois, 1981) and that their usefulness as a stratigraphical marker bed is consequently lessened.

Callomon and Cope (1971) recognised two species of Nannocardioceras in the Warlingham Borehole, the finely ribbed A. (N.) anglicum (Salfeld) and the smooth A. (N.) krausei (Salfeld). These same species are present in Norfolk. Both have similar stratigraphical ranges, but A. (N.) krausei appears to be much the commoner in the upper half of the range. It is of interest that the highest recorded Nannocardioceras both in Dorset and Norfolk is a form of A. (N.) anglicum with distinctive, fine, rectiradiate ribbing.

Plate 15. Amoeboceras (Amoebites) and Amoeboceras (Nannocardioceras).

A. Well preserved Amoeboceras (Nannocardiocerus) anglicum (Salfeld) showing typical ribbing and keel, together with fragments of Aulacostephanus and small bivalves. Specimen no. BDU 0483, Donington on Bain Borehole, 109.65 m, Bed 29. Natural size.

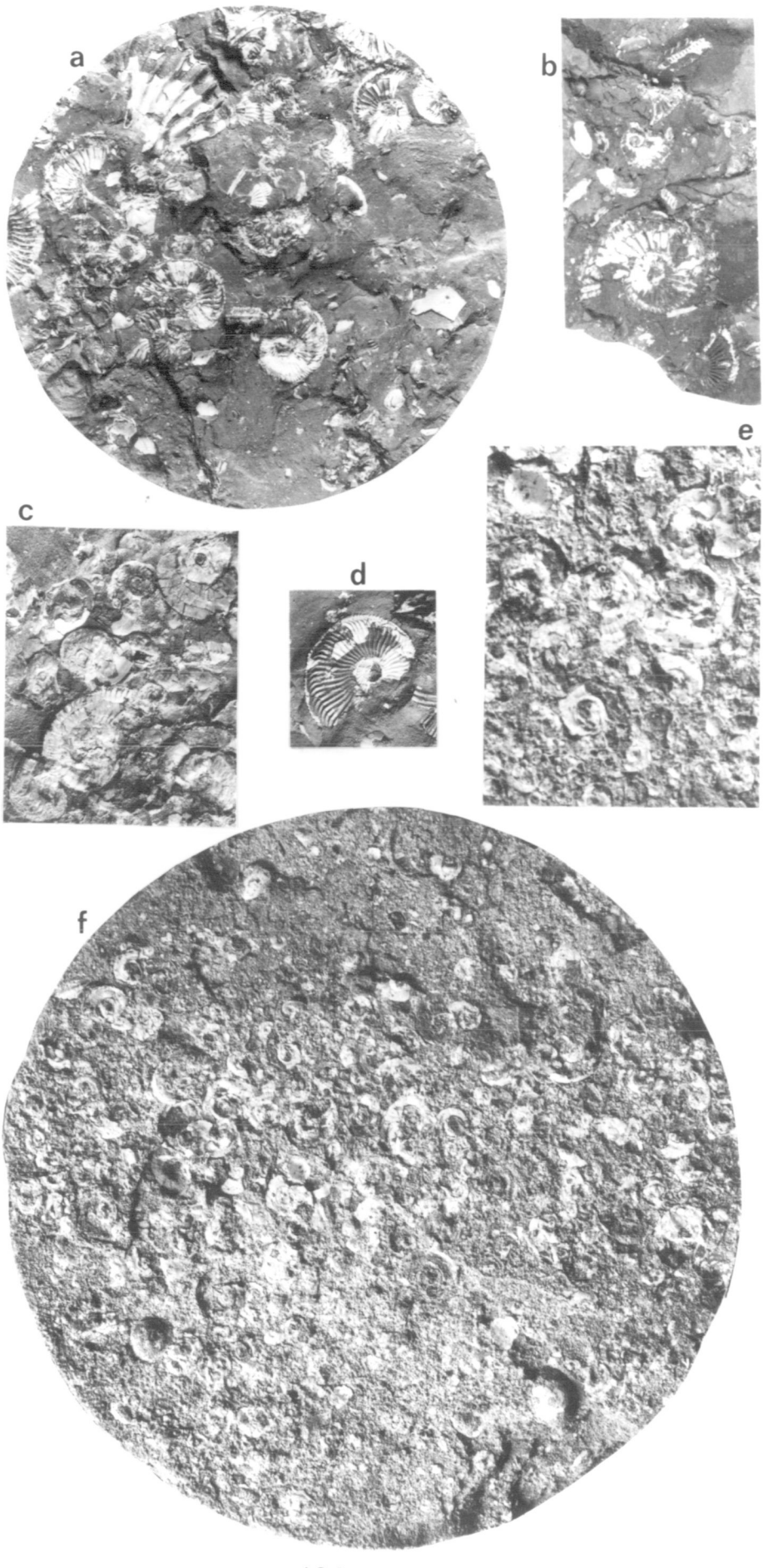
B. Crushed Amoeboceras (Amoebites) with fragments of Nannocardioceras anglicum. Specimen no. BDK 7896, North Wootton Borehole, 81.50 m, Bed 28. Natural size.

C. Crushed but otherwise well preserved Nannocardioceras krausei (Salfeld) showing both smooth and faintly ribbed varieties. Specimen no. BDK 7539, North Wootton Borehole, 60.68 m, Bed 32. Magnification 2x.

D. Amoeboceras (Amoebites). Specimen no. BDK 8299, North Wootton Borehole, 106.90 m, Bed 16. Natural size.

E, F. Plaster composed almost entirely of whole and fragmentary Nannocardioceras krausei. Specimen no. BDK 7580, North Wootton Borehole, 65.16 m, Bed 32. F. at natural size; E. shows 2x magnification of central part of F.

Plate 15



(viii) Aspidoceras

Aspidoceras and its aptychal plate Laevaptychus ranges in Norfolk from the erosion surface at the base of the eudoxus Zone up into the lower part of the autissiodorensis Zone. In the Warlingham Borehole, Callomon and Cope (1971, pp. 159-160) recorded the range as upper mutabilis Zone to low autissiodorensis Zone. In Dorset Aspidoceras is common over the same range as in Norfolk but the presence of rare Laevaptychus in the upper part of the mutabilis Zone suggests that the full range may be similar to that of the Warlingham Borehole. Aspidoceras is commonly abundant in the calcareous siltstone (Bed 24) which marks the base of the eudoxus Zone in East Anglia. Above this level it is uniformly common throughout its range. Callomon and Cope (1971, p. 159) drew attention to the well developed dimorphism in Aspidoceras and Laevaptychus and this has been confirmed in the Norfolk specimens.

(ix) Gravesia

Gravesia is extremely rare in the English Kimmeridgian but it provides an important link between the various faunal provinces - the Kimmeridgian/Portlandian, Tithonian and Volgian - which developed towards the end of the Jurassic. It occurs in the lowest zones of the Tithonian and Volgian stages (Sasonova and Sasonov, 1979) and is the only ammonite genus yet recorded at this stratigraphical level that is also present in the Kimmeridgian. The stratigraphical distribution of recorded specimens of Gravesia in England has been re-examined (Cox and Gallois, 1981) and Salfeld's (1913) and Ziegler's (1962) observations that the genus appears in the autissiodorensis Zone in Dorset have been confirmed. Gravesia has been recorded from several localities in Britain, but only specimens from the Donington on Bain

Borehole, the Warlingham Borehole and Kimmeridge Bay have been confirmed by Dr Cox to be true Gravesia. Pringle's (IGS MSS, 1919) specimen from the West Bilney Borehole, Norfolk could not be traced. The genus is undoubtedly rare but, apart from the Dorset coast, there is no permanent expsoure of the beds at this stratigraphical level and few cored boreholes have penetrated it. Furthermore, there is evidence in Dorset to suggest that Gravesia is more susceptible to weathering than the other ammonites with which it occurs. The range in Dorset is from the middle part of the autissiodorensis Zone to the top of the elegans Zone.

(x) Propectinatites

Cope (1968) introduced the name Propectinatites for pectinatitid ammonites occurring in the autissiodorensis Zone which differ from Pectinatites only in their lack of a ventral horn. Such perisphinctids are very common in Norfolk in the top part of the autissiodorensis Zone, in calcareous mudstones throughout the remainder of the autissiodorensis Zone and in the same lithology at certain levels within the eudoxus Zone. One of these, the Propectinatites?-rich band of Bed 30 (Fig. 21), can be traced throughout the English outcrop. All the Norfolk specimens are crushed and most are much larger than the core diameter (Plate 14). No useful comment can therefore be made at this stage on the range of the genus or its relationship to other Lower Kimmeridgian perisphinctids.

(xi) Sutneria

The distinctive tethyan genus Sutneria was only known in England from a few specimens in loose blocks from Ringstead, Dorset (Ziegler, 1962) and in a borehole in Lincolnshire (Benniworth near Donington on Bain, Spath MSS, 1940) until recorded in profusion in the Ashdown No. 1 (Callomon in Bristow and Bazley, 1972) and Warlingham (Callomon and Cope, 1971) boreholes. In Norfolk, the species S. cyclodorsata (Moesch)

and S. eumela (d' Orbigny) are confined to the eudoxus Zone; a third species, S. rebholzi Berckhemer, has a narrow stratigraphical range a little above the base of the autissiodorensis Zone (Fig. 21). Callomon and Cope (1971, p. 161) recorded the same species and ranges in the Warlingham Borehole but in the Ashdown No. 1 Borehole Callomon (1972) recorded specimens from the mutabilis Zone. In Dorset the ranges are closely similar to those in Norfolk (Cox and Gallois, 1981, Fig. 2).

2.2.2.3 Bivalves

A total of 25 bivalve genera have been recorded in the Kimmeridge Clay but only a few of these are common at any given stratigraphical level. The more common genera, together, with those which are stratigraphically useful or which provide an insight into palaeoenvironmental conditions, are discussed below; a selection are shown in Plate 16.

(i) Astarte

Species of Astarte occur throughout the Kimmeridge Clay and are locally common. They have not been found to be stratigraphically useful except at one horizon in the upper part of the mutabilis Zone in Dorset where Arkell (1947, p. 85) recorded large numbers of Astarte supracorallina d'Orbigny. This same species occurs in great abundance over the same restricted stratigraphical range in boreholes in Norfolk and elsewhere in southern England and Arkell's "Astarte supracorallina Bed" therefore provides a useful marker. In the Upper Kimmeridge Clay Astarte mysis d'Orbigny is common in the elegans to wheatleyensis zones, occasionally completely covering a bedding surface.

(ii) Camptonectes, Chlamys, Entolium and Oxytoma

Small forms of Entolium and Oxytoma are common in the more shelly parts of the Kimmeridge Clay where they usually occur in association

Plate 16. Laevaptychus, Sutneria and bivalves; all photographs at natural size.

A. Large Myophorella preserved in sandy clay. Tisbury Borehole, 95.61 m, Upper Kimmeridge Clay.

B. Laevaptychus showing characteristic pitted outer surface. Specimen no. BDK 7977, North Wootton Borehole, 86.65 m, Bed 26.

C. Large ostreid oysters and crushed Aulacostephanus eulepidus preserved in dark grey mudstone. Specimen no. BDU 9204, Vinegar Middle Borehole, 74.31 m, Bed 16.

D. Sutneria eumela (d'Orbigny); microconch showing characteristic ribbing style and lappet. Specimen no. BDK 7768, North Wootton Borehole, 74.70 m, Bed 29.

E. Crushed Modiolus preserved in calcite-film preservation. Specimen no. BDK 7930, North Wootton Borehole, 86.30 m, Bed 26.

F. Large slug-like Nanogyra virgula (Defrance) preserved in bioturbated mudstone. Specimen no. BDK 7754, North Wootton Borehole, 73.63 m, Bed 29.

G. Abundant Astarte supracorallina d'Orbigny preserved in highly calcareous pale grey mudstone. Specimen no. BDK 8030, North Wootton Borehole, 89.06 m, Bed 22.

H. Concentration of bivalve spat. Specimen no. BDK 7967, North Wootton Borehole, 86.18 m, Bed 26.

I. Crushed 'Lucina' miniscula Blake with partially dissolved shells, preserved in oil shale. Specimen no. BDU 0290, Donington on Bain Borehole, 59.21 m, Bed 37.

J. 'Lucina' miniscula in more normal preservation forming plaster in mudstones. Specimen no. BDC 1321, Marham Borehole, 295 ft 1 in, Bed 40.

K. Pholadomya preserved in silty mudstone. Specimen no. BDK 8321, North Wootton Borehole, 108.53 m, Bed 15.

L. Placunopsis with shell coated by film of gypsum. Specimen no. BDK 8107, North Wootton Borehole, 94.60 m, Bed 19.

M. Lopha preserved in pale grey silty mudstone. Specimen no. BDU 8128, Emorsgate Borehole, 27.72 m, Bed 18.

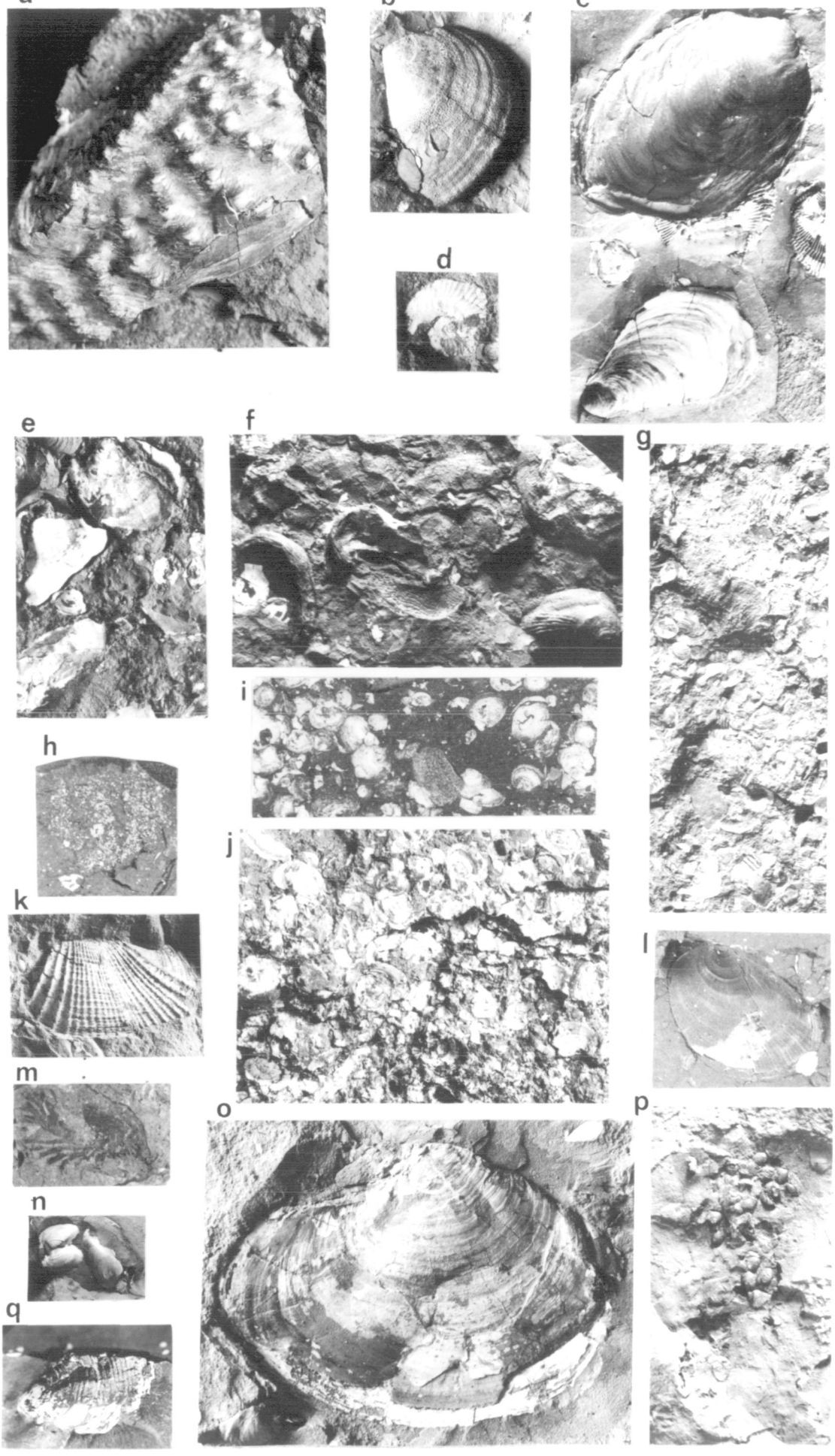
N. Nuculid valves probably close to growth position. Specimen no. BDU 8664, Symington Farm Borehole, 63.55 m, Bed 8.

O. Large Thracia depressa (J. de C. Sowerby) preserved as paired valves parallel to bedding in pale grey mudstone. Specimen no. BDU 8415, Terrington St John Borehole, 42.77 m, Bed 4.

P. Concentration of small nuculids. North Runcton Borehole, Upper Kimmeridge Clay.

Q. Partially crushed Thracia preserved in life position. Tisbury Borehole, 108.26 m, Upper Kimmeridge Clay.

Plate 16



with other small bivalves, including oysters. Larger forms of all four genera occur sparingly throughout the formation with Camptonectes rather more common in the Upper Kimmeridge Clay.

(iii) Deltoideum, Gryphaea, Isognomon, Liostrea, Nanogyra and Plicatula

Oysters are common at many levels in the Kimmeridge Clay and are abundant wherever there are signs of erosion or more turbulent bottom conditions. Even in the most muddy sediment they can be the commonest bivalve because epizoic forms encrust the debris of pelagic fossils such as ammonites.

Large flat oysters such as Deltoideum and Liostrea are common at several levels in the Kimmeridge Clay. They are rarely identifiable specifically in boreholes because of their large size. Deltoideum delta (Wm Smith) ranges in Dorset from Upper Oxfordian to Lower Kimmeridgian (baylei Zone) but because large numbers weather out of the basal beds of the Kimmeridge Clay (Arkell, 1933, p. 451) it has on occasion been mistakenly thought of as characteristic of the Kimmeridge Clay. In Norfolk, D. delta is common at many levels in the upper part of the Ampthill Clay (Gallois and Cox, 1977) and within the baylei Zone. Other ostreid oysters, mostly small forms, occur throughout the Kimmeridge Clay; they are especially common as epizoic encrustations of ammonites in the otherwise almost barren parts of the Upper Kimmeridge Clay.

Gryphaea, Isognomon, Plicatula and small gryphaeid oysters occur in the more shelly parts of the formation, mostly in the Lower Kimmeridge Clay.

Nanogyra is common at many levels in the Kimmeridge Clay and is abundant at some. Arkell (1933, p. 451 and Plate XXI) recorded a thin limestone almost entirely composed of Nanogyra nana (J. Sowerby) with

rarer N. praevirgula Jourdy in the basal part of the baylei Zone in Dorset which he subsequently (1947) called the "Exogyra nana Bed". N. nana is almost ubiquitous in the Corallian of England and Normandy (Fürsich 1977, p. 342) and it would be stratigraphically useful in the Kimmeridge Clay only if it were abundant at a particular level over a wide area. Nanogyra nana is common but not abundant in the basal beds of the Kimmeridge Clay in Norfolk and in the few other boreholes in England which have penetrated the basal beds. It therefore seems likely that Arkell's E. nana Bed is a local development.

In the upper half of the Lower Kimmeridge Clay and the lower part of the Upper Kimmeridge Clay (mutabilis to wheatleyensis zones) the distinctively ornamented Nanogyra virgula (Defrance) is scattered throughout and is abundant at several well-defined levels. In Norfolk, small forms with a large attachment area appear in the mutabilis Zone and are common in the basal bed of the eudoxus Zone. Large slug-like forms are abundant in the upper part of the eudoxus Zone and at one particular level (in Bed 30) form a soft shelly limestone. Bed 30 probably correlates with the Nanogyra virgula-rich Marnes du Kimmeridgien of Bourgogne which, according to Tresise (1981), are largely responsible for the calcareous soils on which the classic Chablis vineyards are sited.

Medium-sized forms are common throughout the autissiodorensis to wheatleyensis zones in Norfolk and locally form a marker bed, in which they are abundant, at the top of their stratigraphical range.

In Dorset, N. virgula ranges from the eudoxus to the scitulus zones. In the upper part of the eudoxus Zone large forms are locally abundant and form a soft shell-limestone, (the Virgula Limestone of Cox and Gallois, 1981) at the same level as in Norfolk. The highest

N. virgula recorded in the Warlingham Borehole was in the scitulus Zone at a similar level to the highest occurrence in Dorset (Callomon and Cope 1971, p. 152). These same authors (1971, p. 162) have stated that the occurrence of N. virgula is wholly unconnected with lithology in the Warlingham Borehole and have suggested that it may not have been benthonic. In Norfolk N. virgula shows a striking affinity for one particular type of intensely burrowed mudstone and may even have been the burrower itself.

(iv) Goniomya, Pleuromya, and Pholadomya

Myid bivalves are common in the Kimmeridge Clay only at those levels at which there is evidence of slow deposition (indicated by phosphatisation) or stronger current activity (indicated by silt, shell debris and phosphatic pebbles). They are therefore most common in the lower part of the baylei Zone and in the silty beds at the bases of the eudoxus, mutabilis and cymodoce Zones. This distribution may simply reflect a preservational bias towards horizons in which these thin-shelled, deep burrowers are preserved by phosphatisation. Specimens in clay-cast preservation occur throughout the Kimmeridge Clay, but are nowhere common.

(v) Lopha

Lopha is rare in the Kimmeridge Clay of Norfolk except in the silty horizons at the bases of the Type A rhythms. At each of these horizons it appears to occur in association with rhynchonellid brachiopods.

(vi) 'Lucina' and Protocardia

'Lucina' miniscula Blake (Codakia (Epilucina) miniscula of some authors) and Protocadia morinica (de Loriol) form shell plasters (bedding planes composed almost entirely of shells) throughout the Upper Kimmeridge Clay in Norfolk and are common at many levels in the upper part of the Lower Kimmeridge Clay. Below the wheatleyensis Zone,

'Lucina' - plasters are generally replaced by Protocardia - plasters and this probably reflects the stratigraphical ranges of the two species with P. morinica appearing earlier and reaching its acme sooner. Scattered specimens of Protocardia are common above the wheatleyensis Zone but these are almost always smaller forms and may be a species distinct from P. morinica.

(vii) Modiolus

In the Warlingham Borehole Modiolus autissiodorensis (Cotteau) is by far the most common bivalve in the hudlestoni and pectinatus zones of the Upper Kimmeridge Clay. Scattered specimens of this species occur at this same level in Norfolk, but are nowhere common. Other species of Modiolus have been recorded at a few, widely spaced levels in the Lower Kimmeridge Clay.

(viii) Myophorella, Pinna and Thracia.

Thracia, usually assigned to Thracia depressa (J. de C. Sowerby), is common throughout the Kimmeridge Clay wherever there are sparsely fossiliferous, pale grey, calcareous mudstones. It is never abundant, but in this lithology it is commonly the dominant bivalve. The same species occurs in similar lithologies in the Corallian Beds and Portland Beds.

Myophorella and Pinna occur in similar pale grey mudstones, but are rare in the Kimmeridge Clay in Norfolk. They are much more common in areas where the Upper Kimmeridge Clay is silty or sandy as in Buckinghamshire and Wiltshire.

2.2.2.4 Brachiopods, belemnites, echinoderms, serpulids and crustaceans

Some of the most easily recognisable marker beds in the English Lower Kimmeridge Clay are the silty and phosphatic horizons associated with minor erosion surfaces which define the bases of the baylei, cymodoce,

mutabilis and eudoxus zones. As well as coinciding with changes in the ammonite assemblages, these beds typically contain a characteristic non-ammonite fauna that includes common rhynchonellid brachiopods, belemnites, echinoid spines and plates, and wood fragments. All of these are rare at other levels in the Kimmeridge Clay.

The abundant occurrence of the distinctive large rhynchonellid Torquirhynchia inconstans (J. Sowerby) in the basal bed of the Kimmeridge Clay in Dorset has long been recognised (e.g. Waagen, 1865). Away from the type section the species is rare and in East Anglia has only been recorded in situ in the North Creake Borehole (Kent, 1947), a former brickpit at Ely in Cambridgeshire (Roberts, 1892, p. 76) and a temporary section at Sutton, Cambs (Forbes, 1960). The Ely occurrences are puzzling because they are associated with an ammonite assemblage that is not older than the mutabilis Zone. Specimens of undoubted T. inconstans from Ely (Sedgwick Museum; Roberts and McKenny Hughes collections) appear to have been collected loose and have probably come from Kimmeridge Clay-rich till that occupies much of the older part of the workings. The Sutton specimens have recently been re-examined (Cox and Gallois in Gallois, in press); they came from the basal siltstone of the Kimmeridge Clay and are therefore at the same stratigraphical as those from Dorset.

Other rhynchonellids, mostly assigned to Rhynchonella subvariabilis Davidson, are common in the basal beds of the mutabilis and eudoxus zones and, more sparingly, at a few levels in the autissiodorensis and wheatleyensis zones (Plate 17).

Belemnites are rare in the Kimmeridge Clay in Norfolk. the few specimens recorded in borehole cores are fragmentary and indeterminate.

Echinoderms are represented in the Kimmeridge Clay by rare echinoid

Plate 17. Brachiopods, echinoderms, crustaceans, serpulids and vertebrate fragments. All photographs except F at natural size.

A. Section normal to bedding, cut through large calcitized and partially pyritized bone fragment. Specimen no. BDK 8157, North Wootton Borehole, 98.55 m, Bed 18.

B. Small crushed ophioroid. Specimen no. BDU 8593, Old Podyke Bank Borehole, 29.70 m, Bed 18.

C. Small shrimp-like crustacean preserved in sandy mudstone. Tisbury Borehole, Upper Kimmeridge Clay.

D. Phosphatised and partially pyritised bone fragment. Specimen no. BDK 8301, North Wootton Borehole, 107.05 m, Bed 16.

E. Fragment of crustacean carapace. Specimen no. BDU 8594, Old Podyke Bank Borehole, 29.72 m, Bed 18.

F. *Pentacrinus* columnals, separated and forming small lengths of stem. Centre picture at natural size, others at 10x. Specimen no. BDK 8164, North Wootton Borehole, 99.06 m, Bed 18.

G. Concentration of faecal debris. Specimen no. BDU 0201, Donington on Bain Borehole, 47.31 m, Bed 41.

H. Concentrations of serpulids in pale grey highly calcareous mudstone. Specimen no. BDK 7632, North Wootton Borehole, 66.30 m, Bed 32.

I. Serpulids encrusting inner surface of body chamber of large ammonite. Specimen no. BDU 7988, Hook Drain Borehole, 35.73 m, Bed 11.

K. Crushed and partially dissolved *Lingula* preserved in oil shale. Specimen no. BDK 7770, North Wootton Borehole, 74.89 m, Bed 29.

J. *Discinisca latissima* (J. Sowerby) preserved in dark grey mudstone. Tisbury Borehole, 114.65 m, Upper Kimmeridge Clay.

L. *Rhynchonella subvariabilis* Richardson. North Runcton Borehole, 42.85 m, Bed 34.

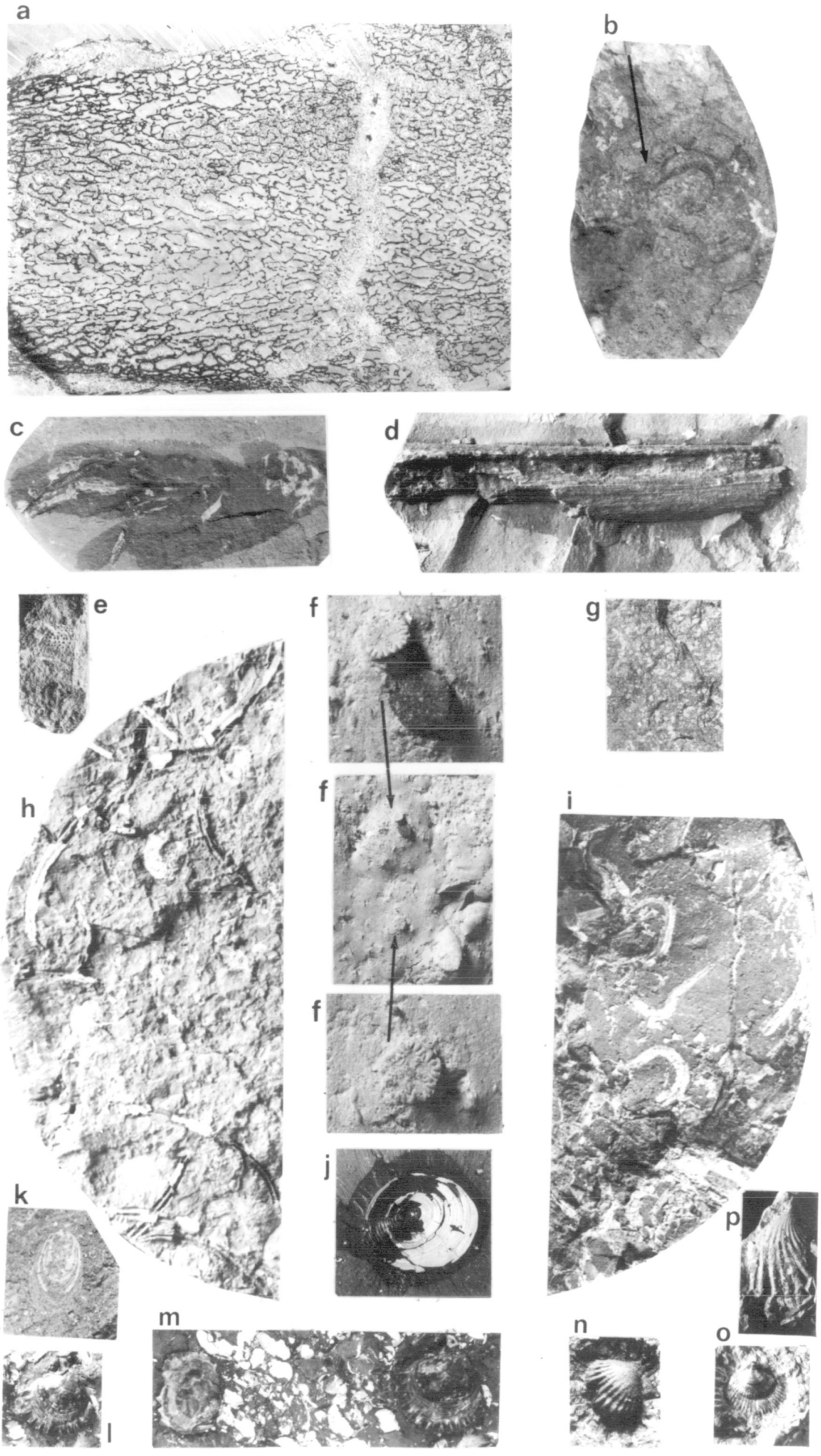
M. Rhynchonellids. Donington on Bain Borehole, 73.30 m, Bed 35.

N. Rhynchonellid preserved in silty mudstone. Specimen no. BDU 9121, Racecourse Road Borehole, 32.43 m, Bed 24.

O. Rhynchonellid preserved in silty mudstone. Specimen no. BDK 8016, North Wootton Borehole, 88.42 m, Bed 24.

P. Large coarsely ribbed rhynchonellid preserved in silty mudstone. Specimen no. BDK 8017, North Wootton Borehole, 88.42 m, Bed 24.

Plate 17



plates, relatively common cidarid spines and by two crinoids, Saccocoma and Pentacrinus. These last are abundant at particular levels but are very rare or absent at other levels.

Pyritized radial plates of the tiny, pelagic crinoid Saccocoma were first recorded in the Kimmeridge Clay by Bather (1911, p. 78) from the Penshurst Borehole in Kent. Although Bather recognised two forms, which he thought might prove to indicate two species, little further work was done on the Kimmeridge Clay specimens and they continued to be assigned to a long-ranging genus known in Britain only from the Kimmeridgian and the Campanian. Peck (1973, p. 94) subsequently separated the Campanian forms under the genus Applinocrinus, and Saccocoma is now restricted to forms known from the Kimmeridge Clay in Britain and the Kimmeridgian Solenhofen Limestone in Germany.

Saccocoma was first recorded at outcrop by Kitchin and Pringle (in Kitchin, 1919) at the level of the Blackstone (hudlestoni Zone) in the Dorset coast sections. Pringle (in Strahan 1920, p. 37) subsequently recorded it at the same stratigraphical level in several of the oil-exploration boreholes in Norfolk. He concluded (1923, p. 134) that in Norfolk Saccocoma had a vertical range of only about 1 ft (0.3 m) compared to a range of 13 ft (4.0 m) in Dorset.

The usefulness of Saccocoma as a stratigraphical marker is dependent upon its occurrence in very large numbers over a narrow vertical range. Kitchin and Pringle (in Kitchin 1919, p. 43) were sufficiently impressed by its usefulness in Norfolk, and by their correlation with Dorset and with other boreholes in south-east England, to suggest that the beds with Saccocoma be designated a separate subzone. However, in the Warlingham Borehole, although Saccocoma was recorded at the same level in the Upper Kimmeridge

Clay as elsewhere, it was also recorded from the autissiodorensis Zone of the Lower Kimmeridge Clay (Casey, 1958).

Saccocoma occurs at three levels (in Beds 29 and 42) in the Wash Feasibility Study boreholes in Norfolk and at these and a fourth level (in Bed 33) in oil-shale boreholes in Lincolnshire and Wiltshire (Fig. 21). The two higher levels, in the autissiodorensis and hudlestoni zones, correspond to the two levels in the Warlingham Borehole. The two lower levels, both in the middle part of the eudoxus Zone, have not previously been recorded. Each of the four Saccocoma-rich bands appears to remain at a constant stratigraphical level and to be persistent throughout the English outcrop and subcrop. Each band is preserved in oil shale and its formation may be related to algal blooms (see 2.4.4 for discussion).

One or more of the bands is apparently absent in several of the continuously cored boreholes that have penetrated the relevant stratigraphical levels. This absence seems to be due to collection failure rather than to the impersistence of the bands. In the Kimmeridge Bay cliffs Saccocoma occurs in the hudlestoni Zone as pale gold-coloured, shiny, pyritized plates over a range of about 6.6 m, but is particularly abundant in oil shales at the upper and lower limits of the range. The same Saccocoma-rich band shows a similar distribution and preservation at Warlingham, where it occurs abundantly at 762.20 to 762.23 m in oil shale and in the same lithology at 766.12 to 766.27 m, but is rare in the intervening beds. In the Norfolk boreholes, Saccocoma was recorded at this stratigraphical level over vertical ranges of only a few centimetres; it is commonly abundant on only one bedding plane, always in oil shale. In many cases the distinctive pyritized plates are masked by overgrowths of secondary gypsum and it is noticeable that the recorded

vertical ranges are greater (up to 1.5 m) in those cores where pyritized plates are still visible. This band has been recorded in every borehole and most exposures that have penetrated the hudlestoni Zone.

The most seemingly impersistent band, that in the autissiodorensis Zone, has only been recorded in boreholes in Sussex, Wiltshire and Lincolnshire. Its apparent absent in other boreholes may be explained by its mode of occurrence in Lincolnshire and Wiltshire. In the Donington on Bain and Swindon boreholes Saccocoma is confined at this stratigraphical level to a single bedding plane on which burrow concentrations of broken radial plates (fragments < 1 mm) are present. A possible fifth Saccocoma-rich band was recorded in the Denver Sluice Borehole as two plates in the basal bed of the eudoxus Zone (Bed 24).

One other crinoid is known from the Kimmeridge Clay and this also forms a marker band. Pentacrinus columnals and short lengths of stem are common at one level (in Bed 18) in the mutabilis Zone throughout southern England and have been recorded at this level in Lincolnshire, Norfolk, Wiltshire and Sussex (Plate 17). At Black Head, Dorset, where the distinctive calcareous clays of Bed 18 crop out, Pentacrinus has not been recorded but echinoid spines are especially common.

Serpulids occur in many of the more shelly horizons of the Kimmeridge Clay. In Norfolk, Serpula tetragona (Sowerby) is particularly common in the highly calcareous mudstones (Bed 30) in the upper part of the eudoxus Zone where it provides a useful, but not uniquely diagnostic, indication of the stratigraphical level. Serpulids, including S. tetragona, S. gordialis Schlotheim, S. intestinalis (Sowerby) and S. concurva (Sowerby) are very common in the basal beds of the Kimmeridge Clay of Dorset (baylei Zone) and

are common at the same stratigraphical level in Norfolk.

Crustacean debris in the form of disarticulated claws and limbs, antennae and carapace fragments are locally common in the most calcareous mudstones in the Kimmeridge Clay. Complete specimens are rare; most are probably species of the shrimp-like malacostracan Meyeria (Plate 17).

2.2.2.5 Microfauna and Microflora

The Kimmeridge Clay contains a rich microfauna and microflora. Foraminifera, ostracods, coccoliths, acritarchs and dinoflagellates are locally abundant. These groups require specialist study and are beyond the scope of the present work. Their occurrence is noted here because they occupied an important place in Jurassic food-chains and their distribution and relative abundance is relevant to any discussion of depositional environments. Most microfaunal and microfloral studies to date have concentrated on the establishment of zonal schemes based on these groups, for although they are made up of forms that are stratigraphically long-ranging in comparison with the ammonites, they are potentially capable of yielding zonal information from small, fragmentary samples such as cuttings from rock-bitted boreholes.

There is no published comprehensive description of the distribution of foraminifera in the Kimmeridge Clay, although Blake (1875) and Woodward (1895) included foraminifera in their faunal lists for the Dorset type section; other authors such as Waterston (1951) include them in lists for particular localities. The most detailed study to date is that of the arenaceous foraminifera of the Kimmeridge Clay of the Dorset coast by Lloyd (1959) who recorded 25 species belonging to 8 genera. All are benthic forms and most are agglutinating and belong to the

Lagenidae. He showed the most common shell-building materials to be, in decreasing order of abundance, quartz and quartz-substitutes (rare glauconite and garnet), pyrite (including tiny framboids), shell debris, echinoderm debris and fish debris.

Current work in IGS has shown that, in addition to arenaceous forms, benthic calcareous foraminifera are common in the Kimmeridge Clay in Norfolk and are abundant in some lithologies, notably some of the oil shales. The encrusting foraminifera Bullapora and Nubeculinella are common on fragments of thick-shelled bivalves in the more silty parts of the Norfolk Kimmeridge Clay.

Ostracods occur throughout most of the Kimmeridge Clay but their relative abundance varies markedly at different stratigraphical levels. In a study of the ostracods of the Dorset coastal sections Kilenyi (1969) described 59 species of Ostracoda belonging to 21 genera. Their distribution was found however to be very uneven. Ostracods are abundant in the basal zones of the formation (baylei, cymodoce and mutabilis) and in the highest zones (pectinatus, pallasioides, rotunda and fittoni) but are very rare in the intervening zones. Kilenyi (1969, p. 155) concluded that this difference was due largely to lithological variations, the barren beds being composed of "paper [oil shale] and hard shales". The lowest and highest zones of the Kimmeridge Clay in Dorset contain a greater proportion of highly calcareous mudstone (which may be more conducive to ostracod preservation than oil shale) than do the intervening zones. It would, nevertheless, require a major sampling bias to produce the marked differences in distribution recorded by Kilyeni. Work on the ostracod succession in the Kimmeridge Clay of the North Wootton Borehole (Wilkinson, in prep.) has shown a similar ostracod fauna and distribution to that of Dorset to be present in the baylei

to pectinatus zones in Norfolk.

Coccoliths occur throughout the Kimmeridge Clay, but apart from the coccolith-rich bands referred to in Section 2.2.1.7 few lithologies contain more than 3% coccoliths/whole rock, although some of the most calcareous clays have yielded up to 12.5% coccoliths/whole rock. The coccolith-rich bands are generally dominated by one species, Ellipsagelosphaera brittanica (Stradner) (Plate 10), although up to 21 species have been recorded in individual bands (Gallois and Medd, 1979).

Dinoflagellates and acritarchs are common at many levels in the Kimmeridge Clay and are locally abundant in organic-rich bands such as the oil shales. Apart from the early work of Downie (1957), who recorded the first English assemblages from Dorset, little has been published concerning their distribution in the formation. Gitmez (1970) and Gitmez and Sarjeant (1972) have described dinoflagellate and acritarch assemblages from the basal part of the Kimmeridge Clay (baylei and possibly cymodoce zones) from Dorset, Skye and France, and from the Lower Kimmeridge Clay (mutabilis Zone) in a borrow pit at Stretham, Cambridgeshire. They recorded 82 species of dinoflagellate and 11 species of acritarch and commented that this flora was remarkably rich and varied. Some of these species are thought to have relatively limited stratigraphical ranges. Although dinoflagellates have been much used in recent years to make correlations in the Kimmeridgian in rock-bitted boreholes drilled for hydrocarbon exploration in the U.K., no general account of their stratigraphical distribution has been published. Lam and Porter (1977, Fig. 7) have described the ranges of 56 species of dinoflagellate in the Kimmeridge Clay in the faulted inlier at Helmsdale, Sutherland. The most varied flora occurs in the oil-shale-

rich part of the formation.

2.2.2.6 Plants and vertebrates

Land-derived plants occur as coalified wood, small indeterminate scraps, fine-grained carbonaceous dust and pollen at many levels in the Kimmeridge Clay, and are common at some (Plate 17). Bits of wood occur in the more silty horizons and fine-grained plant debris is scattered throughout the darker grey mudstones. The darkest mudstones usually owe their colouration to clay- and silt-grade plant debris in their matrix. Lam and Porter (1977) have described pollen assemblages from the plant-rich Kimmeridge Clay of Helmsdale; no similar study has been described for the English Kimmeridge Clay.

Fish teeth, scales and bone fragments, together with faecal pellets of presumed fish origin, are common in the oil shales and occur scattered throughout the formation. Complete or almost complete fish have been collected from many of the former brickpits in the Kimmeridge Clay and from the Dorset coastal sections. Such material is understandably rare in borehole cores; the rear half of a small cartilagenous fish was recorded in the Swindon Borehole.

The Kimmeridge Clay has yielded many fine reptile skeletons in the past. In Norfolk marine reptile bones, mostly vertebrae of icthyosaurs and plesiosaurs, were relatively common in the Kimmeridge Clay exposed in the excavations for the Fenland Flood Relief and Cut-Off channels between King's Lynn and Fordham [TL 607 996]. A small plesiosaur, about 2 m long, was found near Fordham (R.G. Thurrell, personal communication) and icthyosaur bones were found at Downham Market and Stowbridge (Eastern Daily Press, 28/7/58). This last named specimen (Sedgwick Museum J 66237) has been described by McGowan (1976) and named Grendelius mordax gen. et sp. nov. Woodward (in Whitaker et

al. 1893, p. 8) noted that saurian bones were not uncommon in a former brickyard (in Bed 44) at Downham Market. One of the Wash Feasibility Study boreholes (Denver Sluice) partially cored a large phosphatised bone (presumed saurian) in the Upper Kimmeridge Clay (Plate 17).

The stratigraphical distribution of these reptiles is as yet unknown, but all the well preserved specimens found in recent years have probably come from the thicker calcareous beds in the Kimmeridge Clay. These include a pliosaur (Crane, 1980) from Bed 30 at Westbury, Wiltshire; Stretosaurus (Tarlo, 1959a) from Bed 18 at Stretham, Cambs, Pliosaurus (Tarlo, 1959b) probably from Bed 30 at Ely, Cambs and the Grendelius referred to above, probably from Bed 44.

2.2. .7 Trace fossils

Trace fossils, in the form of trails and burrows, are common throughout the English Kimmeridge Clay (Plate 18) despite the absence of reference to them in the literature. At many levels they are picked out by conspicuous colour or lithological changes. At other levels, where the mudstones appear to be uniform, similar structures occur as faint mottling or as irregularities in the texture of the mudstones. Even apparently structureless lithologies can be seen to be burrowed when X-rayed. Unbroken lamination, a clear indication of the absence of burrows, is rare in the Kimmeridge Clay. Many trace-fossil ichnogenera are still poorly described, and even among the better known there are probably many homeomorphs and synonyms. These are of limited stratigraphical value; many of the commoner genera are known from sediments ranging in age from Cambrian to Recent and similar forms have almost certainly been made by different animals at different times. Trace fossils can, however, be useful as indicators of palaeoenvironmental conditions because they mostly represent the feeding trails or burrows

Plate 18. Burrows; all photographs at natural size.

A. Large burrow system or systems, infilled or lined with pale grey mudstone and within a medium grey mudstone matrix; possible spreiten in upper right. Burrow boundaries diffuse and irregular presumably due to soft nature of sediment at time of burrowing. Specimen no. BDK 8192, North Wootton Borehole, 100.45 m, Bed 17.

B. Interburrowed junction of dark and pale grey mudstone. Specimen no. BDU 2381, North Wootton Borehole, 80.30 m, Bed 28.

C. Crushed, silt-lined burrow preserved in silty mudstone; lower picture illustrates degree of compaction of probable elliptical or cylindrical original burrow. Tisbury Borehole, 108.26 m, Upper Kimmeridge Clay.

D. Silt-filled burrow in pale grey mudstone, viewed from below. Tisbury Borehole, Upper Kimmeridge Clay.

E. Cone-shaped burrow, cf. Tisoa, with partially phosphatised centre and pyritised axial rod. Tisbury Borehole, 93.55 m, Upper Kimmeridge Clay.

F. Large burrows infilled with oil-shale (dark) within coccolith-rich, very pale grey mudstone. Specimen no. BDK 7575, North Wootton Borehole, 62.92 m, Bed 32.

G. Horizontal burrows lined with thin-shelled bivalve and ammonite debris, preserved in medium grey mudstone. Original shape probably as C. Specimen no. BDK 7537, North Wootton Borehole, 60.60 m, Bed 32.

Plate 18

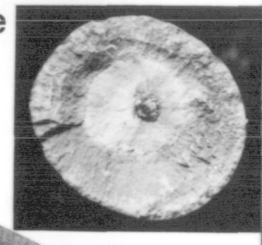


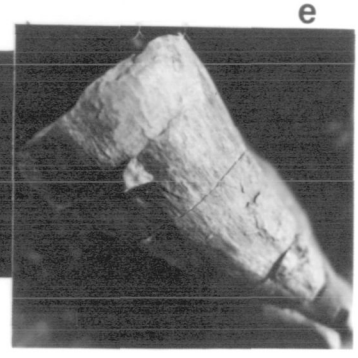


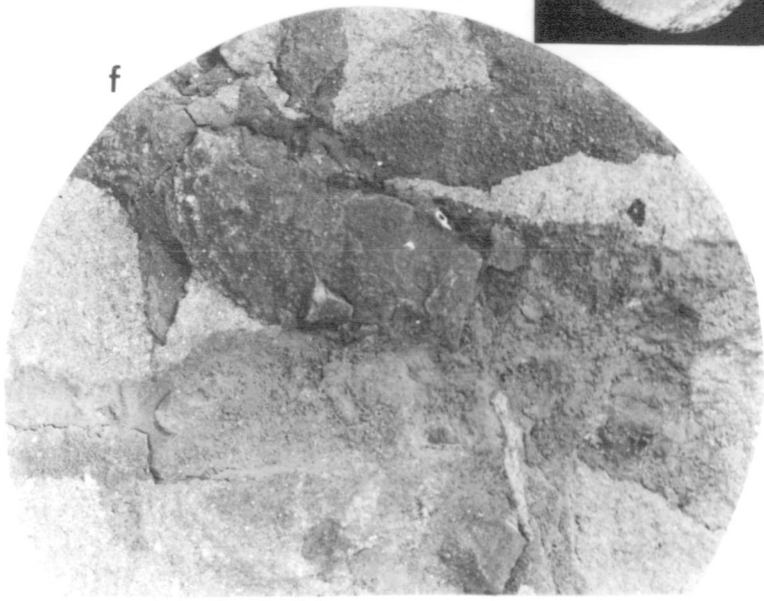


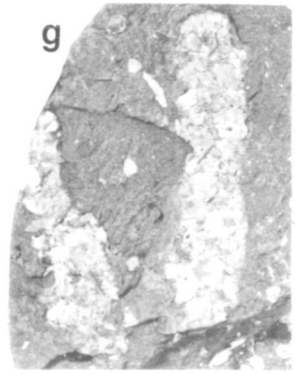












of sediment-ingesting or sediment-sifting invertebrates, or the dwelling burrows of filter-feeding invertebrates.

The terminology, stratigraphical usefulness and environmental significance of trace fossils has been much discussed in recent years. Summaries are given in Crimes and Harper (1970), Häntzchel (1975) and Frey (1976). The following trace fossils have been recognised in the Kimmeridge Clay during the present work.

(i) Arenicolites: simple U-shaped tubes perpendicular to the bedding and believed to have been the living tube of a worm or worm-like animal. Kimmeridge Clay examples are rare and restricted to fine-grained sandstones and siltstones.

(ii) Chondrites: dendritic patterns of small, cylindrical, ramifying tunnel systems believed to be the feeding structure of a sediment eating animal, possibly a siphunculoid worm. Common in the Kimmeridge Clay wherever there is a sharp enough colour change to provide a contrast between the burrow infills and the surrounding rock. Probably also common, but not easily seen, at many levels in uniformly coloured mudstones.

(iii) Ophiomorpha: horizontal and sub-horizontal branching burrows with an external ornament made up of ovoid pellets. Thought to be the feeding and living burrows of decapod crustaceans such as callianassids. Kimmeridge Clay examples are restricted to a few levels in the siltstones and fine-grained sandstones that occur in the Upper Kimmeridge Clay between Dorset and Buckinghamshire.

(iv) Palaeophycus: cylindrical or sub-cylindrical, straight or gently curved, horizontal or sub-horizontal burrows of unknown origin. Many Kimmeridgian burrows fall into this broad description; especially common within the top few centimetres of beds overlain by an erosion surface or where there is a marked lithological or

colour change.

(v) Planolites: morphology as Palaeophycus but the sediment filling the burrows is markedly different in lithology from that of the host rock and is believed to have passed through the gut of a worm or worm-like animal. Rare in the Kimmeridge Clay; occurs in the same situation as Palaeophycus to which it appears to be related.

(vi) Rhizocorallium: network of horizontal, sub-horizontal and rare vertical burrows with well developed spreiten. Kimmeridge Clay examples have to date only been recorded in the coccolith-rich limestones of the Upper Kimmeridge Clay in Dorset.

(vii) Scolicia (= Palaeobulla): ribbon-like horizontal trails with a variety of groove, ridge and axial ornaments; believed to be gastropod trails. Probably common at many levels in the Kimmeridge Clay, but often partially preserved in pyrite which becomes oxidised and leaves a nondescript trail. The rarity of gastropods, other than the burrowing Dicroloma, in the Kimmeridge Clay suggests their probable formation by some other organism.

(viii) Skolithos: (? = Monocraterion) closely spaced, simple, straight, vertical tubes believed to have been the dwelling burrows of a filter-feeding worm. This ichnogenus has been recorded from strata ranging in age from Precambrian to Cretaceous and is likely to include more than one homeomorph. Kimmeridge Clay examples are common in the beds immediately beneath erosion surfaces and major lithological or colour changes. Poorly defined simple vertical burrows also occur at many levels where there is little sediment contrast.

(ix) Spongelimorpha: complex branching network of large diameter,

elongate, cylindrical burrows with a characteristic surface tracery of scratch marks. Believed to be the dwelling burrows of crustaceans and may be related to Ophiomorpha and Thallasinoides as different parts of the same burrow system. Rare in the Kimmeridge Clay but this may be due to the failure of the characteristic scratch marks to be preserved in mudstones.

(x) Teichichnus: long horizontal burrows forming vertical stacks; origin unknown but structure similar to that produced by a modern polychaete worm. Common in fine-grained sandstones and siltstones in the Upper Kimmeridge Clay in the southern England outcrop.

(xi) Thalassinoides: network of large diameter, branching burrows, mostly sub-horizontal. Believed to be the feeding and dwelling burrows of crustaceans, probably callianassids. Probably relatively common in the Kimmeridge Clay but too large to identify with confidence in borehole cores. Many of the larger burrows in the Kimmeridge Clay are probably parts of this type of network.

(xii) Trypanites: closely spaced, small (1 to 2 mm diameter) straight, vertical borings in hard materials; probably made by a polychaete worm. Restricted in the Kimmeridge Clay to pebbles of phosphate, lydite and thick chips of shell material which have been exposed on the seafloor.

(xiii) Pyritized trails: ribbon-like, horizontal, straight or gently twisting, parallel-sided trails, commonly 2 to 6 mm width and of considerable length; presumably made by worms or worm-like animals. Extremely common at many levels in the Kimmeridge Clay. Although they appear to traverse the surface of the

sediment, the almost ubiquitous presence of a pyritic film suggests that they may originally have been unlined, horizontal, cylindrical tubes which were subsequently compacted.

(xiv) Pyritized pins: vertical and sub-vertical cylindrical tubes of solid pyrite, rarely more than 1 mm in diameter and commonly less than 0.5 mm, up to several centimetres in length, without ornament except for kinks and node-like constrictions at irregular intervals. Believed to be the dwelling tube of a worm. Extremely common at some levels in the Kimmeridge Clay.

(xv) Pyritized knots: irregularly shaped short, fat (up to 5 mm diameter), vertical and sub-vertical tubes which commonly form a growth centre for concretions of well crystallised pyrite. Origin unknown but probably formed by a worm. Extremely common at some levels in the Kimmeridge Clay.

(xvi) Unknown form: vertical, inverted cone-shaped burrows with a maximum diameter of 1 to 2 cm and a length of 3 to 5 cm and with a narrow axial tube, 1 to 2 mm diameter. Common at a few levels in the Kimmeridge Clay. In each example the infilling consists of uniform clay of different lithology to the host rock, and the axial tube is preserved in pyrite. Similar in form to the ichnogenus Tisoa, which differs from it by having two vertical tubes, which is believed to be a crustacean burrow.

2.2.2.8 Calcispheres

Scanning-electron-microscope studies of the Kimmeridge Clay show that calcispheres - small, hollow, spherical calcitic bodies of uncertain origin - are relatively common in some lithologies. Calcispheres have been recorded from strata ranging from Cambrian to Recent

in age. Rupp (1967) has described oogonia from modern green algae (dasycladaceans) that superficially resemble calcispheres but other authors have suggested possible links with foraminifera, acritarchs or other algae and it may be that not all calcispheres have the same affinities (Häntzchel,1975).

Calcispheres have not previously been recorded from the Kimmeridge Clay, probably because their small size necessitates SEM studies and little systematic work of this type has been published on the formation. They are not a major rock-forming element of the Kimmeridge Clay but are sufficiently common at some levels, notably in the oil shales, to make a significant contribution to the calcite content. Drummond (1967) noted that calcispheres were a major component of hard-grounds and nodular beds in the Chalk, and suggested they were indicative of shallowing.

The calcispheres recorded in the Kimmeridge Clay consist of a thin, smooth inner shell layer (< 0.1 μm thick) surrounded by a thicker (1 to 5 μm thick) layer of radially orientated prismatic calcite crystals (Plate 5). Most of the spheres are partly or wholly infilled with sediment or with microscrystalline spar (Plate 5). The precise nature of the outer layer of the calcispheres is still uncertain; it has the appearance of a layer of calcite overgrowths (Plate 5) and has been assumed by some authors (e.g. Mortimore, 1979 describing specimens from the Chalk) to be of secondary origin. This may be true for the Kimmeridge Clay specimens, but the general absence of secondary calcite in the formation, and the ubiquitous and uniform nature of the outer layer of the calcispheres suggest a primary origin.

2.2.3 Faunal and lithological associations

The study of fossil communities as a means of determining the nature of the palaeoenvironment has become an increasingly important part of palaeontology in recent years. When combined with sedimentological work it has been claimed that such studies can enable very specific palaeoenvironments to be recognised with confidence. However, the results of this type of work should be treated with caution.

Mobius (1871, 1877) is generally credited with the first recognition of natural associations of genera with mutual relationships within marine benthonic faunas. Peterson (1911, 1913) carried out quantitative investigations of the benthonic fauna of parts of the Danish North Sea and noted that large areas of similar substrate were characterised by one or more dominant species, which he termed 'assemblages'. Subsequent work throughout the world has confirmed the usefulness of the assemblage concept but has shown that misleading results can be obtained if the studied sample is statistically too small or if part of the assemblage, such as the microfauna, is ignored.

The main (inter-related) factors which affect the composition of benthonic assemblages at generic level are thought to be salinity, depth of water, current velocity, nature of substrate and its degree of aeration (which affects its organic content). Thus, near-shore muddy substrates in the North Sea, Atlantic Ocean and Pacific Ocean are characterized by species of Macoma, and sandy substrates in the same areas by Venus. This feature led Thorsen (1957) to use the phrase "parallel animal communities"to describe assemblages from widely spaced geographical areas which have the same dominant genera. This same concept is applied palaeontologically to assemblages which are widely spaced in time when conclusions on palaeoecology are drawn

from a comparison of fossil genera with their modern equivalents. Although in many cases such conclusions are undoubtedly valid, unknown factors may have been present which profoundly affected the assemblage. For example, Peterson (1913) noted that forms characteristic of the intertidal zone in the North Sea, such as Cerastoderma edule, Macoma baltica, Mya arenaria, Hydrobia and Corophium volutator, occur at depths of 50 to 100 m in the Baltic Sea. Similarly, McNulty et al. (1962) have shown modern species of Tellina to be characteristic of sandy bottoms in temperate seas and muddy bottoms in tropical seas. Fossil assemblages which are likely to have been subjected to rapid changes in abiotic factors, either laterally or vertically (i.e. with time), should clearly be interpreted with caution.

Little palaeocological work has been published to date on the Kimmeridge Clay, but studies of other Jurassic formations have included descriptions of some of the types of lithology and fauna that can be recognised in the Kimmeridge Clay. Hallam (1960, 1967) and Sellwood (1972) have discussed the palaeoenvironment of parts of the Lias; Duff (1975) has described the palaeoecology of the kerogen-rich mudstones of the Lower Oxford Clay and Fürsich (1975, 1976a, 1976b, 1977) has described the benthonic faunas, including trace fossils, of the Corallian Beds and the basal beds of the Kimmeridge Clay in Dorset.

The most comprehensive of these studies is that of Fürsich (1977) in which over 30,000 benthonic macrofossils were collected from Corallian sections in Yorkshire, Dorset and Normandy and were used to define seventeen macroinvertebrate and one trace-fossil association*.

* Peterson's original term 'assemblage' for characteristic faunas was subsequently corrupted to 'association'. More recently (e.g. Jones, 1950; Peres, 1957) have used 'association' to mean the characteristic fauna and its related lithology. This latter use of the term 'association' is the one adopted here.

The fauna from each locality was divided into associations using the trophic-group method of analysis (Turpaeva, 1948). A 'trophic nucleus' (Neyman, 1967) was defined for each association consisting of those numerically dominant species which made up 80% of the fauna. Few argillaceous Corallian lithologies were examined, probably because of the paucity of exposure and their deeply weathered state, and only three of the assemblages are described as characteristic of low-energy environments with muddy substrates. None of these associations can be closely matched with Kimmeridge Clay faunas. By contrast, several associations which are said to be indicative of current-swept oolite bars or of offshore limestone and sandstone substrates are similar to associations in the predominantly muddy Kimmeridge Clay.

Trophic-group analysis of the type described by Fürsich (1977) cannot be carried out on borehole cores for a number of reasons. Firstly, the area of each bedding plane preserved in the core is usually too small to provide sufficient macrofossils for quantitative analysis. In a uniform lithology the core can be thinly split to reveal successive bedding planes so that a one metre run of 100 mm-diameter core can yield about 0.8 sq. m of bedding plane. Few Kimmeridge Clay lithologies occur in beds more than few metres thick and few are sufficiently fossiliferous to yield a large and diverse fauna from such a small area.

Secondly, the core diameter is large in relation to some parts of the fauna and small in relation to others. As many as 100 specimens of the small bivalve Astarte supracorallina can occur on single bedding plane in a 100 mm-diameter core, but a single specimen of Deltoideum delta would more than cover the same bedding plane. Thirdly, the

fossil record represents only a small part of the original assemblage and important elements such as soft-bodied animals are either absent or are only indirectly known as trace fossils. Fourthly, and this is commonly true of exposures as well as cores, the core area is minute in relation to the area of any particular bedding plane which would need to be examined to statistically determine the complete faunal assemblage as distinct from its local variations.

Although only a small part of the fauna of the Kimmeridge Clay is preserved in situ, there are nevertheless a number of well defined faunal and lithological associations which can be recognised throughout the English outcrop and subcrop. This is probably because uniform conditions existed over large areas of the basin of deposition at any given time so that the fauna preserved at any particular locality has either been derived locally or from a more distant locality within the same environment. No incompatible faunal elements were recorded. Even the pelagic faunas and their mode of preservation combine with the benthonic forms to make characteristic faunal and lithological associations.

The presumed feeding positions of the benthonic fauna, by analogy with that assumed for similar faunas described by Walker and Bambach (1974) and Fürsich (1977), is shown in Table 11.

Nine common associations have been recognised. Following current practice in marine biology each has been given a name taken from the dominant faunal element or some exotic, but characteristic, part of it. Gradations occur between many of the associations but it is of interest to note that most are distinctive and that similar associations can be recognised at other stratigraphical levels within the argillaceous parts of the British Jurassic.

	Low and medium-level suspension feeders
(i)	Shallow burrowers: Protocardia; Anisocardia; Myophorella; Isocyprina; Astarte; ?Nanogyra virgula; 'Lucina'; Dentalium; ostracods
(ii)	Deep burrowers: Goniomya; Pholadomya; Pleuromya; Thracia
(iii)	Bysally or pedically attached to sea-bed (or to debris): Chlamys; Entolium; Oxytoma; Isognomon; Plicatula; Meleagrinella; Pinna; Gervillella; arcids; Modiolus; Placunopsis; Discinisca; Lingula; Rhynchonella; Torquirhynchia
(iv)	Cemented to sea-bed (or to debris): Lopha; Nanogyra nana; serpulids; some foraminifera; epizoic oysters
(v)	Resting on sea-bed: Deltoideum; Liostrea; Gryphaea; other small oysters.
	High-level suspension feeders
(i)	Bysally attached to algae: Meleagrinella; Oxytoma
(ii)	Stem attached to sea-bed: Pentacrinus
	Deposit feeders
(i)	At sea-bed: certain foraminifera; Procerithium; various worms and gastropods represented by trails; cidarid echinoids;
(ii)	Within the sediment: nuculids; Meyeria and other crustaceans represented by Ophiomorpha and Spongelimorpha; worms represented by Chondrites, Palaeophycus, Planolites, Teichichnus etc; some ostracods, Dicroloma?

Table 11. Presumed feeding positions of the benthonic fauna.

1. Plant-fish debris Mudstone

Smooth textured dark and very dark grey, sparsely shelly mudstones with much disseminated plant debris and fish scales and bones; rare burrows, including Planolites, and trails disturb well developed thin lamination; rare small, thin shelled bivalves in life position, mostly nuculids, some with original colour banding; well preserved crushed iridescent ammonites relatively common, some with epizoic oysters; crinoid debris and bivalve spat locally common; burrow-linings of angular ammonite and bivalve debris relatively common.

2. Lingula-oyster Mudstone

Smooth textured dark grey mudstone; sparse benthonic fauna of Lingula, epizoic oysters (mostly on ammonites) and pyritized trails and burrows; well preserved crushed ammonites scattered throughout, usually preserved in white calcite.

3. 'Lucina'-Protocardia Mudstone

Smooth textured medium and dark grey shelly mudstones; bivalves, mostly disarticulated valves of Astarte, 'Lucina' or Protocardia preserved in calcite, form shell plasters at some levels; crushed ammonites common, usually iridescent but locally pyritized; pyritized trails and burrows common; foraminifera, shell debris and plant debris locally concentrated in burrows; Dicroloma, Discinisca, Lingula, small oysters and pectinids also common.

4a. Pinna-Thracia Mudstone

Smooth textured, medium and pale grey, highly calcareous mudstones; sparsely fossiliferous but with Pinna, Thracia and myid bivalves present, commonly in life position; crustacean, crinoid and echinoid debris and pectinids also locally relatively common; pyritized trails and burrows very common; scattered crushed ammonites, mostly large

perisphinctids, occur in white calcitic preservation; rare rhynchonellids.

4b. Nanogyra Mudstone

Medium and pale grey, silty textured (due to secondary gypsum crystals formed from disseminated pyrite) very calcareous mudstones; intensely bioturbated and crowded with Nanogyra, other small oysters and serpulids; locally passing into soft limestone cf. shell coquina as in the Nana Bed of Dorset and the Virgula Limestone of Norfolk.

5. Rhynchonellid-myid Siltstone

Medium grey bioturbed clayey siltstone and silty mudstone; cross lamination locally present; shelly with common ammonites and aragonitic bivalves preserved as clay casts and rotted calcite films; myids common in life position; common rhynchonellids; abundant oysters, both whole and fragmentary, many encrusted with serpulids, foraminifera (e.g. Bullapora) and small oysters; rare belemnites and wood fragments; burrow concentrations of plant debris and foraminifera; pyritized trails and small burrows common.

6. Phosphatic Pebble Bed

Phosphatic pebbles, some bored and encrusted, set in intensely bioturbated, gritty (due to comminuted shell debris) silty mudstone and muddy siltstone matrix; fauna as Rhynchonellid-myid Siltstone but with common angular fragments of thick-shelled oysters, water-worn belemnites and plant debris.

7. Shelly Oil Shale

Bioturbated oil shale with abundant benthonic fauna of bivalves, mostly Astarte 'Lucina', Protocardia, small oysters, pectinids and bivalve spat, foraminifera and faecal pellets; pelagic fauna of abundant crushed ammonites, fish debris and, at four levels, the free-swimming crinoid Saccocoma; finely interlaminated with coccolith-

rich limestone at several levels.

9. Barren Oil Shale

Laminated oil shale with rare thin-shelled bivalves, small oysters, Lingula, common plant debris and sparse pelagic fauna of ammonites, Saccocoma and fish debris.

2.3 Stratigraphy

2.3.1 Introduction and methods

The history of stratigraphical research on the Kimmeridge Clay in Britain is summarised in Section 2.1. The earliest workers such as William Smith (1815-16), Webster (in Englefield 1816) and Fitton (1836) defined the Kimmeridge Clay as the thick clay sequence lying between the limestones and sandstones of the Corallian Beds and Portland Beds on the Dorset coast. Subsequent workers, notably d'Orbigny (1842-51), Oppel (1856-58) and Salfeld (1913, 1914) refined this definition by describing the formation in terms of its ammonite and bivalve fauna and introduced the Kimmeridgian Stage for the interval of time represented by the Kimmeridge Clay. These and more recent studies of the Kimmeridge Clay have concentrated on improving the ammonite zonal scheme. One exception, was the work of Blake (1875) who described the lithologies of the Upper Kimmeridge Clay, bed by bed, in the cliff sections at Kimmeridge Bay with little reference to their fauna.

In 1972, the need arose in Norfolk for a detailed classification of the Kimmeridge Clay for the Wash Water Storage Feasibility Study. An attempt was therefore made to describe the combined lithological, faunal and geophysical characters of the formation to produce more detailed correlations within it than could be made using either the lithology or fauna on its own.

The purpose of the onshore geological work for the feasibility study was to comment on the possible occurrence of a suitable medium in which to construct tunnel aqueducts down to depths of 150 m within an area 15 km by 20 km running from possible reservoir sites in the southern part of The Wash to a freshwater source at Denver Sluice. The most economical tunnelling system available at that time was one using a soft-ground tunnelling machine in combination with a concrete-segment tunnel lining. The main limitation of this method is its sensitivity to relatively small variations in ground conditions. Delays at the tunnelling face can cause costly disruption of the large support team (spoil removers, segment fabricators etc.) that is necessary to maintain a rapid rate of tunnel completion.

It was thought that the Kimmeridge Clay, or one of the other Upper Jurassic clays, would be a suitable medium because this method had already been successfully used in the Lias at Empingham, near Peterborough (subsequently described by Horswill, 1976) and the Gault near Ely (Samuels, 1975) in soft mudstones that have similar engineering properties to those of the Kimmeridge Clay. The last named was known to include bands of siltstone and oil shale which might impede or even stop the tunnelling machine and which might make it difficult for the concrete lining to be expanded uniformly into the tunnel wall. Thin limestones and siltstones had caused these problems in the Lias at Empingham.

In an investigation such as The Wash feasibility study, where the potential properties of a large volume of rock were assessed solely from samples from cored boreholes (the whole of the investigation area is overlain by Recent deposits), it was economically possible to examine only a very small part of the material under consideration.

An even smaller part was available for geotechnical testing. The borehole cores in the feasibility study represent about one part in 500 million, and the soil-tested samples about one part in 250,000 million, of the total rock mass involved. It was therefore necessary to devise a local stratigraphy for the Kimmeridge Clay that was sufficiently detailed to enable the positions of any potentially difficult strata to be accurately determined everywhere beneath the site. The positions of the limestones were particularly difficult to predict because they commonly occur as lines of discontinuous doggers. Furthermore, such doggers are difficult to sample in cored boreholes because of their curved edges. Much of the stratigraphical effort in the study was therefore directed towards determining the precise levels at which persistent and impersistent limestone bands occurred.

An attempt was made to establish a standard stratigraphical sequence by recording faunal and lithological changes with time. Such changes reflect events in the depositional environment; where these events are of a regional nature they might be expected to give rise to lithological and faunal variations which can be correlated over much larger areas than that under consideration for the feasibility study. It was hoped that many of the variations might be sufficiently laterally persistent to offset the problems arising from sampling failure in the boreholes. This was found to be the case in practice and the stratigraphical classification devised for the feasibility study has subsequently been shown to be applicable to much of southern England.

Examples of lithological variations recorded in the borehole cores include changes in the silt, calcium carbonate, kerogen and shell contents of the mudstones as shown by variations in their texture and colour (Fig. 10). Palaeontological examples include changes in the

relative abundance of particular bivalves or ammonites, sudden influxes of uncommon faunas such as crinoids, echinoids and brachiopods, and interburrowed horizons (Fig. 21). These changes probably occurred in response to variations in rates of clastic influx, current strength and direction, water depth and temperature and the climate of the land areas supplying the sediments and nutrients.

Changes in the general conditions of the depositional environment and the sediment source are also reflected in the mineral compositions of the clastic materials. The distribution of one particular group of minerals, those containing radioelements in the uranium and thorium decay series, although usually present in quantities below the level of analytical detectability, can be readily studied by recording their gamma-ray decay emissions. Total gamma-ray signatures were obtained for most of the boreholes referred to in this thesis and these were used, in conjunction with the lithological and palaeontological data, to obtain correlations between the boreholes and to refine the stratigraphical sequence.

2.3.1.1 Faunal and lithological features

The most useful single feature for determining the stratigraphical position of any quarry, cliff or core section within the Kimmeridge Clay is the ammonite assemblage. Most sections are sufficiently fossiliferous for the zonal position to be determined and, in many cases in the Lower Kimmeridge Clay, the position within the zone (either low or high) can commonly also be determined from the ammonites alone. In addition to the zonal indices, species of *Amoeboceras*, *Amoeboceras* (*Nannocardioceras*), *Aspidoceras* and its aptychal plate *Laevaptychus*, *Aulacostephanus*, *Propectinatites*?, *Rasenia*, *Sutneria*

and Xenostephanus are useful at many levels and enable subdivisions of zones to be identified with confidence. In boreholes, the zonal boundaries and selected marker beds can be rapidly identified using a combination of a small number of core specimens and geophysical logs.

Thin marker bands containing flood occurrences of coccoliths, crinoids, certain species of bivalve, brachiopods or serpulids occur at many levels and these provide additional stratigraphical information. When combined with the rhythmic variation in lithology that occurs throughout the Kimmeridge Clay these faunal markers provide a ready means of subdividing the formation. In many cases faunal changes coincide with lithological changes that can be recognised throughout southern England. This suggests that the associated faunal and lithological features reflect widespread events affecting the Kimmeridge Clay basin of deposition.

The stratigraphical method described above has proved to be equally useful in borehole cores (where a relatively small area of bedding plane is available for study at any given stratigraphical level) and in cliff and temporary sections.

In Norfolk, the Lower Kimmeridge Clay has been divided into 35 beds and the Upper Kimmeridge Clay into 14 beds. Bed by bed descriptions of the Lower Kimmeridge Clay are given in Gallois and Cox (1976) and of the Upper Kimmeridge Clay in Cox and Gallois (in Gallois, 1979a). A classification of the boreholes known to have penetrated the Kimmeridge Clay in Norfolk has been placed on open file. An example of a graphic section of a continuously cored borehole is shown in Fig. 22; other examples are given in Gallois (1979a).

The succession is condensed and highly fossiliferous in Norfolk and many of the individual beds can be recognised from a single hand

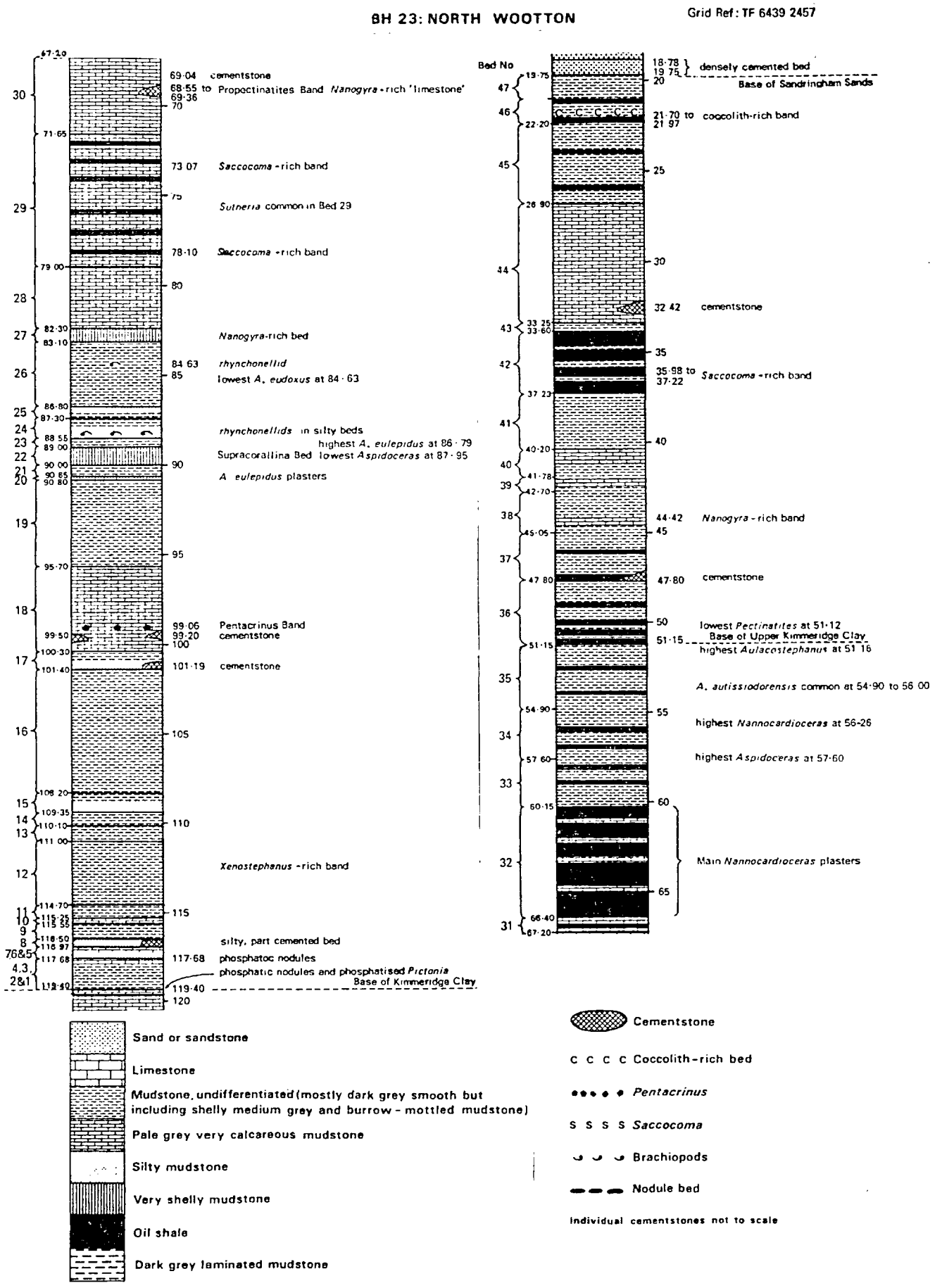


Figure 22. Graphic log of part of the North Wootton Borehole showing bed classification and the main lithological and faunal features.

specimen. Even the most intractible horizons can be placed within the sequence on the basis of about 2 m of core. Some of the more distinctive marker beds in Norfolk are briefly described below. Each has been traced throughout the Norfolk outcrop and much of the English Kimmeridge outcrop and subcrop.

Bed 1: strikingly interburrowed pale and dark grey mudstones with an erosion surface at their base marked by gritty shell debris, oysters and phosphatic nodules; sparsely fossiliferous but with some bivalves and ammonites, including very common Pictonia, preserved in soft, pale brown phosphate. This nodule bed, together with a marked lithological contrast with the highest bed of the underlying Amphill Clay (a very pale grey highly calcareous mudstone) gives rise to a distinctive peak in the total gamma-ray log.

Bed 5: medium and dark grey mudstones, silty at base and with angular chips of hard, black phosphate, some of which include ammonite fragments, resting on a burrowed, minor erosion surface; sparsely shelly but with partially phosphatised Rasenia, Pachypictonia? and bivalves; the correlative of the Wyke Siltstone of Birkeland et al. (1978) in Dorset.

Bed 8: medium grey silty and very silty mudstone with erosion surface marked by complex phosphatic nodule bed and burrowing at base. Shelly, with common Amoeboceras and very common Rasenia; correlative of the Black Head Siltstone of Cox and Gallois (1981) in Dorset.

Beds 1, 5 and 8 rest on widespread erosion surfaces that can be traced throughout the English Kimmeridge Clay south of the River Humber. Each surface is overlain by a concentration of silt and a new fauna; the bases of Beds 1 and 5 mark the bases of the baylei and cymodoce zones

respectively. Each bed retains its characteristic lithology and fauna throughout the outcrop between Humberside and Dorset although at localities where the sequence is condensed, for example in Buckinghamshire and Cambridgeshire, all three erosion surfaces can come together and be represented by a single thick nodule bed.

Bed 15: Medium to pale grey silty and very silty mudstones; shelly with very common Aulacostephanus and rare Rasenia, bivalves (including oysters) and rhynchonellid brachiopods. Bed 15 and the lithologically similar Bed 17 can be differentiated by their aulacostephanid faunas. Both overlie widespread erosion surfaces.

Bed 16: Interbedded dark grey and dark brownish grey, faintly organic-rich, smooth-textured, fissile mudstones with much comminuted plant and fish debris and a rich ammonite fauna including abundant well preserved, iridescent specimens of a coarsely ribbed variety of Aulacostephanus eulepidus (Schneid).

Bed 18: Pale grey highly calcareous mudstone with one or more thin bands of muddy limestone; sparsely shelly but with much broken shell debris and with relatively common Thracia and crustacean fragments; Pentacrinus columnals form a widespread marker band at one level.

Bed 22: Pale and medium grey shelly mudstones, intensely shelly in part with myriads of tiny crushed Astarte supracorallina (d'Orbigny); the Supracorallina Bed of Arkell (1947, p. 85) in Dorset.

Bed 24: Dark grey silty and very silty mudstone; richly fossiliferous with Aspidoceras and Laevaptychus, Aulacostephanus of the eudoxus group and Sutneria appearing in this bed; Aulacostephanus of the eulepidus

and mutabilis groups also present; oysters, Lopha and rhynchonellids common. Bed 24 rests on an important erosion surface throughout southern England; because of its rich fauna, it is probably the most distinctive single bed in the Kimmeridge Clay.

Bed 29: Medium and pale grey mudstones interbedded with thin oil shales. Moderately shelly with a rich bivalve and ammonite fauna in which Sutneria is especially abundant and Amoebites, Aulacostephanus and Aspidoceras are very common. Flood occurrences of Saccocoma provide additional marker bands at two levels within the bed.

Bed 30: Medium and pale grey shelly mudstones, with a persistent muddy limestone at one level; rich in bivalves and ammonites; Sutneria, Aspidoceras, Amoeboceras and Aulacostephanus of the eudoxus groups common; Propectinatites? forms a marker band at one level; large, slug-like forms of Nanogyra virgula (Defrance) are abundant and locally form soft limestones; Serpula tetragona abundant throughout.

Bed 32: Very shelly oil shale with closely spaced plasters of Amoeboceras (Nannocardioceras) throughout; thin interbeds of pale grey mudstone; upper limit of Aulacostephanus of the eudoxus group; flood occurrences of Saccocoma and Sutneria rebholzi (Berckhemer) form useful marker bands in the basal few centimetres of the overlying Bed 33.

Bed 34: Medium and dark grey mudstones with a few thin beds of oil shale; shelly and very shelly with common large Aulacostephanus autissiodorensis and relatively common rhynchonellid brachiopods; upper limit of Amoeboceras (Nannocardioceras) marked by a band rich in a distinctive finely rectiradiate form of A. (N.) krausei (Salfeld).

Bed 42: Interbedded oil shale and dark grey mudstone; shelly with bivalves and pectinatitid ammonites, with a flood occurrence of Saccocoma in the upper part of the bed. This group of oil shales includes a laterally persistent thick seam that can be correlated with the Blackstone of Dorset.

Bed 44: Pale and medium grey highly calcareous mudstones with a persistent tabular limestone near base; sparsely fossiliferous with Pectinates and a few bivalves; a thick bed (more than 6m in Norfolk and > 20m in Dorset) with a distinctively low total-gamma count and a high resistivity that can be traced in boreholes throughout England.

Bed 46: Medium and dark grey mudstones with thin interbeds of shelly oil shale and including several thin coccolith-rich bands; oil shales commonly crowded with Pectinatites eastlecottensis (Salfeld). The base of this bed is marked by a prominent coccolith-rich band that can be correlated with the White Stone Band of Dorset.

2.3.1.2 Geophysical logging

2.3.1.2.1 Introduction

A selection of geophysical logs was run in the earlier IGS boreholes drilled in the research area, those at Skegness, Hunstanton, Gayton and Marham, to find out if such logging could be used to make detailed correlations in the Upper Jurassic and Lower Cretaceous. Geophysical logging has been used for many years in oil exploration to make broad correlations and to determine the physical properties of potential reservoir and source rocks, but it had not at that time been used for stratigraphical purposes in which it was hoped to identify marker beds only a few centimetres thick.

The results of the first logging were better than had been anticipated in the Kimmeridge Clay, and worse than had been expected in the Lower Cretaceous. Subsequent geophysical logging in boreholes drilled in the Lower Cretaceous in The Wash and in the Kimmeridge Clay throughout England (for the Wash Feasibility Study and the Oil-Shale Project) confirmed this, and showed that the usefulness of geophysical logging for correlation purposes is dependent upon the lateral persistence of the lithologies being logged. To a large extent, it is independent of the lithologies themselves because of the wide range of properties that can now be measured with logging tools.

Geophysical correlations can be made over long distances in the Kimmeridge Clay because the formation contains lithologies that are persistent over very large areas. Many of these lithologies are similar in hand specimen, but the range and sophistication of geophysical logs available is such that combinations of logs can be used to detect all but the most subtle lithological changes. By contrast, the Lower Cretaceous sequences of Norfolk and Lincolnshire contain a great variety of rock types that give distinctive traces on even the crudest geophysical equipment. However, these cannot be used for correlation purposes because of rapid lateral variations in the sequence. Geophysical correlations could not be made between the Lower Cretaceous successions in IGS boreholes at Hunstanton, in the Wash (IGS 72/77 and 72/78) and at Skegness, that are a maximum of 24 km apart.

The initial investigation showed that total gamma-ray logging and, to a lesser extent, resistivity logging could be used to make detailed correlations in the Upper Kimmeridge Clay (Gallois, 1973a). Subsequent stratigraphical work on the borehole cores confirmed these correlations

(Gallois and Cox, 1974; Cope, 1974b) but changed the emphasis of future geophysical logging. Once the local sequence had been established and had been shown to persist throughout the area, the usefulness of the geophysical logging in continuously cored boreholes depended upon the rapidity and accuracy with which it could be interpreted. In the Wash Feasibility Study total gamma-ray logging was used to deduce the stratigraphy of the boreholes within 2 to 3 hours of their completion. This rapid assessment enabled the best use to be made of the four drilling rigs on site by avoiding the long delays that core examination would have entailed and by eliminating duplication of sequences already sampled. In addition, the geophysical logs provided a useful check on the core labelling (incorrect depths and upsidedown cores are a relatively common occurrence), gave information on the lithologies in areas of core loss and indicated the presence of lithologies such as limestone doggers that had been missed by the core barrel.

Subsequent work on the Oil-Shale Project boreholes, suggests that the long term value of geophysical logging in the Kimmeridge Clay will mostly stem from its use in the correlation of sequences in rock-bitted boreholes. This type of interpretation has been in use in hydrocarbon exploration for many years, but it has rarely been used to make detailed correlations within thick mudstone formations. It is clear from the present work that many of the individual beds in the standard sequence can be recognised with confidence from geophysical logs alone.

The geophysical logging described below was carried out by a number of organisations using a variety of equipment. The Skegness, Hunstanton, Gayton and Marham boreholes were logged by the Geochemical and Geophysical divisions of IGS using UKAEA and Neltronic equipment respectively. The Wash Feasibility Study boreholes were mostly logged by the

author using a Widco Portalogger; a few boreholes were logged by staff of the then Water Resources Board using Gerheart Owen equipment. The Oil Shale Project boreholes were logged by a specialist contractor, BPB Logging Ltd., using BPB-designed equipment. Practical details of the various geophysical techniques used are discussed elsewhere (Gallois, 1979a).

Total gamma-ray and resistivity logging offer the best prospects of success for establishing detailed correlations within argillaceous formations such as the Kimmeridge Clay. In practice the total gamma-ray log was found to be the more useful for site investigation purposes such as the Wash Feasibility Study because it gave more distinctive signatures than the resistivity log and had the added advantages that it could be used above the water-table and in lined or cased boreholes.

2.3.1.2.2 Total gamma-ray logging

The total gamma-ray log measures the natural radioactivity of rocks, the gamma radiation being emitted almost entirely by the radioactive isotope of potassium (K^{40}) and by radio-elements in the uranium and thorium decay series (Anon, 1966). In sedimentary rocks these radioactive isotopes are usually concentrated in the argillaceous formations.

The relationship of the total gamma-ray log to lithology in part of the Upper Kimmeridge Clay in the Hunstanton Borehole is shown in Figure 23. At this stratigraphical level the sequence is made up of Type B rhythms and this is reflected in the gamma-ray log. High gamma counts correlate with those parts of the succession that are composed dominantly of oil shale or fissile shelly mudstone, whilst the major troughs in the trace occur opposite calcareous mudstones and cementstones. Comparison of the gamma-ray traces for the Upper Kimmeridge

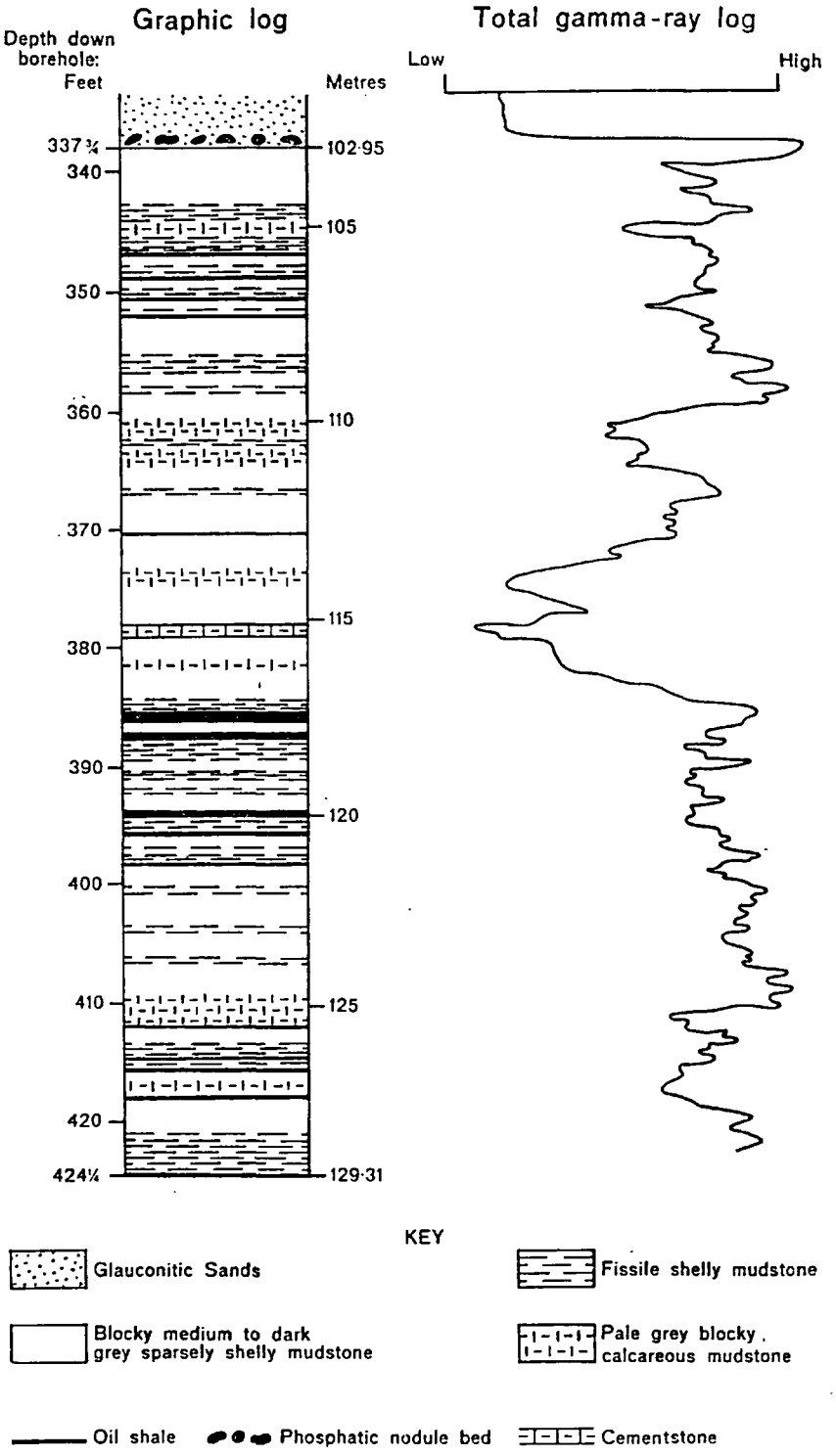


Figure 23. Relationship of the total gamma-ray log to lithology for the Kimmeridge Clay of the IGS Hunstanton Borehole. Gammas 'lows' A to F and 'highs' R to W are used for correlation in Figure 24.

Clay of the Skegness, Gayton and Marham boreholes shows a similar relationship to that at Hunstanton and the traces can be used to make detailed correlations between the four boreholes.

The combination of rapidly alternating sedimentary rhythms together with variations in the gamma-ray counts produced by the various lithologies within the rhythms produces complex total gamma-ray signatures which can be matched from borehole to borehole (Fig. 24a). The more prominent gamma lows are labelled A to F, and the highs R to W. A summary of the more distinctive lithologies, and their correlation as determined by the gamma-ray logging, is shown in Fig. 24b. It is clear from this latter figure that the most laterally extensive, 'gamma-distinctive' lithologies, and therefore those most suitable for long-distance correlations, are the cementstones and calcareous mudstones. The oil shales, although occurring at roughly the same levels in each borehole, cannot individually be correlated with one another because they are thinly interbedded with fissile shelly mudstones that produce similar gamma-ray counts. Although the calcareous content of some of the cementstones can be observed to vary laterally, this variation makes little difference to their gamma-ray counts. Phosphatic nodule beds at the base of the Sandringham Sands in Norfolk, at the base of the Spilsby Sandstone in Lincolnshire and at the Jurassic-Cretaceous boundary give consistently high gamma counts, probably due to secondary uranium enrichment.

A similar method of correlation can be used in the Lower Kimmeridge Clay, where Type A and Type B rhythms are present. In the Type A rhythms phosphatic pebbles in the basal silty mudstones give high gamma-ray counts that contrast with the low counts in the calcareous mudstones (Fig. 25).

When examined in their entirety gamma-ray traces from the full

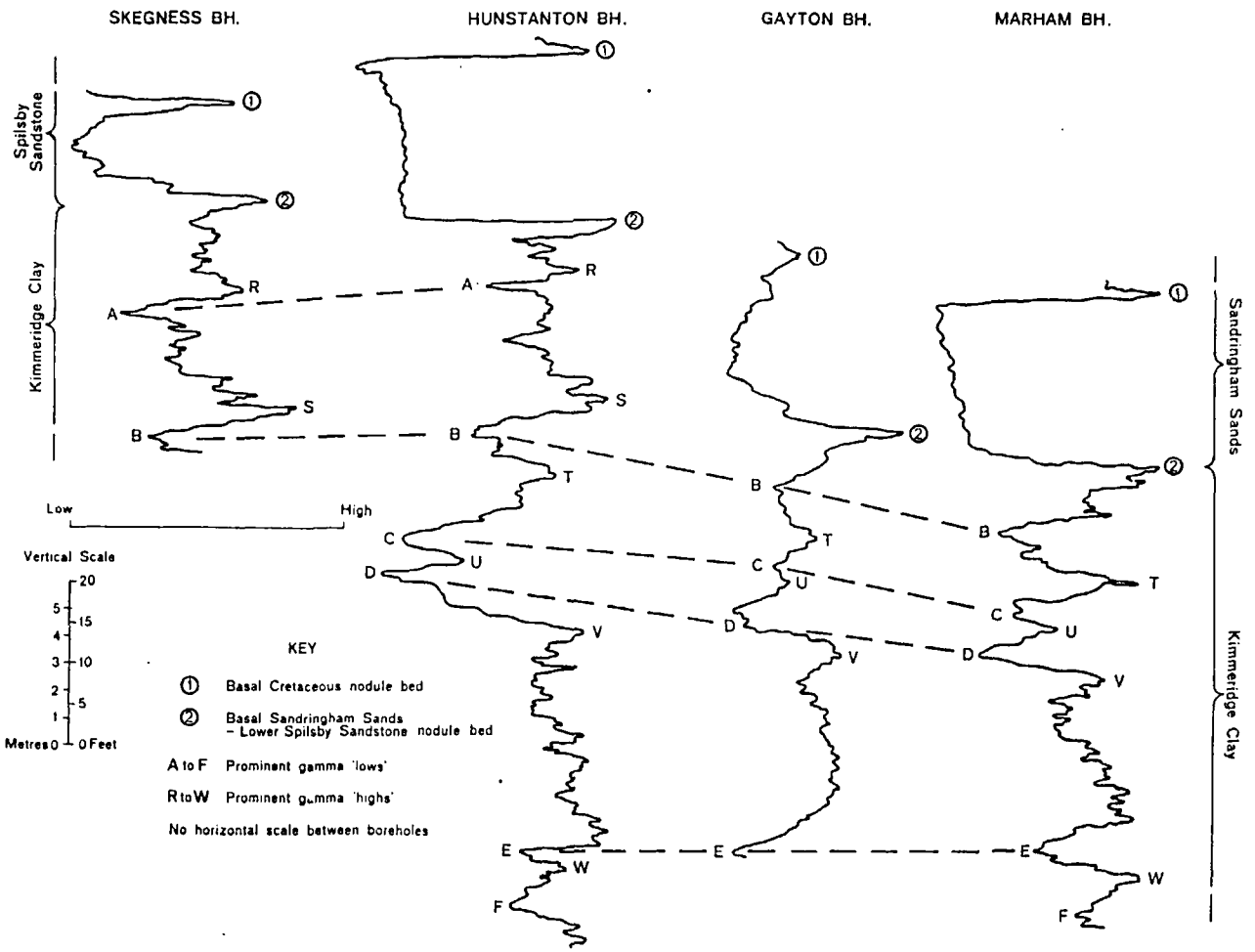


Figure 24a. Correlations between the gamma-ray logs of the Kimmeridge Clay in the Skegness, Hunstanton, Gayton and Marham boreholes.

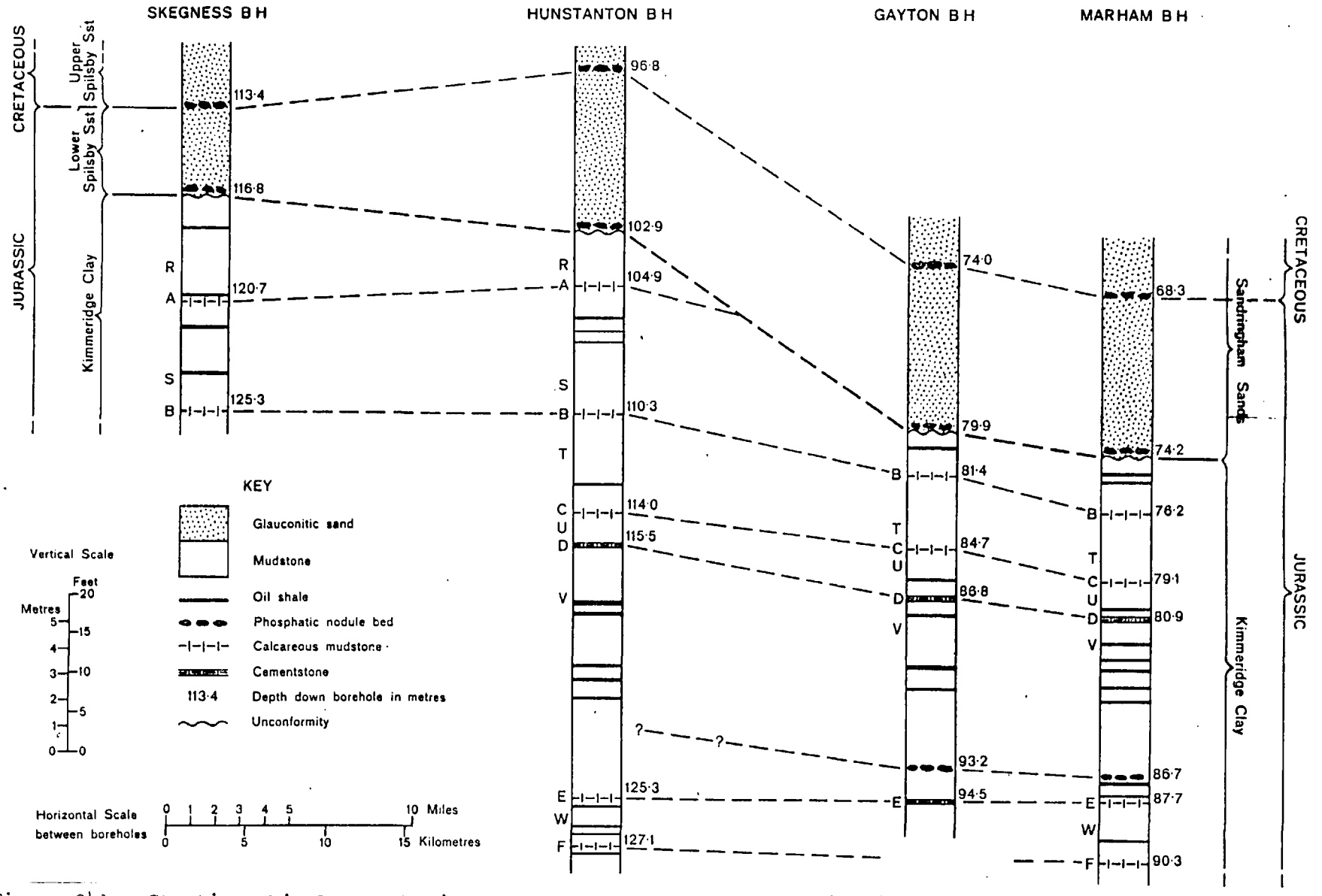


Figure 24b. Stratigraphical correlations between the four boreholes in Fig. 24a based on gamma-ray logging and lithological marker bands.

thickness of the Kimmeridge Clay (Fig. 26) contain a number of distinctive large features that can be recognised in traces from localities as far apart as North Yorkshire and the Weald, and a large number of small features (individual peaks and troughs) that can be recognised throughout local areas such as Norfolk. In the example illustrated (Fig. 26) the gamma-ray logs were run by three different contractors; BPB at North Runcton, the Water Resources Board at North Wootton and Schlumberger in the Place Oil Company's Hunstanton No. 1 Borehole. Each used counters with differing sensitivities, set at differing time-constants (the time interval over which the gamma-ray counts are averaged to lessen the effect of the statistical nature of the radioactive decay) and logged at differing speeds. Despite these differences, the three traces can be correlated in detail and 23 'highs' and 17 'lows' are picked out in each to illustrate the correlations that can be achieved. The marked difference between the smoothness of the North Runcton and Hunstanton No. 1 traces is due to a high background count in the North Runcton trace (slow logging speed) and a low background count in the Hunstanton trace (fast logging speed). The optimum logging speed varies with the equipment and the strata under consideration*.

The North Wootton and North Runcton boreholes were continuously cored; the former was used as a stratigraphical standard for part of the Wash Feasibility Study. By contrast, the Hunstanton No. 1 Borehole was rock-bitted throughout the Mesozoic and its Upper Jurassic clay sequence (Oxford Clay, West Walton Beds, Ampthill Clay and Kimmeridge

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* In horizontal strata, such as the Kimmeridge Clay in Norfolk, the maximum logging speed that can be used to detect a bed x metres thick is $\frac{d + x}{t}$ m/sec where d is the active probe length and t is the time constant. Assuming the thinnest bed to be 0.05m, the maximum logging speed with the Widco Portalogger (active length 0.1m) set at 5 secs time constant, is 108 m/hr. In practice a speed of about 60 m/hr was used; this is capable of detecting beds >3 cm thick provided their counts are high enough not to be masked by the background count.

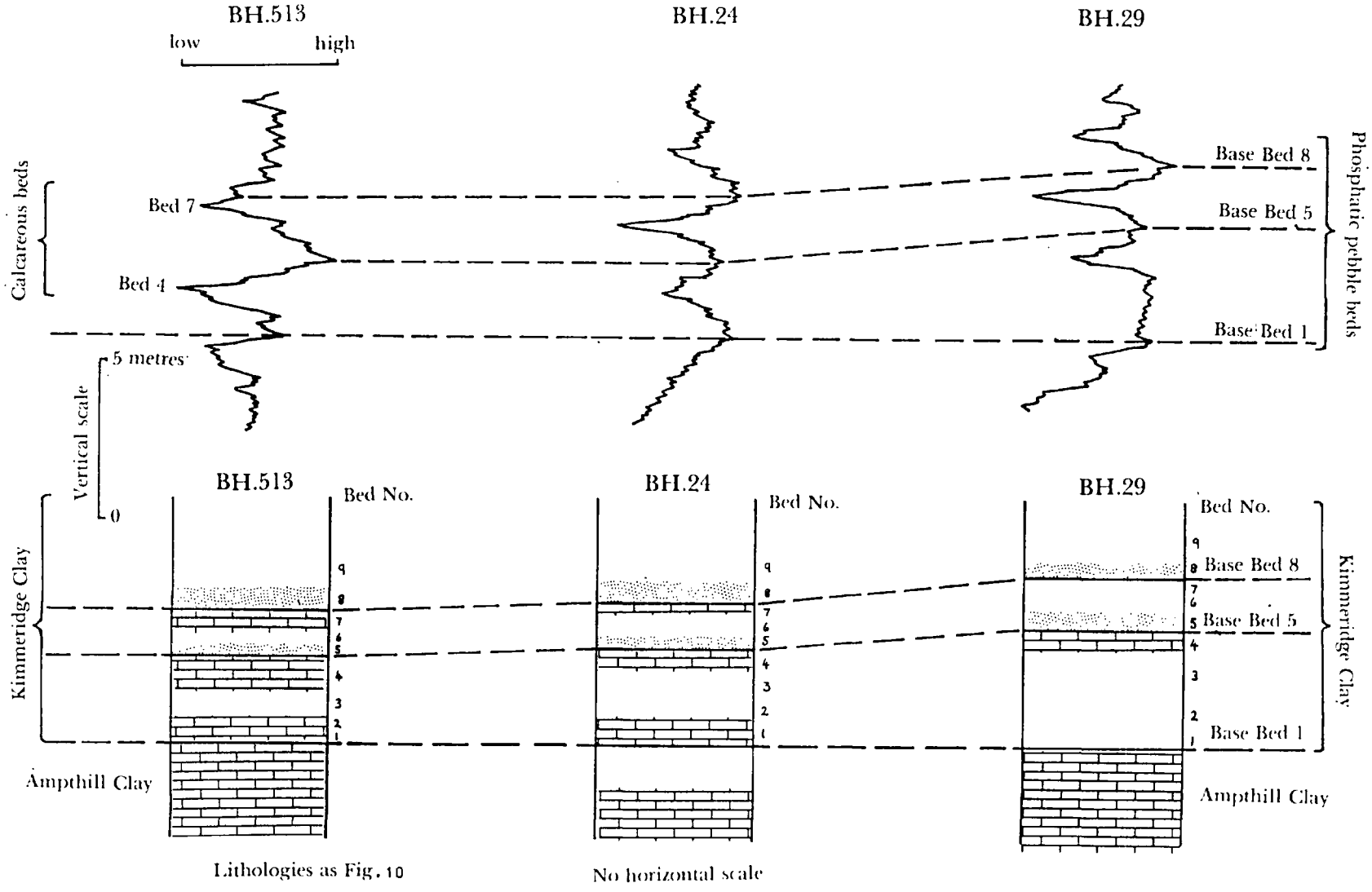


Figure 25. Comparison of total gamma-ray traces and lithologies for Type A rhythms in the basal beds of the Kimmeridge Clay in selected feasibility study boreholes.

Clay) has previously only been divided (albeit incorrectly) into formations. Comparison of the gamma-ray traces shows that zonal boundaries, and many of the individual bed boundaries, can be positioned with confidence in the Hunstanton No. 1 Borehole despite the absence of lithological or faunal data.

The high gamma-ray counts in the oil shales in the Kimmeridge Clay can probably be attributed to uranium absorption by their organic and phosphatic contents, although no uranium enrichment has yet been analytically proved in them. In a number of instances a single bedding plane of shelly material within the blocky mudstones, often an ammonite plaster, also appears to produce a small gamma peak. This may be due to partial phosphatisation.

It is difficult to make an accurate quantitative assessment of the absolute radioactivities produced by the various lithologies in the Kimmeridge Clay because of difficulties of instrument calibration, variations in the gamma-ray absorption properties of the mudstones, and variations in the geometries of the boreholes. The oil shales and the fissile shelly mudstones give consistently high gamma-ray counts in all the boreholes logged to date. The pale calcareous mudstones give low counts and the cementstones the lowest counts of all. The blocky mudstones, including those with shelly burrowfills, give counts intermediate between those of the calcareous mudstones and the shelly mudstones as one might expect. Although it has not been possible to measure the radioactivities of these lithologies there is reason to believe that their counts are comparable with those described for the Kimmeridge Clay in the Warlingham Borehole, Surrey, where Burley (in Worssam and Ivimey Cook, 1971, p. 116 and pl. v) recorded radiation levels of around 5.5 µg Ra equiv./ton.

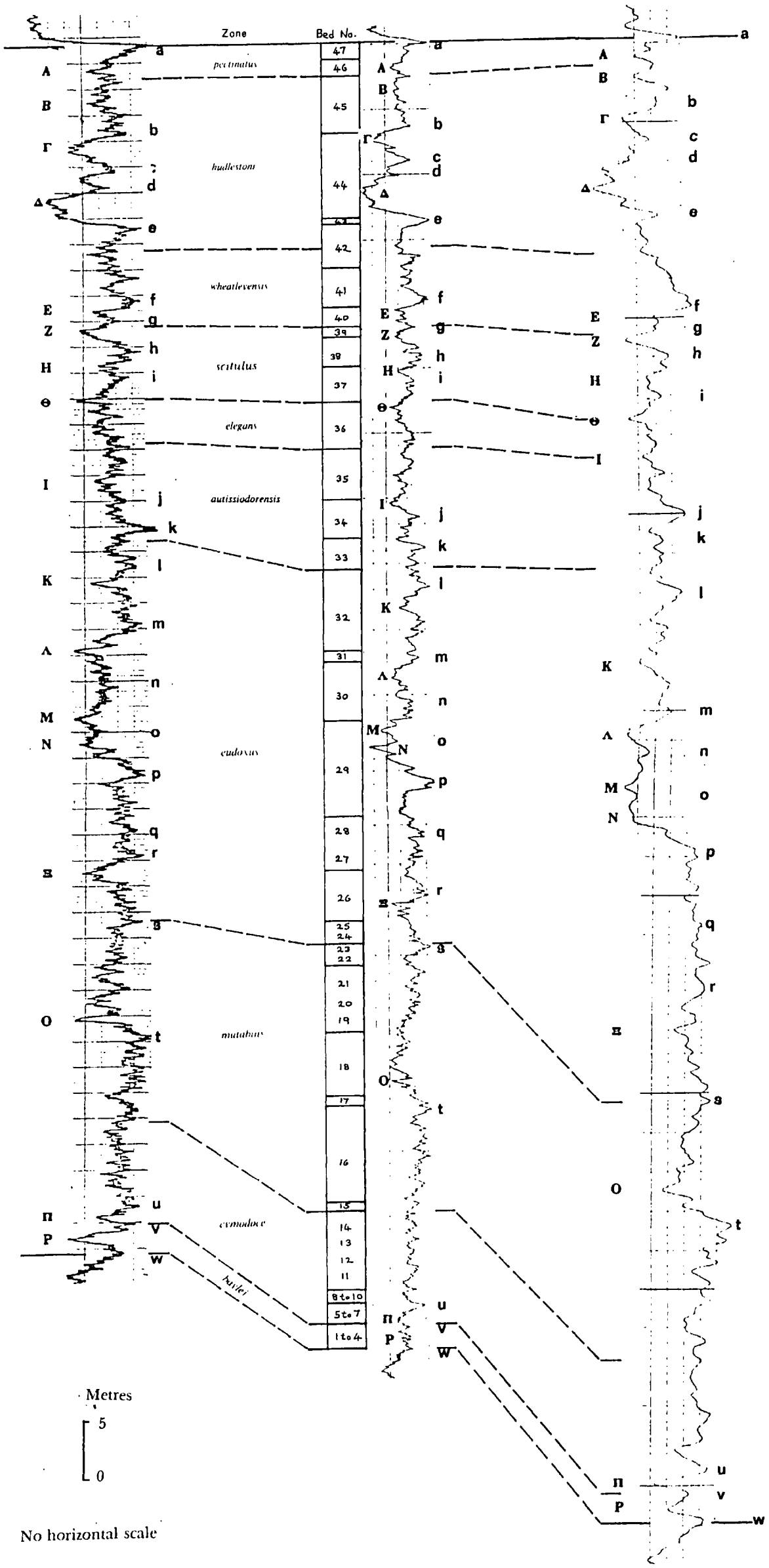


Figure 26. Total gamma-ray correlations between the Kimmeridge Clay sequences in the North Runcton, North Wootton and Hunstanton No. 1 boreholes.

The peaks in gamma-ray traces from the Kimmeridge Clay in hydrocarbon boreholes in the English land area rarely exceed 120 API gamma-ray units. This is much lower than the counts recorded in the Kimmeridgian 'hot shales' in the northern North Sea where peaks commonly exceed 300 API units, presumably because of the availability at the time of their deposition of uranium minerals from the nearby Scottish granites.

2.3.1.2.3 Resistivity and other methods

Few geophysical borehole logging methods other than total gamma-ray were found to be suitable for stratigraphical purposes in shallow, small diameter (< 130 mm) boreholes in the Kimmeridge Clay. Methods which might be expected to yield information on the *in situ* density of the rock, such as the sonic log and the formation-density (gamma gamma) log, are not cheaply available. Furthermore, they are greatly affected by variations in borehole diameter, and in soft friable rocks such as the Kimmeridge Clay caving is nearly always present. It should be possible to distinguish oil shales (low density) and limestones (high density) from Kimmeridge Clay mudstones using sonic and formation-density logs. However, none of the small number of logs made by these methods was satisfactory because of the irregular profiles of the boreholes.

Neutron and neutron-gamma logs are also considerably influenced by variations in borehole diameter and are not useful stratigraphical tools for shallow, small diameter boreholes at the present time. Both methods detect variations in moisture content and can provide traces in which the highly calcareous mudstones can be distinguished from other lithologies. The spontaneous potential (SP) log, which is used

in the oil industry primarily to detect permeable formations, has not been found to be stratigraphically useful in the Kimmeridge Clay.

The only borehole log which currently compares in usefulness with the total gamma-ray log for stratigraphical purposes in the Kimmeridge Clay is the electrical or resistivity log. In the Wash Feasibility Study the most useful techniques were found to be the 'short normal' and the 'single electrode' methods. Both give comparable results; in recent years the 'focussed electric' method has partly replaced the 'short normal'. For stratigraphical purposes the 'single electrode' method is probably the most useful since it has the advantages of being simple and quick to use and is incorporated into most portable logging equipment. Resistivity methods can be used to distinguish clay-mineral-rich mudstones (low resistivities) from calcium-carbonate-rich mudstones (high resistivities) and limestones (very high resistivities). They can provide the basis for detailed correlations, especially when used in conjunction with the gamma-ray log. Resistivity logging has two main disadvantages; it can only be used below the water-table, and it cannot be used in the cased parts of boreholes. These limitations are not commonly a problem in the Kimmeridge Clay because it usually crops out in low, poorly drained ground where the water-table is close to ground-level, and it will stand unsupported in boreholes.

2.3.2 Norfolk outcrop and subcrop

The Kimmeridge Clay is poorly exposed in Norfolk. The highest part of the formation crops out along the eastern edge of Fenland between King's Lynn and Southery, but the bulk of it is covered by the Pleistocene and Recent deposits of Fenland and The Wash (Fig. 27). No natural exposure of Kimmeridge Clay occurs within the county and

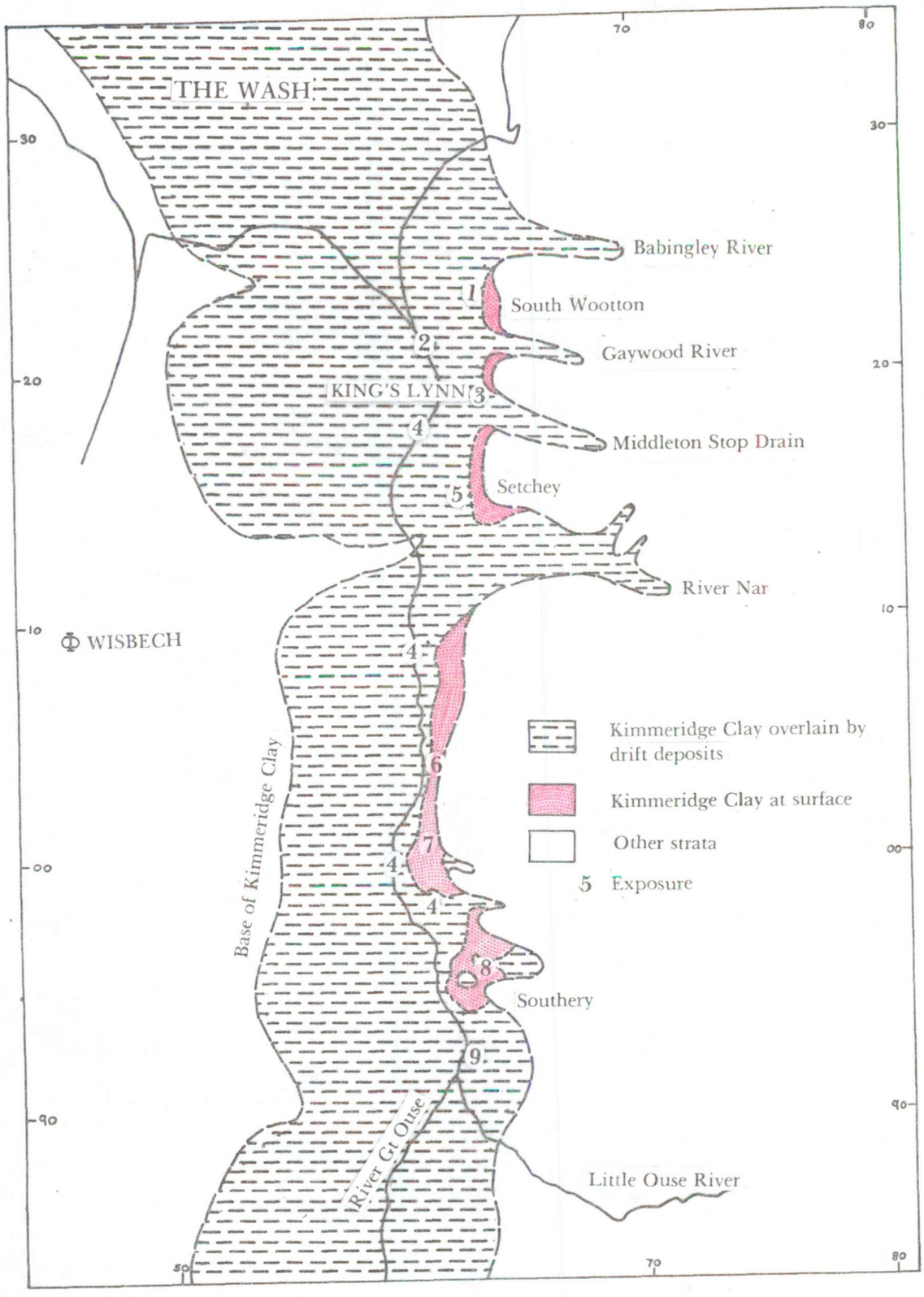


Figure 27. Geological sketch map showing the outcrop of the Kimmeridge Clay in Norfolk and the positions of recent exposures.

few artificial exposures have been recorded. Rose (1835, p. 175) noted Kimmeridge Clay in a brickpit at Southery and Whitaker et al. (1893) recorded small sections in the Upper Kimmeridge Clay in brickpits at Downham Market and Wormegay. Forbes-Leslie (1917a) noted oil shales in the Puny Drain at Setchey and Drs R. Casey and R.G. Thurrell collected fauna from the Kimmeridge Clay in the excavations for the Cut-Off Channel between Downham Market and Hilgay. Descriptions of the sections exposed at the time of the field survey are on open file.

The most complete stratigraphical account of the Kimmeridge Clay of Norfolk prior to the present work was that by Pringle (1923) based on partially cored oil-shale exploration boreholes at Methwold Common and Severals House in south-west Norfolk. He thought that the Sandringham Sands in both boreholes rested on the lower part of the '*Perisphinctes*' *pallasianus* Zone (*sensu* Chatwin and Pringle 1922, p. 163; *Pavlovia* zones of modern authors). This zonal assignment was based on several poorly preserved fragments of '*Perisphinctes*' (Pringle, 1923, p. 134) which, in the light of Cope's subsequent (1967, 1978) work on the ammonite succession in the Upper Kimmeridge Clay, can no longer be regarded as conclusive.

About 5.5m below the supposed *pallasiodes* Zone ammonites Pringle (1923, p. 134) recorded a bed crowded with pyritized *Saccocoma* and noted that this crinoid was (at that time) only known elsewhere from 4m of strata at the level of the 'Blackstone' (*wheatleyensis* Zone) in Dorset. He also noted (Pringle MSS) this distinctive fossil in other oil-shale boreholes in west Norfolk including those at Setchey, East Winch and West Bilney (see Appendix A for details). Other faunal features that were noted by Pringle in the Methwold Common and

Severals House boreholes, and which have subsequently proved to be useful marker bands, were plasters of Amoeboceras (Nannocardioceras) and beds rich in Nanogyra virgula.

Taken together, the stratigraphical details obtained by Pringle from the various oil-shale boreholes in Norfolk showed that Forbes-Leslie's (1917a) account of the Kimmeridge Clay succession (said to have been proved in boreholes at Setchey and which included "yellow sandstones" and up to 250m of predominantly oil shale) was grossly distorted.

The first complete section through the Upper Kimmeridge Clay in Norfolk was that proved in IGS Boreholes 71/75 and 71/76 drilled by the drilling ship m.v. Whitethorn in the central part of The Wash. The first section through the whole formation was that proved in the North Wootton Borehole in 1972. The complete sequence was subsequently penetrated in 1974 in the IGS oil-shale borehole at North Runcton. Parts of the sequence were also proved in the continuously cored Wash Feasibility Study boreholes at Denver Sluice, Ongar Hill, Tilney All Saints, Hook Drain, Walkers Marsh, Emorsgate, Terrington St John, Old Podike Bank, Symington Farm, Balaclava Farm, Admirals Farm, Pierrepont Farm, The Grange, Stowbridge, Racecourse Road, New Common Marsh Farm, Vinegar Middle and Daseley's Sand. The sites of these boreholes are shown in Fig. 4. Graphic logs and gamma-ray logs are given elsewhere (Gallois, 1974).

Within the area of primary interest to the feasibility study, the Fenland part of Norfolk, the boreholes were sufficiently closely spaced to enable the base of the formation to be contoured (Fig. 28).

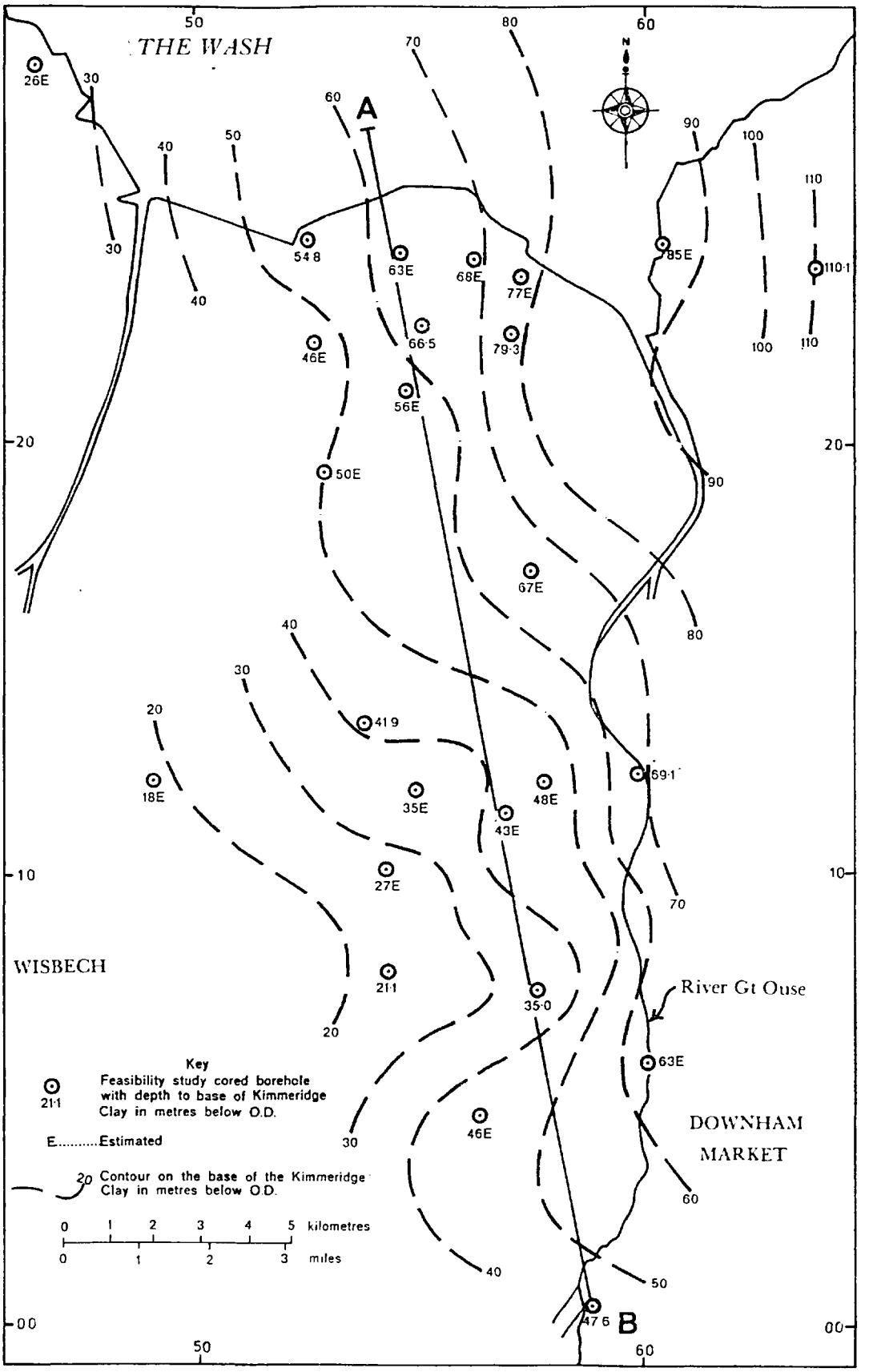


Figure 28. Structure contours on the base of the Kimmeridge Clay in the Fenland part of Norfolk.

This shows the structure of the area to consist of a number of broad, very gentle folds, with dips <1°, that plunge gently eastwards or north eastwards. Because of the simplicity of the structure and the correlations achieved between the boreholes it is possible to use them to construct a detailed geological section between any two points in the area. An example, along a line from Terrington Marsh to Denver Sluice, is shown in Figure 29.

All the feasibility study boreholes referred to above were drilled on, or close to, the Kimmeridge Clay outcrop. In the subcrop area the upper part of the Upper Kimmeridge Clay was continuously cored in the IGS boreholes at Hunstanton, Gayton, Marham and Mundford (Borehole C), and parts of the formation were cored in the 1916-23 oil-shale exploration boreholes (Fig. 3).

The complete formation has been penetrated in a number of deep boreholes drilled in Norfolk for hydrocarbon exploration since the Second War (Fig. 30), notably those at North Creake (drilled by British Petroleum in 1945; described by Kent, 1947), Hunstanton (Place Oil, 1969), Wiggenhall (Texaco, 1971) and South Creake (British Petroleum, 1969). The top of the Kimmeridge Clay (beneath unconformable Cretaceous sands) was proved in a site-investigation borehole drilled for the Ely-Ouse Water Transfer Scheme at Hockwold (Borehole 23).

The limits of the Kimmeridge Clay subcrop in East Anglia can be approximately determined from other deep boreholes, at Trunch (IGS, 1975), East Ruston (Hamilton Brothers, 1971), Somerton (Conoco, 1969, Saxthorpe (Duntex Petroleum, 1970), Culford (for water, 1890), Great Ellingham (Superior Oil, 1965), Rocklands (Norris Oil, 1969), Lowestoft (for water, 1902), Four Ashes (Superior Oil, 1965), Lakenheath (Superior Oil, 1965) and Breckles (Norris Oil, 1969), which proved Cretaceous

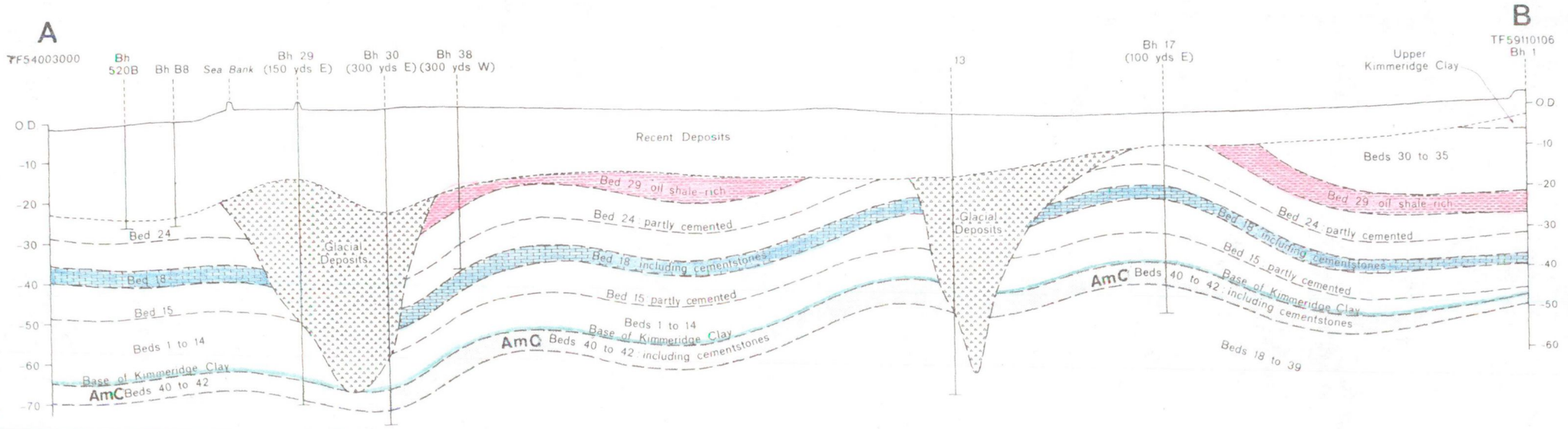


Figure 29. Geological section between Terrington Marsh and Denver Sluice (line of section shown in Figure 28). Vertical exaggeration x80 approx.

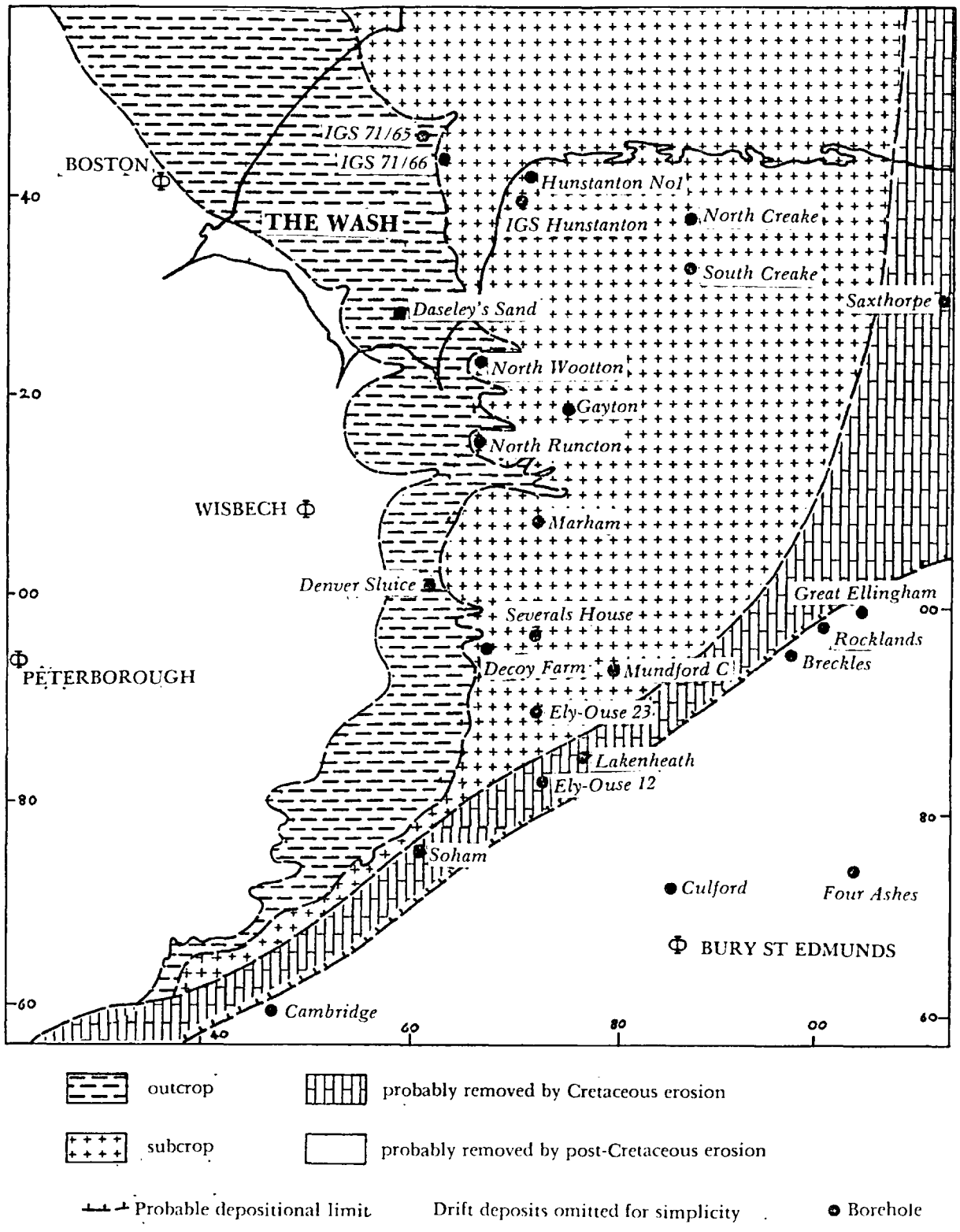


Figure 30. Distribution of the Kimmeridge Clay in Norfolk and the positions of deep boreholes referred to in the text.

rocks resting on pre-Kimmeridgian rocks (Fig. 30). The absence of the Kimmeridge Clay over much of Norfolk is due to a number of factors including non-deposition, attenuation and late Jurassic and early Cretaceous erosion adjacent to the northern edge of the London Platform.

At its most complete in Norfolk the Kimmeridge Clay ranges from about 65 to 130m in thickness and is much thinner than the sequences in the Warlingham Borehole or at Kimmeridge Bay. At Warlingham, 217m of Kimmeridge Clay was proved (Worssam and Ivimey-Cook, 1971) but the lower beds (Beds 1-17 inclusive) are cut out by faulting. At Kimmeridge, Arkell (1947, p. 64) estimated the full thickness of the formation to be more than 500m.

Isopachytes for the preserved Kimmeridge Clay in the English land area are shown in Figure 31 (see Gallois, 1979b for details of the boreholes on which this is based). These thicknesses correspond with the original depositional thicknesses only in the coastal part of Dorset and beneath the Weald, areas where the Kimmeridge Clay is conformably overlain by Portland Beds. Throughout most of the remaining outcrop and subcrop, with the exception of narrow strips adjacent to the London Platform and the Market Weighton Axis, the youngest preserved Kimmeridge Clay is pectinatus Zone or younger in age, and its preserved thickness is probably within 20% of its depositional thickness. Figure 31 therefore gives a picture of the original pattern of deposition of the Kimmeridge Clay that is only slightly distorted. The regional variations in thickness are thought to be due to differences in rates of subsidence within the Kimmeridgian area of sedimentation. For example, the thick Kimmeridge Bay sequence probably lay close to the axis of a subsiding basin whilst the Norfolk succession was deposited on the flanks of a stable massif

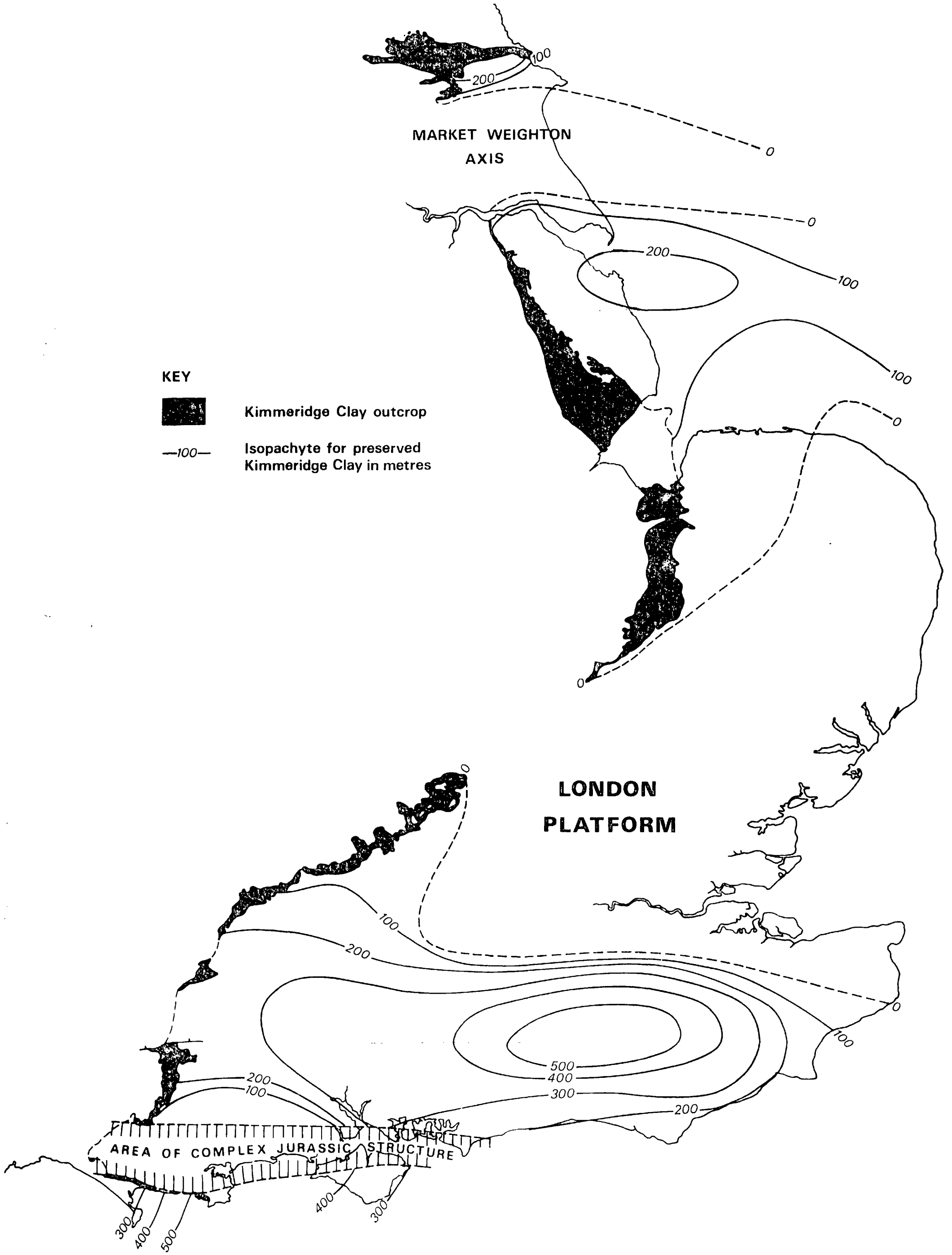


Figure 31. Isopachytes for the preserved Kimmeridge Clay of the English land area.

(the London Platform).

The Kimmeridge Clay thins southwards in Norfolk from about 130m in the central part of The Wash, to nothing in the southern and eastern parts of the county. This thinning is made up of two components, contemporaneous attenuation as the London Platform is approached and late Jurassic and early Cretaceous erosion caused by the progressive southerly and easterly overstep of the Sandringham Sands in Norfolk and the Woburn Sands and Carstone (Lower Greensand) in Cambridgeshire and Suffolk.

Between Daseley's Sand (Bh. 513B) and Denver Sluice (Bh. 1), the Lower Kimmeridge Clay thins from an estimated 80 to 42.3m (Fig. 32), but does so without any change in lithology or loss of beds. No lithological evidence was seen in the area north of Denver Sluice to suggest that this thinning indicates the approach to a shoreline. Southwards and southeastwards from Denver Sluice, the thinning continues in the general direction of the London Platform to a large borrow-pit at Roslyn Hole, Ely [TL 552 807] (the largest exposure of Kimmeridge Clay currently visible in East Anglia) and to the Mundford C Borehole (Fig. 33). In the Denver Sluice and Ely sections, two thin siltstone bands are present in Bed 28 at a stratigraphical level at which silt is unknown elsewhere in Norfolk. A marked thinning accompanied by a lithological change, also occurs between the Denver Sluice and Mundford C boreholes (Fig. 34). In the latter borehole, the Lower Kimmeridge Clay is thinner and is more calcareous at any given stratigraphical level than are the comparable beds elsewhere in Norfolk. This attenuation and lithological change are presumed to indicate the approach to a shoreline or an area of shallows.

The manner in which individual beds or groups of beds within the Lower Kimmeridge Clay vary in thickness in Norfolk is illustrated in

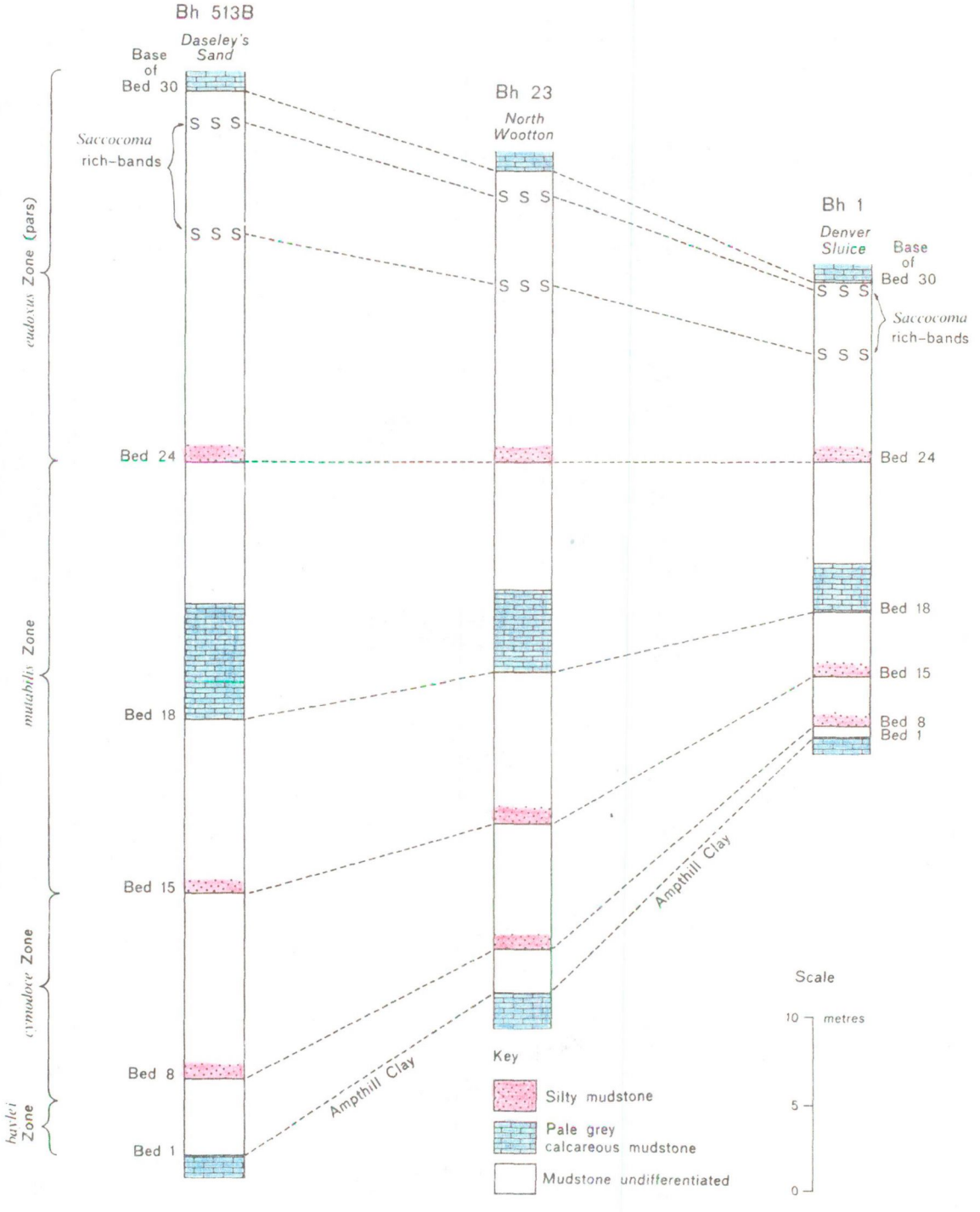


Figure 32. Attenuation in the Lower Kimmeridge Clay between the southern part of the Wash (Bh. 513) and Denver Sluice (Bh. 1).

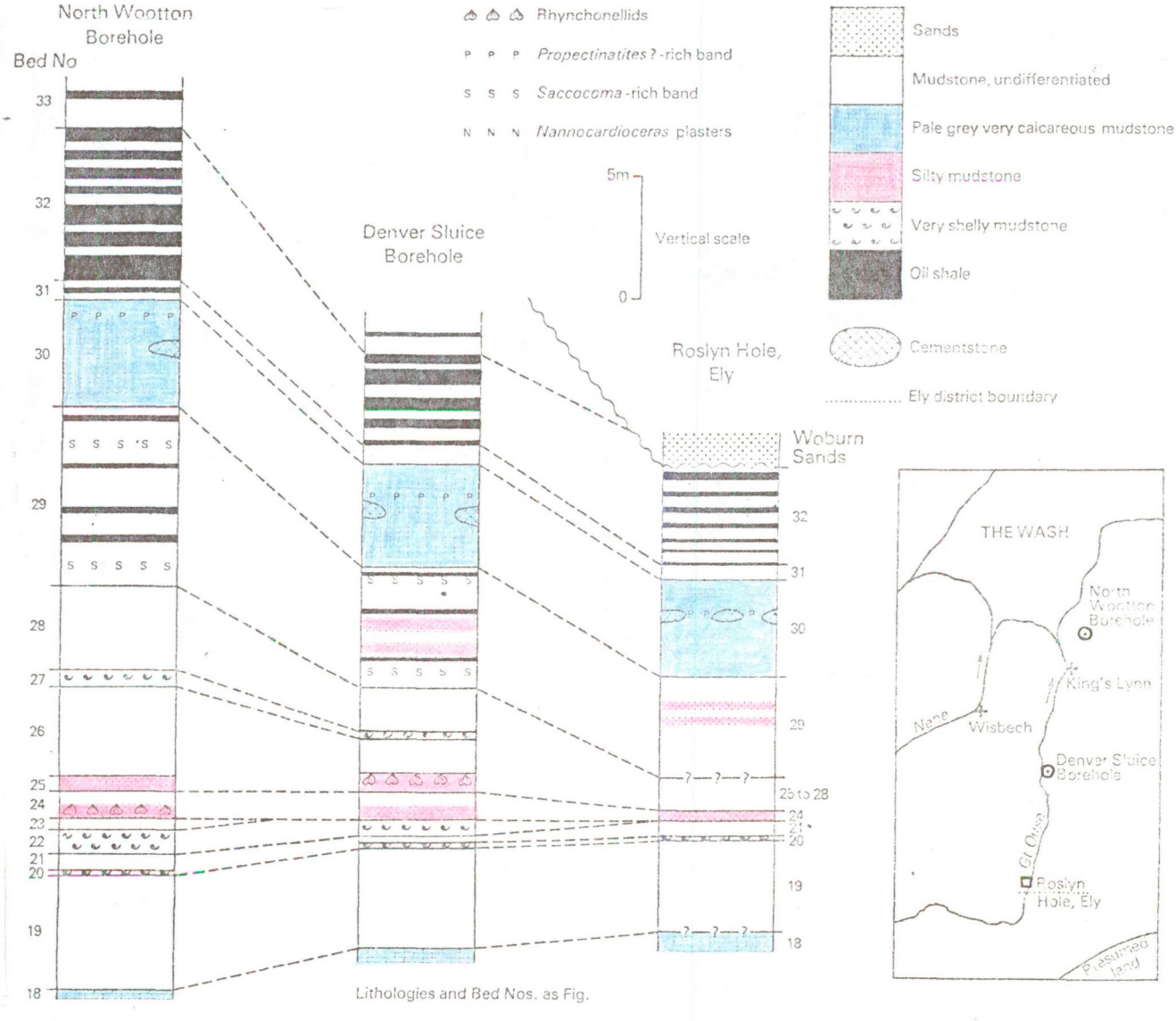


Figure 33. Attenuation in part of the Lower Kimmeridge Clay between North Wootton (Bh. 23), Denver Sluice (Bh. 1) and Roslyn Hole, Ely.

Figures 29, 32 and 34. It is noticeable that the lower part of the sequence (Beds 1 to 23) becomes more rapidly attenuated than the higher part as the London Platform is approached. This seems to be due to the erosion surfaces at the bases of Beds 1, 5, 8, 15, 17 and 24 becoming more dominant in this direction. In Cambridgeshire, boreholes and exposures at Ely, Haddenham, Littleport, Sutton and Stretham suggest that the beds below Bed 24 are considerably reduced in thickness and that Beds 1 to 8 inclusive are locally represented by a single complex phosphatic nodule bed (Cox and Gallois in Gallois, in press). A similar situation occurs at Hartwell, Buckinghamshire where a thick phosphatic nodule bed (presumed to be the equivalent to Beds 1 to 8 inclusive) rests on the Ampthill Clay (Gallois, 1979c). The two most attenuated sequences of the lowest part of the Kimmeridge Clay recorded to date (Haddenham and Hartwell) are close to the disappearance of the formation beneath the Woburn Sands overstep. This attenuation may therefore represent the approach to a Kimmeridgian shoreline that was reactivated, and consequently extensively eroded, in Aptian times.

Recent work by Dr B.M. Cox and the author on the better exposed coastal exposures in Dorset and a re-examination of the IGS collection of specimens from the Warlingham Borehole has shown that those two sequences can be matched in lithologically and faunal detail with that of Norfolk (Fig. 35a and b; from Cox and Gallois, 1981). The more prominent lithological markers such as the silty Beds 5, 8, 15 and 24, the thick calcareous Beds 18, 30 and 44 and the oil-shale-rich bands in Beds 29, 32, 36, 42 and 46, can be readily recognised in all three sections. So too can a number of lesser lithological marker bands. The faunal ranges of the more common ammonites and bivalves are similar in each section and the more prominent faunal

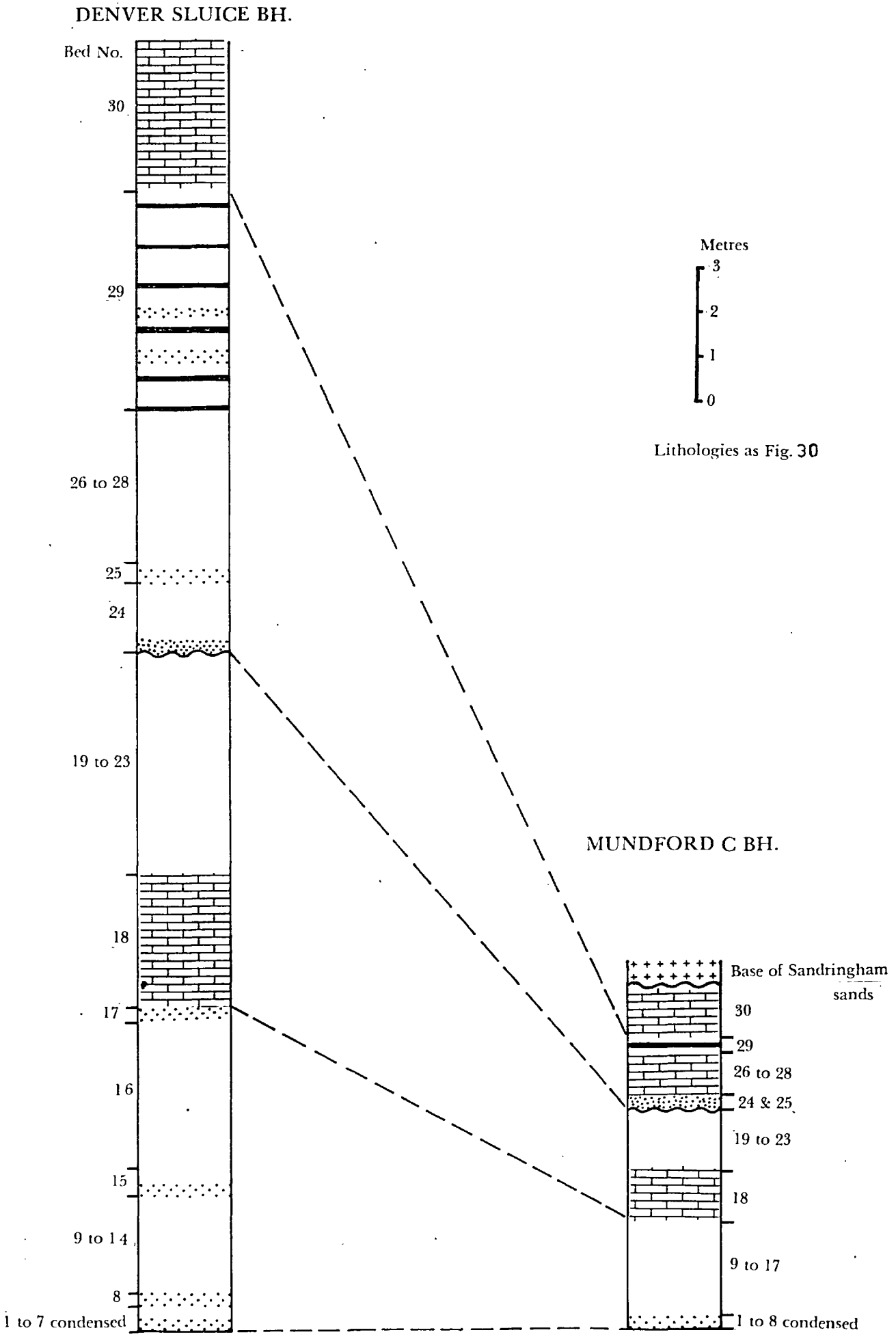


Figure 34. Attenuation and facies change in the Lower Kimmeridge Clay between Denver Sluice (Bh. 1) and Mundford (Bh. C).

marker bands, those rich in Xenostephanus, Pentacrinus, Astarte supracorallina, Saccocoma, Nannocardioceras, Sutneria rebholzi, Nanogyra virgula and Pectinatites eastlecottensis, are present in each sequence.

The Norfolk sequence has also been correlated with the argillaceous parts of the Kimmeridge Clay in the more recent oil-shale exploration boreholes (Figs. 17 and 18). At selected levels, where the faunal evidence is sufficiently good, oil-shale seams and coccolith-rich bands, ranging from a few centimetres to a few tens of centimetres in thickness, can be correlated between Wiltshire and Lincolnshire (Fig. 13).

Throughout the greater part of its outcrop the English Kimmeridge Clay is composed of its 'normal' mudstone facies and contains the same range of fine-grained sediments that have been described above as characteristic of the Norfolk succession. Other lithologies occur locally at several stratigraphical levels and these can be regarded as 'members' within the Kimmeridge Clay 'formation'. The best documented of these are the Abbotsbury Ironstone of Dorset (Blake and Hudleston, 1877; Brookfield 1973a) the Cemetery Beds of the Swindon, Wiltshire area (Buckman, 1923) and their lateral continuation the Shotover Grit Sands (Blake, 1880) and Thame Sands (Buckman, 1927) of Oxfordshire/Buckinghamshire, and the Elsham Sandstone of Lincolnshire (Kent and Casey, 1963). All these coarse lithologies are restricted to either the lower part of the Lower Kimmeridge Clay (baylei to basal mutabilis zones; Abbotsbury Ironstone, Elsham Sandstone and un-named sands recorded by Lamplugh and Kitchin (1911) in the Kent Coalfield) or the Upper Kimmeridge Clay (wheatleyensis to pectinatus zones; Cemetery Beds, Shotover Grit Sands and Thame Sands).

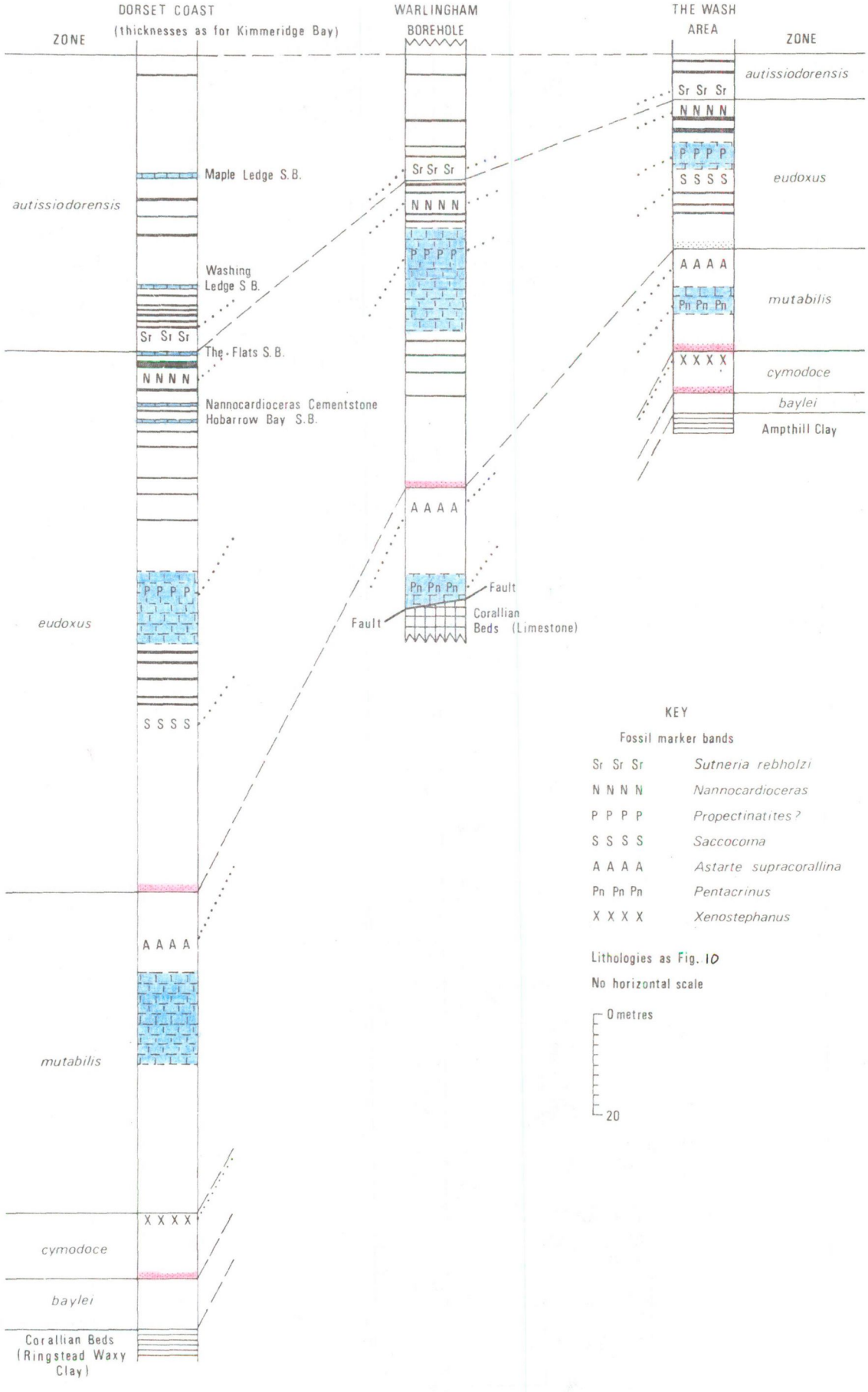


Figure 35a. Correlation of the Lower Kimmeridge Clay sequences of the Dorset coast and the Warlingham Borehole with that of Norfolk (Cox and Gallois, 1981).

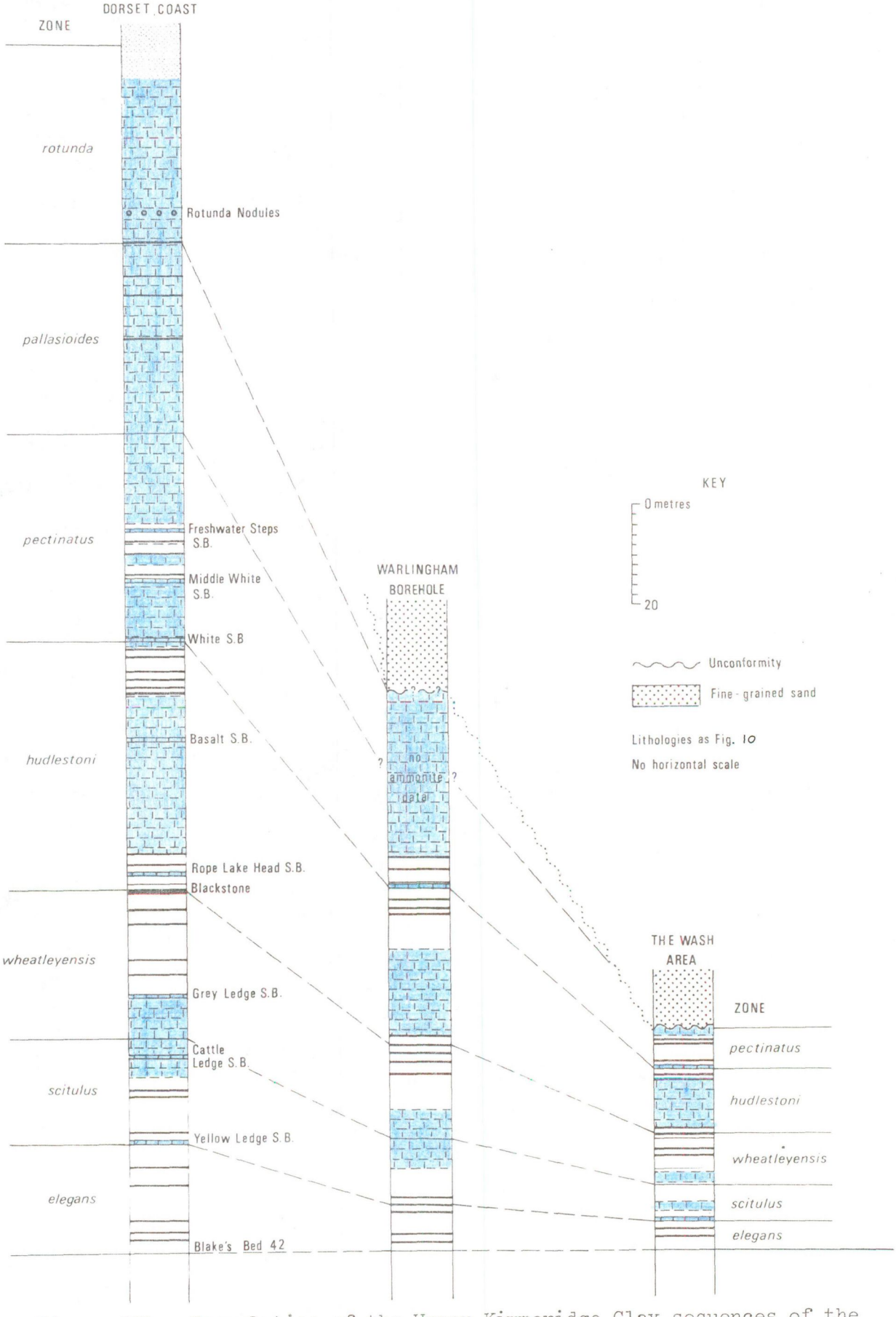


Figure 35b. Correlation of the Upper Kimmeridge Clay sequences of the Dorset coast and the Warlingham Borehole with that of Norfolk (Cox and Gallois, 1981).

The tendency for coarser sediments to be locally present in the basal beds of the Kimmeridge Clay can also be observed in Scotland. At Helmsdale, Sutherland the bulk of the cymodoce Zone (the baylei Zone is not exposed) is occupied by the Allt na Cuile Sandstone and although this sand-body may only be a relatively small fan at the foot of a submarine fault scarp, it is overlain by argillaceous Kimmeridge Clay and clearly reflects a temporary change in the pattern of sedimentation.

In Cromarty (Ethie) and Skye (Staffin) the basal part of the Kimmeridge Clay (baylei and cymodoce zones) is made up of a large number of small Type A rhythms and is markedly more silty than the sequence at that stratigraphical level in Norfolk and much of the remainder of the English outcrop. The broad distribution of lithologies in the cymodoce and pectinatus zones is shown in Fig. 36.

2.4 Depositional environments

2.4.1 Introduction

Any attempt to determine the nature of the environments in which the Kimmeridge Clay was deposited must take into account not only the lithological, palaeontological and chemical data obtained from an examination of the sediment, but must also consider the geographical distribution of the formation at the present time and its probable past distribution. It is also useful to consider the depositional environments of the underlying Corallian Beds from which the Kimmeridge environments evolved.

No work has been published on the depositional environments of the Kimmeridge Clay as a whole, but Brookfield (1973a) has discussed the palaeoenvironment of the Abbotsbury Ironstone (Upper Oxfordian -

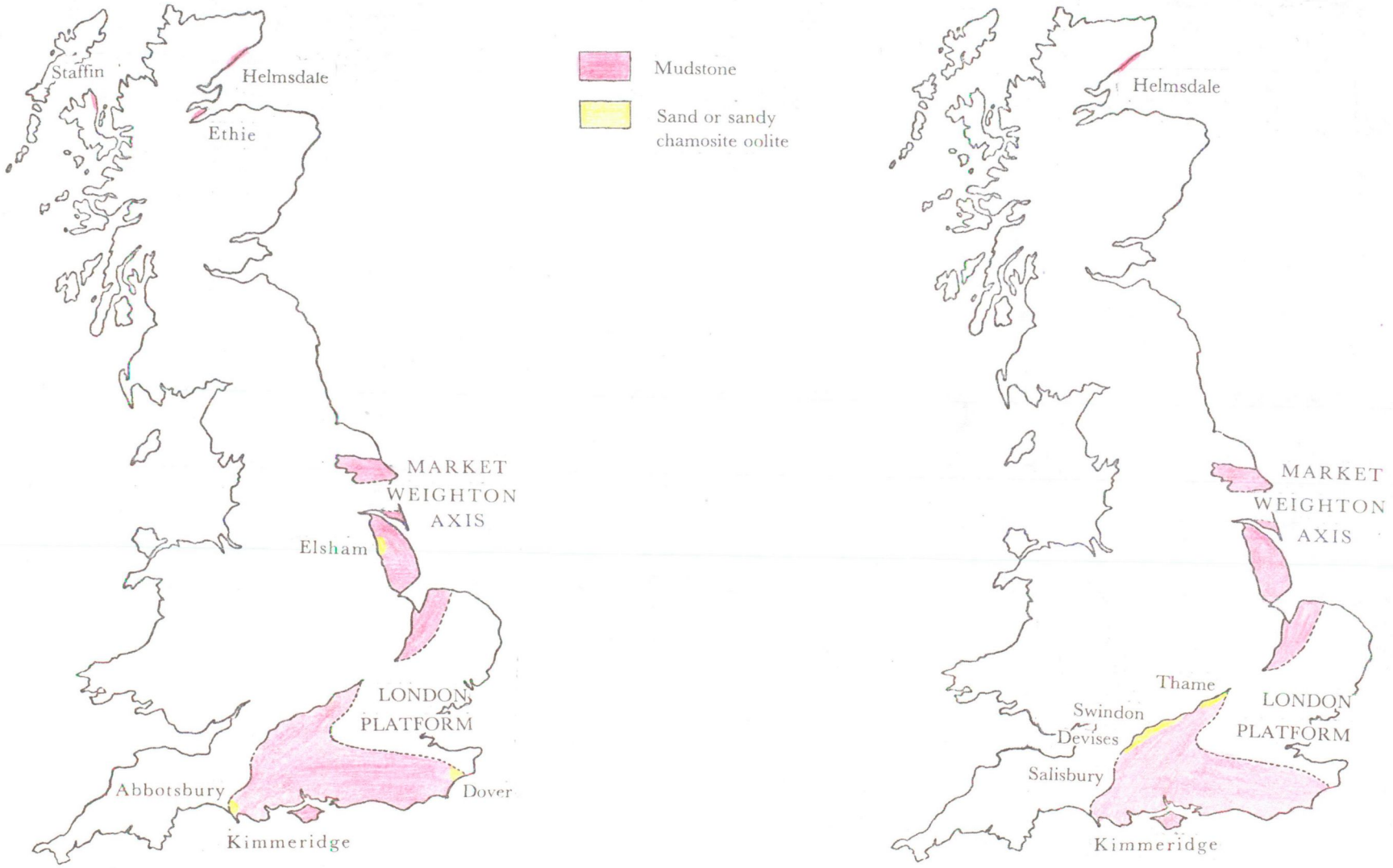


Figure 36. Distribution of lithologies in the English Kimmeridge Clay in the cymodoce and pectinatus zones.

Lower Kimmeridigan) and their correlatives in the Weymouth area (1978), and the palaeogeography of the Upper Oxfordian and Lower Kimmeridgian of England (1973b). Talbot (1973) and Fürsich (1977) have described aspects of the lithological and faunal associations of the Corallian Beds of Dorset and have attempted facies interpretations.

2.4.2 Evidence for palaeogeography

The thickness of the preserved Kimmeridge Clay of the English land area and part of the southern North Sea, based on outcrop and borehole data, is shown in Fig. 31; the borehole data is summarized in Appendix C. The maximum proved thickness of preserved Kimmeridge Clay is 560m in the Weald of Sussex. Thicknesses of over 500m have been recorded in south Dorset, but elsewhere the formation is generally less than 250m thick.

The present distribution of thickness of the formation is related to two factors, the original depositional thickness and the amount removed by late Jurassic and early Cretaceous erosion. Postulated isopachytes for the original depositional thickness, based on the preserved thicknesses and estimates for those parts of the sequence that are missing, are shown in Fig. 37.

The thick succession of the Dorset coast is complete, being conformably overlain by Portland Beds. It is separated from the Vale of Wardour (north Dorset and Wiltshire) outcrop, in which a complete sequence is preserved, by a complex west-east trending fold and fault belt that includes the Isle of Purbeck-Isle of Wight monocline. Within this folded and faulted belt the Kimmeridge Clay is thin and incomplete and has been locally removed by erosion during post-Portlandian to pre-Aptian times. Similar fold/fault belts probably

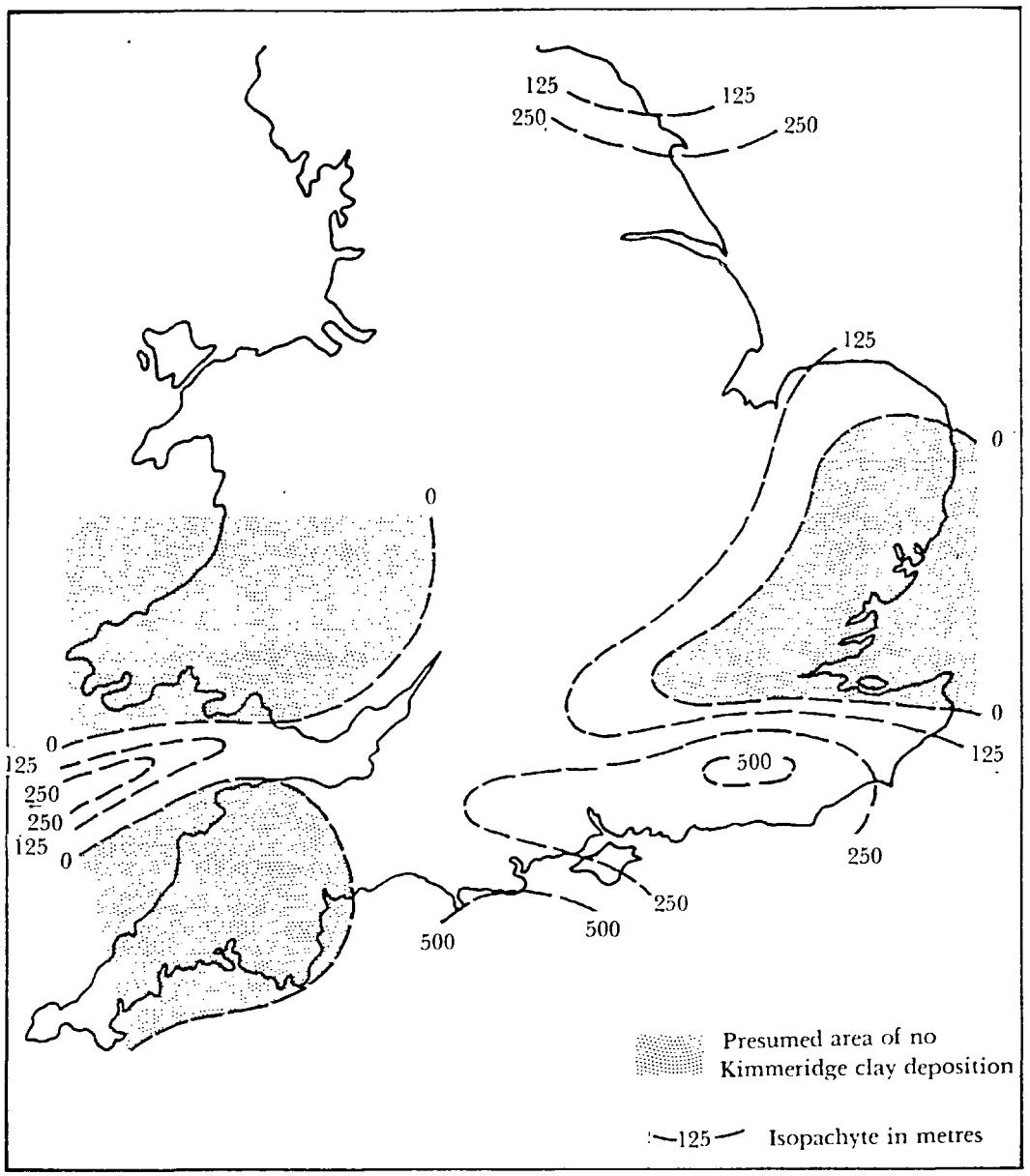


Figure 37. Postulated isopachytes for the original depositional thickness of the Kimmeridge Clay in southern Britain.

separate the Vale of Wardour outcrop from that of the Vale of Pewsey, and Pewsey from the Swindon-Aylesbury outcrop (Fig. 2). Between north Dorset and Buckinghamshire the original thickness of the Kimmeridge Clay at outcrop thins steadily northwards, a feature that reflects the transition from the Dorset depositional basin to a more stable shelf that fringed the London Platform.

Thin, but mostly complete, Kimmeridge Clay sequences occur along the southern edge of the London Platform beneath Berkshire, Surrey, Sussex and Kent. The more easterly of these sequences thicken southwards into the Wealden depositional basin where the Kimmeridge Clay is again complete and more than 500m thick. The Wealden and Dorset basins may be separated by an area of thinner Kimmeridge Clay beneath the western Weald and Hampshire Basin, where the sequence has been partially eroded, but the concealed geology of this area is poorly known and the evidence from the borehole data is inconclusive.

The formation thickens steadily northwards at outcrop from Cambridge to the River Humber. Nowhere is it complete in that area but only the higher beds have been removed by erosion and this thickening is largely a true depositional thickening. Kimmeridge Clay is absent due to erosion across the Market Weighton axis but reappears as a relatively thick, and much faulted sequence, in the Vale of Pickering in North Yorkshire.

The position of the zero depositional isopachyte, which may or may not have been coincident with the Kimmeridgian shoreline, cannot be determined with confidence. Around the edges of the London Platform, where its feather edge might have been preserved, the Kimmeridge Clay is rapidly overstepped by the nearshore, coarsely sandy facies of the Lower Greensand. At one locality, however, there is sufficient borehole data to attempt to reconstruct the position of the original limit of the Kimmeridge Clay.

Between Denver Sluice and Mundford the preserved Kimmeridge Clay thins from about 60m to 8m. This thinning is partly due to overstep of the formation by the Sandringham Sands (Fig. 34) and partly to attenuation within the Kimmeridge Clay. The attenuation between Beds 1 to 30 in these two boreholes and the intervening Severals House Borehole is very regular (Fig. 38). To the east of Mundford the Breckles, Great Ellingham and Rocklands boreholes (Fig. 30) proved Lower Greensand resting on Middle Jurassic rocks (Gallois in Cox, F.C. et al., in press).

By assuming the same rate of overstep by the Sandringham Sands, and the same rate of attenuation in the Kimmeridge Clay south eastwards from the Mundford C Borehole as occurs between it and the Denver Sluice and Severals House boreholes, it is possible to predict the positions of the probable limit of the modern subcrop and the original depositional limit (Fig. 38). The subcrop probably extends for only 2km beyond the Mundford C Borehole; the projected depositional limit of the base of Bed 30 (the youngest Kimmeridge Clay preserved in the borehole) is about 8km. Evidence is given in Section 2.4.5 to suggest that the maximum extent of the Kimmeridge Clay was during the deposition of Bed 24 or soon after; if this is correct, the original limit of Bed 30 was similar to the maximum for the formation.

The evidence provided by the variations in the preserved thickness of the Kimmeridge Clay, and that of its inferred original thickness, does not by itself enable a Kimmeridgian palaeogeography to be built up. The distribution of thicknesses onshore in England suggests that two basins of deposition, North Yorkshire and the Hampshire Basin/Weald, were separated by an area of thin sedimentation adjacent to a land area

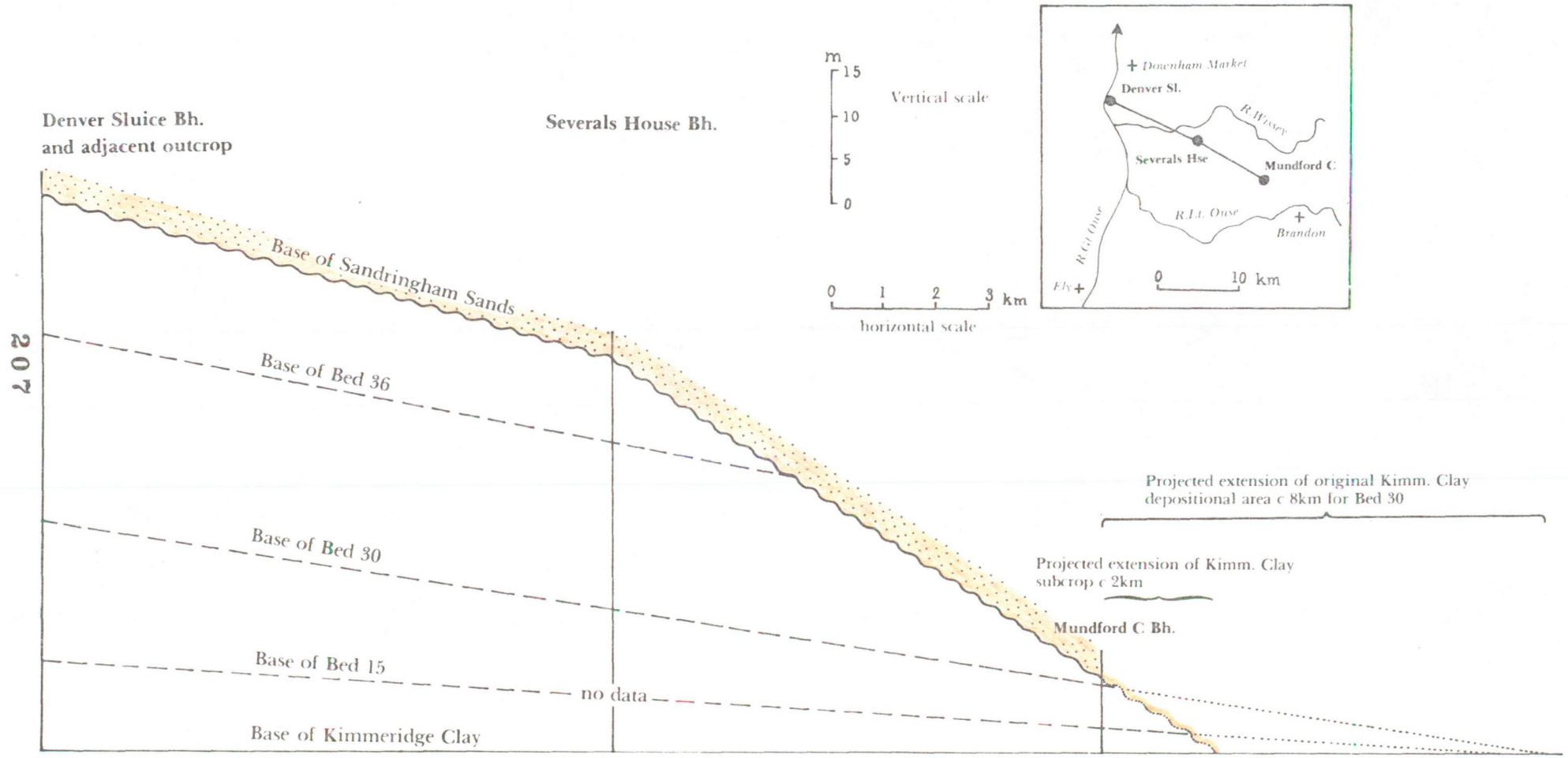


Figure 38. Geometrical construction to estimate the original depositional limit of the Kimmeridge Clay in south-west Norfolk.

formed by the London Platform.

The data from offshore boreholes shows these apparent basins to be merely embayments on the edges of much larger basins (Fig. 39). These occupied parts of the North Sea, the English Channel and Western Approaches and the Celtic Sea (no onshore representative of the Kimmeridge Clay). The evidence described above suggests that a shoreline was present in south-west Norfolk, and a similar situation probably existed around the edge of the London Platform and its extension south eastwards into France. The distribution of Mesozoic rocks in Britain suggests that shorelines are also likely to have been present in northern England, south west England, Wales (Fig. 40) and Scotland, but no direct evidence has survived in any of these areas.

Evidence from oxygen isotope and palaeontological studies suggests that the Kimmeridge Clay was deposited in a tropical, marine environment. Under such conditions, coral reefs comparable to those of the underlying Oxfordian might have been expected to have developed in nearshore areas in Kimmeridgian times. The Corallian Beds around the edge of the London Platform include a great variety of lithologies indicative of deposition in nearshore environments under subtropical or tropical climates. These include coral reefs, detrital shell banks, oolite and pisolite banks, lagoonal and intertidal deposits and algal mats (e.g. Arkell, 1933; Talbot, 1973). No similar lithology has been recorded in the Kimmeridge Clay, either at outcrop or in boreholes. In the Corallian Beds, the limestones are well exposed and have been extensively quarried; any hard bands in the adjacent Kimmeridge Clay outcrop are unlikely to have been overlooked. The nearest equivalent to the Corallian Beds lithologies in the Kimmeridge Clay is the Abbotsbury Ironstone, a

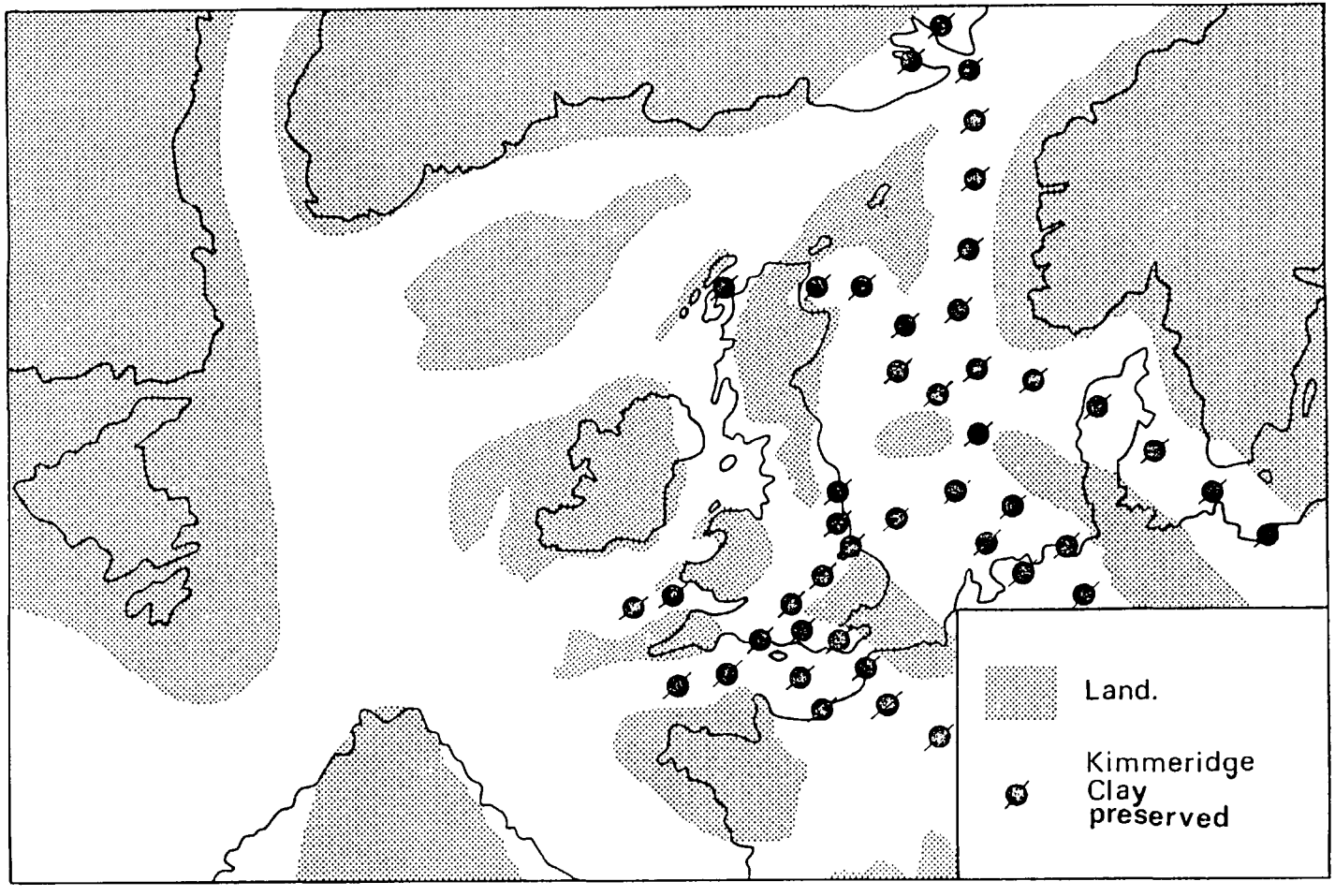


Figure 39. Palaeogeography of the North Atlantic and N.W. Europe in mid-Kimmeridgian times.

limonite-oolith sandstone. This has been described by Brookfield (1973a) as a probable offshore bar.

The evidence from Britain as a whole is no more helpful. The Kimmeridge Clay of Cromarty, Skye, Sutherland and the northern North Sea consists largely of argillaceous deposits as in England. Even the much quoted occurrence of large loose blocks of the reef-forming corals Isastraea oblonga (Fleming) and Stylina alveolata (Goldfuss) in the boulder beds of the Kimmeridge Clay of Sutherland, cannot be regarded as unequivocal evidence of reefs of Kimmeridgian age. Bailey (1928) suggested that these corals were derived from reefs built in shallow water on the landward side of the Helmsdale Fault and were therefore contemporaneous with the boulder beds. No Mesozoic rock is preserved on the landward side of the fault in the area adjacent to the present-day Kimmeridge Clay outcrop and it cannot now be proved that the blocks are Kimmeridgian in age. Both species of coral are known from the Oxfordian and could have been derived from former outcrops of Corallian Beds on the landward side of the fault when the Helmsdale Fault became reactivated in Kimmeridgian times. Shallow-water Corallian shelly limestones crop out on the landward side of the Helmsdale Fault at Brora, within 5 km of the present day Kimmeridge Clay outcrop.

Discussion of the palaeogeography of N.W. Europe during Kimmeridgian times is beyond the scope of the present work, but recent reconstructions (e.g. Enay, 1980) are in accord with that envisaged here for the English Kimmeridge Clay. The distribution of the latter suggests that it was deposited on a broad marine shelf on which small islands separated basinal areas, but not necessarily deep water, in which sedimentation was concentrated.

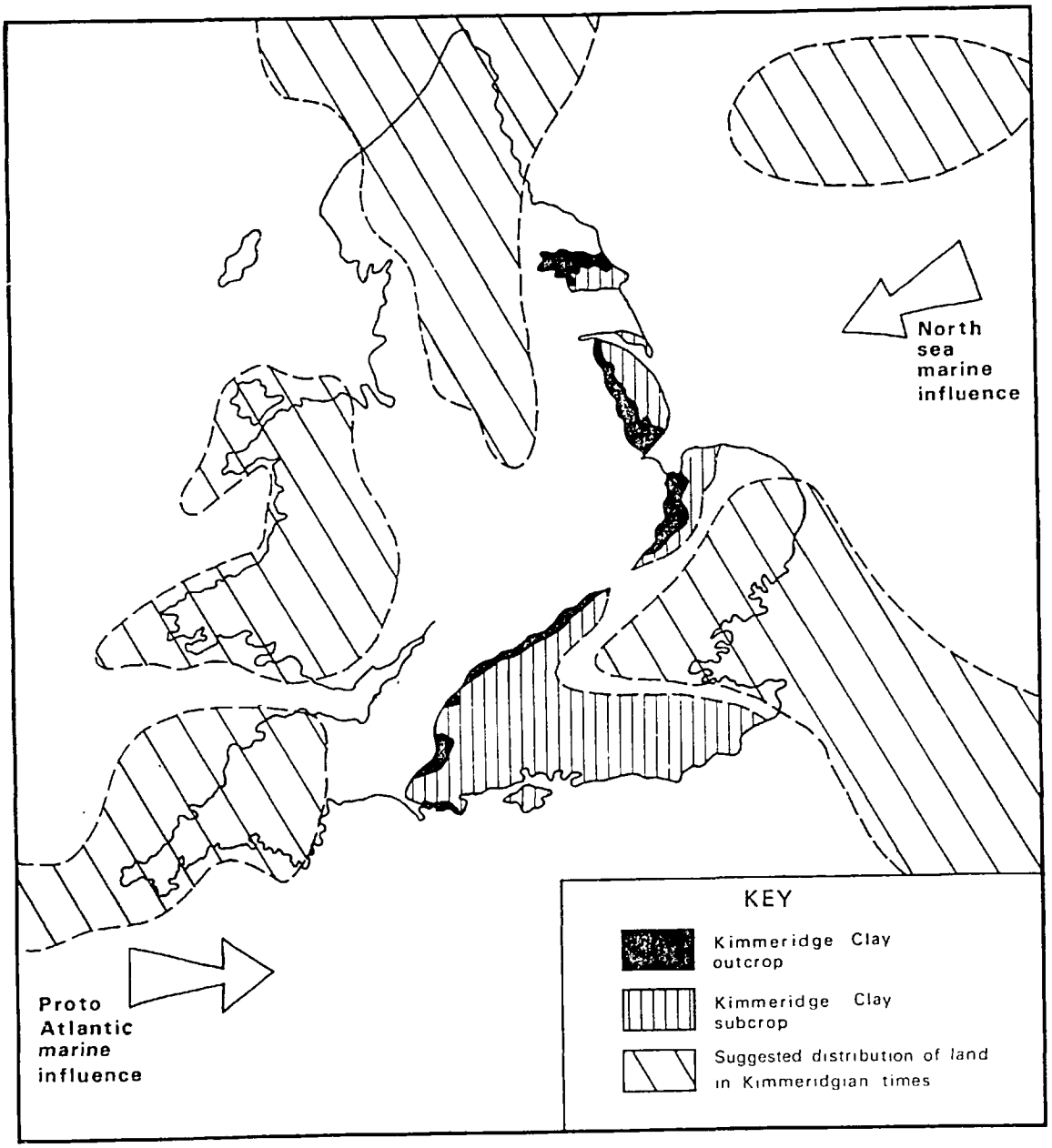


Figure 40. Palaeogeography of southern Britain in mid-Kimmeridgian times.

The critical question in Norfolk is whether or not the London Platform was land at this time and therefore able to contribute to the siliciclastic content of the Kimmeridge Clay.

2.4.3 Sources of clastic materials

2.4.3.1 Clay minerals

Despite the potential difficulties of interpretation that can arise from their complex origins and transport histories and their possible subsequent diagenetic transformations, it is nevertheless useful to attempt to determine the provenance of the relatively simple clay-mineral compositions recorded from the Kimmeridge Clay of Norfolk. Such an attempt might enable some of the factors that could have affected the clay mineralogy to be identified and considered in the light of the probable depositional and tectonic history of the Mesozoic rocks of East Anglia.

X-ray diffraction analyses have shown that the clay-mineral fraction of the Kimmeridge Clay of Norfolk is composed of clay mica, kaolinite, chlorite, vermiculite, smectite and mixed-layer minerals made up largely of randomly interlayed clay mica, smectite and vermiculite. Considering the clay minerals class by class the following comments can be made:

(i) Clay mica usually occurs in marine sediments as detrital high temperature muscovite whose grain size depends upon the nature of its transportation history (or histories if re-worked), or as fine-grained sericite and degraded mixed-layer micas derived from weathering and soil formation in most climates except those that form laterites. The structure of fresh muscovite is not appreciably affected by transport in water but degraded, open-structure

micas can adsorb potassium when transferred from a fresh to a brackish or marine environment and develop more ordered structures. During diagenesis all clay micas become progressively more perfectly crystallized and ultimately give rise to the micas or mica-schists.

Neoformation to produce authigenic micas is theoretically possible in marine sediments, but the process is believed to occur so slowly as to make a negligible contribution to the clay-mineral content of all but the purest limestones or the most condensed mudstone sequences.

(ii) Kaolinite is a weathering product of all rocks under strong leaching conditions; it is not neoformed in sediments. It is little affected by freshwater so that, after transport, freshly formed kaolinite can be indistinguishable from that derived from older kaolinite-bearing sediments. Kaolinite is thought to be slowly transformed to illite in marine environments.

(iii) Chlorite in marine sediments can be derived from one or more of a number of sources, the more important being the partial weathering of ferromagnesian minerals in temperate to cold climates, erosion of chloritized igneous rocks and chlorite-bearing sediments, and neoformation in magnesium and iron-rich environments. Chlorite can also be formed by the diagenesis of degraded micas, smectites, vermiculites, mixed-layer minerals and chamosite (Fig. 41 after Perrin 1971, Fig. 1). Chlorite is less stable in freshwater than either clay mica or kaolinite and is thought to survive as a detrital mineral only where a combination of minimal leaching during weathering has been combined with rapid transport to a marine environment.

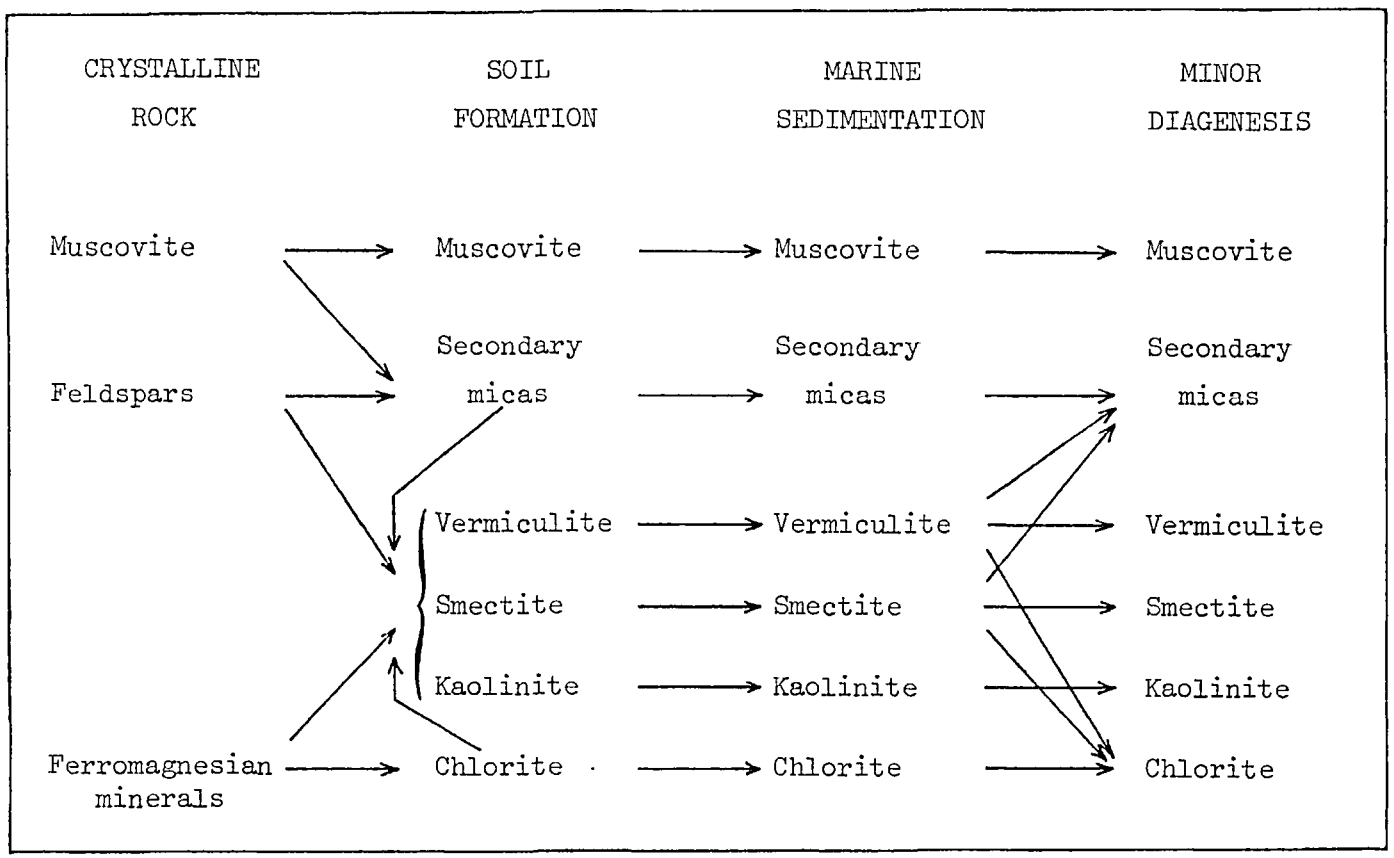


Fig. 41. Formation of detrital clay minerals (after Perrin,1971).

(iv) Smectite forms in three principal ways; by the degradation of clay micas under suitable weathering conditions, from the decomposition of volcanic ash (either subaerially or in the basin of deposition) and by neoformation in marine environments. Smectite is stable in sea-water but is capable of diagenetic alteration to mica and chlorite. Mixed-layer minerals, such as the clay mica/smectite mixtures recorded in the Kimmeridge Clay, represent a degree of degradation in the mica lattice (due to weathering) intermediate between that of mica and smectite.

(v) Vermiculite in clays is a weakly-bonded mica that mostly forms as irregularly interlayed mixtures with clay mica, chlorite and smectite during weathering. It embraces a poorly defined, broad range of mica structures intermediate between those of the clay minerals described above. Discrete vermiculite is rare in the Kimmeridge Clay. Perrin (1957) noted up to 10% of the mineral in samples from Norfolk and Cambridgeshire (Table 6). These came from shallow exposures where the vermiculite is likely to have been formed by recent weathering.

Clay mica and kaolinite dominate almost everyKimmeridge Clay sample analysed. Quantitative estimates of the clay mica and kaolinite contents of the Kimmeridge Clay of Norfolk suggest that clay mica is two to three times more abundant than kaolinite in most samples (Table 12; derived from analyses by Merriman and Jeans in Gallois, 1979c). Griffin et al. (1968) have noted that, at the present day, kaolinite is concentrated in the coastal regions in low latitudes and Hallam (1975, p. 31) has therefore suggested that the ratio clay mica to kaolinite provides a useful indication of depositional environment.

Borehole	Kaolinite % Range	Kaolinite % Average	Clay mica % Range	Clay mica % Average	Expansible minerals % Range	Expansible minerals % Average	Clay mica/Kaolinite ratio Range	Clay mica/Kaolinite ratio Average
Marton	28 to 44	36	28 to 57	42	8 to 34	22	0.7 to 1.8	1.2
Reighton	19 to 41	28	28 to 67	45	14 to 35	27	0.7 to 3.5	1.6
Donington on Bain	17 to 33	26	38 to 58	50	11 to 39	24	1.7 to 2.6	2.0
North Runcton	15 to 25	20	43 to 71	54	9 to 41	26	1.8 to 3.6	2.7
Hartwell	6 to 25	19	27 to 76	50	7 to 67	31	1.8 to 5.2	2.6
Swindon	12 to 23	20	44 to 62	52	19 to 42	28	2.2 to 3.8	2.6
West Lavington	16 to 27	22	37 to 56	48	22 to 47	30	1.6 to 2.7	2.2
Tisbury	12 to 28	22	33 to 68	48	9 to 55	30	1.6 to 3.0	2.2
Portesham	13 to 34	23	31 to 63	53	9 to 51	24	1.7 to 3.8	2.3
Encombe and Kimmeridge Bay	15 to 27	22	44 to 70	53	10 to 39	25	1.6 to 2.2	2.4
Foudry Bridge	14 to 25	21	46 to 77	58	<1 to 38	21	2.2 to 3.9	2.8
Warlingham	14 to 27	19	43 to 77	60	<1 to 37	21	2.2 to 4.2	3.2

Table 12. Summary of quantitative results of XRD analyses of clay minerals (see Figure 2 for borehole sites).

Grim, however, in a review of the origin and occurrence of clay minerals (1968, pp. 479-574), had already shown such generalisations to be gross over-simplifications because the clay mineralogy of modern sediments is related to a number of factors. In fresh-water and near-shore marine environments the most important of these are the nature of the source rocks and the climate acting on those rocks. Clay mica, kaolinite and chlorite are common components of recent sediments, with kaolinite locally abundant in nearshore areas. There continues to be disagreement concerning the degree of alteration that kaolinite undergoes to clay mica when transferred from fresh to saline water. Grim (1968, p. 534) quotes examples of drainage systems in which the clay mica-kaolinite ratio increases as more marine conditions are approached, and examples in which this ratio remains very high throughout the drainage system from river to near-shore marine shelf. In addition, differing floculation rates in sea-water can cause lateral variations within the clay mica-kaolinite ratio even within a constant environment. These rates themselves vary considerably in response to the buffer action arising from the presence of other clay and organic material in the sea-water.

The clay-mineral constituents of the weathering products from most land areas consist largely of degraded clay mica, chlorite, kaolinite and smectite from which the alkalis have been partially leached. These degraded minerals can react with the alkaline environment provided by sea-water by adsorbing potassium and magnesium. In the case of clay mica, chlorite and kaolinite this adsorption effect can cause a regeneration of a previously disordered mica structure. In the case of smectite, Milne and Earley (1958) have suggested that the adsorption of potassium and magnesium causes the mica structure

to collapse and yield clay mica and chlorite. Other authors have reported the transformation of kaolinite to clay mica by a similar process. Harley et al. (1963), using potassium-argon dating techniques on clay mica, have shown that many sediments contain a mixture of old (detrital) clay mica and young (presumed authigenic) clay mica.

Because of these complications the clay mica/kaolinite ratio in modern sediments is not a reliable indicator of depositional environment. Rocks rich in kaolinite indicate that they have been derived either from a source area undergoing weathering under strong leaching conditions, or one in which kaolinite-rich sediments crop out. If the rocks are marine, they may indicate that rapid sedimentation and burial occurred to enable the kaolinite to survive in an environment in which it is unstable. Marine sediments with a low kaolinite content merely indicate the presence of a kaolinite source somewhere in the catchment area.

The clay mica/kaolinite ratios for the Kimmeridge Clay of the English outcrop and subcrop show a broad pattern in which the higher ratios occur close to the London Platform, at North Runcton, Hartwell, Swindon, Foudry Bridge and Warlingham, and lower ratios occur in the North Yorkshire and Wessex depositional basins (Table 12). This is the pattern that would be expected if the ratio increases as the rate of sedimentation decreases, due to the transformation of kaolinite to clay mica whilst in contact with sea-water. Little comment can be made about the sources of the clay mica and kaolinite from these ratios alone; the high kaolinite contents in North Yorkshire may indicate proximity to a kaolinite-rich source.

The common presence of chlorite in the Kimmeridge Clay of Norfolk, albeit as a minor accessory mineral, and its comparative scarcity at

the same stratigraphical level in Lincolnshire (Table 4) may indicate derivation from different source areas. The Kimmeridge Clay in eastern England is unlikely to have ever been sufficiently deeply buried for diagenetic chlorite to form (see below). Furthermore, the Kimmeridgian climate was probably tropical and not conducive to the formation of chlorite by weathering of ferromagnesian minerals. The most likely sources of chlorite in Norfolk are outcrops of chlorite-bearing rocks. The relative instability of chlorite in freshwater suggests that it would need to be rapidly transported to the sea from such a source.

No igneous or high grade metamorphic rock is known from East Anglia that could have acted as a chlorite source. Chlorite-bearing rocks of believed Precambrian age directly underlie the Mesozoic sequence beneath much of west Norfolk, Fenland and the east Midlands, but the subcrop of these rocks is everywhere covered by Triassic or Lower Jurassic rocks. However, beneath much of the southern and central parts of East Anglia Cretaceous rocks are underlain by indurated, poorly cleaved, marine Lower Palaeozoic mudstones (Fig. 42). These are likely to be rich in diagenetic chlorite, as are the comparable rocks at outcrop in England and Wales. It is also possible that parts of the Keuper Marl and Lias, both chlorite-bearing at outcrop in England, were re-worked around the edges of the London Platform to yield a little chlorite in Kimmeridgian times.

In addition to East Anglia, much of Wales, Cornwall and southern Scotland, areas composed largely of indurated Palaeozoic mudstones, were probably land in the Kimmeridgian (Fig. 40). The presence of chlorite in Norfolk in greater amounts than in Lincolnshire does not prove that Palaeozoic rocks were being eroded in East Anglia, because

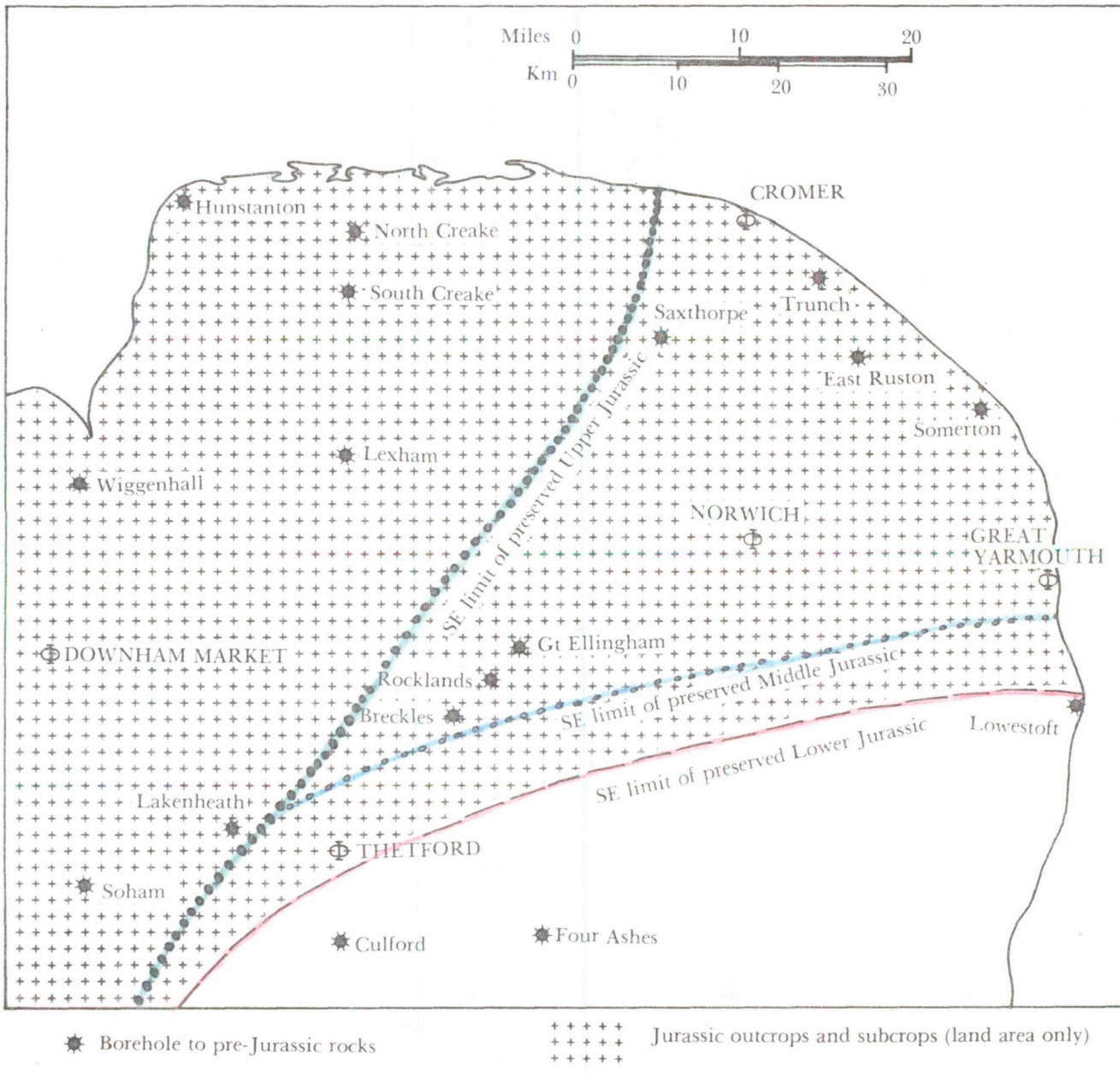


Figure 42. Distribution of the preserved Jurassic rocks in Norfolk.

such fine-grained material could be far travelled. However, if these Palaeozoic rocks were being eroded in close proximity to the area in which the Norfolk Kimmeridge Clay was being deposited, then chlorite would be commonly present.

The restricted occurrence of smectite in the calcium carbonate-rich lithologies, in which it may have been protected from diagenesis by the calcite cement, in the Kimmeridge Clay of Norfolk suggests that this mineral was formerly more abundant in the formation. The origin of smectite in ancient sediments has been the subject of much discussion in recent years, with controversy focused on the question of whether smectite-rich clays such as the Jurassic and Cretaceous fuller's earths are volcanic or neoformed in origin. The presence of small amounts of euhedral sphene, zircon and high-temperature feldspar in these fuller's earths has long been recognised, and Grim (1933) even recorded glass shards and relict ash structures in the Bathonian fuller's earth of Avon.

The main difficulty preventing general acceptance of the volcanic origin of this smectite was the absence of Mesozoic volcanic activity within the U.K. province. The discovery in recent years of Jurassic and Cretaceous volcanism in the North Sea has led to a reappraisal of the origin of all smectite-rich clays in the British Mesozoic and their almost universal acceptance as being derived largely from the submarine weathering of wind-borne volcanic detritus. In some cases this acceptance of their volcanic origin has undoubtedly gone too far and it is likely that neoformation of smectite has been underestimated.

Jeans et al. (1977) have confirmed the volcanic origin of the commercially useful deposits of fuller's earth in the Middle Jurassic and Lower Cretaceous in south-east England, and have suggested that

the ash source might have been a volcanic vent discovered beneath the Waddenzee in Holland (Cottencon et al., 1975). If this suggestion is correct, then this volcano may have been active at times other than the mid Jurassic and early Cretaceous and could have supplied ash to parts of southern England during the late Jurassic. Jurassic volcanicity has been reported from the northern North Sea (Howitt et al, 1975) and early Cretaceous volcanicity from south-west England (Wolf Rock; Harrison et al., 1977). Zimmerle (1979) has suggested that these were parts of widespread phases of volcanicity related to rifting phases in the North Atlantic.

Although smectite is rare in the Kimmeridge Clay of Norfolk and Lincolnshire it is reported (Perrin, 1957) to be the dominant clay mineral in parts of the Kimmeridge Clay of Buckinghamshire and Oxfordshire and is a major constituent in parts of the Dorset sequence. Brown and Du Feu (quoted in Perrin, 1971, pp. 132-3) have recorded clays with 75% and 60% smectite from Culham, Oxon and Aylesbury, Bucks respectively, and Cosgrove and Salter (1966) noted up to 35% smectite in clays from Dorset (Table 6). Elsewhere in Britain, Knox (1977) has recorded thin smectite-rich bands, which he has interpreted as rotted, waterlaid volcanic ashes, in the Kimmeridgian of Skye.

The presence of high smectite concentrations in the Kimmeridge Clay of Buckinghamshire, some 100 km from the Norfolk outcrop, is of particular interest because the two areas have similar tectonic and burial histories. Burst (1969) has suggested that the diagenetic transformation of smectite to clay mica does not commence below temperatures of 100°C*. At the present time in East Anglia this

* This has been demonstrated in practice by examination of variations in clay mineralogy with depth in deep hydrocarbon boreholes. For example, Foscolos and Powell (1979) have shown that the transformation of smectite and kaolinite to clay mica with depth of burial in Triassic to Cretaceous mudstones in boreholes in the North-west Territories of Canada, is a temperature dependent dehydration process that is not apparent at burial depths of less than about 5,500 ft (1680m). Similar studies in the Tertiary clays in boreholes in the North Sea failed to detect any major diagenetic change in clay mineralogy down to burial depths of more than 8 000 ft (2440m) (e.g. Karlsson et al., 1979, Fig. 5).

temperature is reached at about 2.5 to 3.0 km depth (Oxburgh and Richardson, 1978, Fig. 5 extrapolated), a much greater depth than the burial experienced by the Kimmeridge Clay of either Norfolk or Buckinghamshire.

In both areas the maximum burial depth of the Kimmeridge Clay probably occurred during the Oligocene, immediately prior to the Miocene folding that uplifted the Jurassic rocks of the East Midlands to their present position. At this maximum the overburden probably consisted of horizontal late Jurassic and early Cretaceous rocks (c100 to 150m), Chalk (c650 to 800m; the thickness of Maastrichtian Chalk removed prior to deposition of the Tertiary is unknown but by comparison with Denmark it is not likely to have exceeded 150m) and possible thin Eocene deposits (up to 100m), giving a maximum depth of burial of little more than 1 km. This depth could have been exceeded during the latter part of the deposition of the Chalk if the Chalk sea was much deeper than 100m. It is also possible that the heat-flow rate in East Anglia has been higher in the past than at present, but it is unlikely that the rate was ever sufficiently high to cause diagenesis of smectite. Estimates of the net global outflow of heat suggest that a peak was reached in the late Cretaceous, but that the total geothermal heat loss at that time exceeded that of the present by no more than 15% (Smith et al., 1980). Finally, it is improbable that the heat-flow rate was sufficiently different between Norfolk and Buckinghamshire to cause the destruction of smectite in the former area and not in the latter.

In the present limited state of knowledge of the regional pattern of clay-mineral variations in the Kimmeridge Clay, it seems probable that these differences in smectite content are an original depositional

feature. Small amounts of neoformed and/or secondarily derived smectite probably occur in the Kimmeridge Clay throughout East Anglia. In addition, large amounts of smectite of unknown origin occur in parts of the Kimmeridge Clay of the more southerly parts of England. It may be no coincidence that the most smectite-rich parts of the Kimmeridge Clay recorded to date lie at a similar latitude to some of the Bathonian and Aptian fuller's earths and their supposed volcanic source beneath the Waddenzee.

There is little published discussion of the origin of the clay minerals in the Kimmeridge Clay or other Jurassic clays. Three main possibilities exist for those in the Kimmeridge Clay. That they are derived from:

(i) older argillaceous Jurassic sediments such as the Lias, Oxford Clay and Ampthill Clay

(ii) Palaeozoic sediments exposed in relatively near areas such as East Anglia, Cornwall and Wales

(iii) Palaeozoic and Precambrian sediments, metasediments and igneous rocks exposed in more distant areas such as Scotland, France and Scandinavia.

The first can be largely discounted by considering the present and probable past distributions of the Jurassic clay formations beneath East Anglia. Donovan et al. (1979) have shown that the Rhaetic and Lower Lias progressively overstep the London Platform in such a way that a complete Rhaeto-Liassic sequence (Rhaetian, Hettangian, Sinemurian and Lower Pliensbachian) was probably only deposited beneath north-west Norfolk; only Lower Pliensbachian sediments were deposited beneath south-west Norfolk and north-west Suffolk. Lower Lias is absent beneath much of the central part of East Anglia and it could be argued that Liassic

mudstones deposited in that area became a major source of clay minerals in Kimmeridgian times. This is unlikely for the following reasons. Firstly, the rate of overstep of the Lower Lias onto the London Platform described by Donovan et al. (1979, Fig. 4) is such that only the youngest zones, those of Tragophylloceras ibex and Prodactylioceras davoei, are likely to have ever been deposited south-east of a line from Oxford to Lowestoft. Where fully preserved in boreholes adjacent to the London Platform their total thickness is less than 50m. They could therefore, at most, have provided only a small supply of sediment to later Jurassic formations.

Secondly, the Lower Lias is overlain with marked unconformity by arenaceous, oolitic (chamositic) Middle Lias or by calcareous and arenaceous Middle Jurassic (Bathonian and Bajocian) sediments everywhere around the edge of the London Platform. The younger parts of the Lower Lias, together with any argillaceous Upper Lias that might have been deposited in areas marginal to the platform, were either removed by erosion in the mid Jurassic or are now separated from the overlying Upper Jurassic by Middle Jurassic sediments. They were not therefore available as a clay-mineral source in Kimmeridgian times.

A similar argument can be used for the Oxford and Ampthill clays. The Kimmeridge Clay is separated from the Oxford Clay by the Ampthill Clay everywhere in its East Anglian subcrop. The Kimmeridge Clay rests unconformably on the Ampthill Clay, but the ammonite evidence suggests that the time break is small. The subcrops of the Oxford and Ampthill clays locally extend beyond that of the Kimmeridge Clay around the margins of the London Platform, but this present day distribution is largely due to late Jurassic folding in which all three formations acted as a single unit. There is no evidence to

suggest that either the Oxford Clay or the Ampthill Clay formerly had an extensive outcrop on the London Platform that could have been eroded during the Kimmeridgian.

The question of the former outcrops of Jurassic clay in more distant areas is difficult to resolve, and it could be argued that Liassic outcrops that formerly covered areas such as Wales were a source of clay minerals in the late Jurassic. However, the distribution of Jurassic rocks onshore and offshore in the United Kingdom, suggests that the main palaeogeographic elements were relatively constant and that deposition recurred in much the same areas throughout the period, the intervening areas receiving little or no sediment.

The possibility of Precambrian and Palaeozoic sources, both near and distant, has been discussed above with respect to particular clay minerals. The great thickness of early Palaeozoic mdustones that directly underlies Cretaceous rocks beneath much of East Anglia remains the most probable source of the bulk of the clay minerals in the Kimmeridge Clay of Norfolk.

2.4.3.2 Calcium carbonate

Much of the calcium carbonate in the Kimmeridge Clay is preserved as recognisable shell and other biogenic material or as diagenetic concretions, and its origin is obvious. However, large amounts of finely crystalline calcite (< 2μm) are present at many levels, notably in the pale grey mudstones that form the upper parts of the Type A and Type B rhythms and in the thick highly calcareous mudstones of Beds 18, 30 and 44. There, SEM studies show the mudstone matrix to be composed largely of fragments of calcite crystals that cannot obviously be related to either microalgae such as coccoliths and calcispheres, or micritized shell debris.

The limited oxygen isotope data available for Kimmeridgian carbonates indicates that the coccoliths in the coccolith-rich limestones lived in water at about 25°C (Irwin et al., 1977). The record by Seward (1911-13) of 65 species of terrestrial plant in the Kimmeridge Clay of Sutherland, the majority of which have tropical affinities, supports the suggestion that the Kimmeridgian seas were similar in temperature to those of the modern tropics. At the present time, large quantities of lime mud are accumulating on many subtropical and tropical continental shelves such as those of the Bahama Banks, British Honduras, Cuba, Florida and the Persian Gulf. Much of this mud is composed of aragonite needles and ooids, and a large part of the extensive literature on recent carbonate sedimentation is devoted to its precise method of formation.

There is general agreement that lime mud can be observed to form by:

(i) mechanical abrasion of shells and skeletal debris to form individual crystals

(ii) breakdown by boring sponges and algae

(iii) collapse of calcareous skeletons of certain organisms (mostly algae) when their organic parts decompose.

There is less agreement as to whether or not aragonite mud naturally precipitates from water supersaturated with respect to $CaCO_3$. Smith (1940) studied the sea-water carbonate chemistry of the Great Bahama Bank and measured salinity, temperature, pH and alkalinity. He concluded that aragonite was precipitated inorganically and that the rate of precipitation was directly related to salinity. Black (1933) had earlier reached a similar conclusion and believed that high salinities (up to 40‰) were an essential condition of the process.

Cloud (1962) confirmed Smith's findings that the muds were chemical precipitates formed by supersaturated open-ocean water coming into contact with suspended aragonitic sediment that acted as nucleation centres. In addition, Cloud suggested that 'whitings', water cloudy with aragonite needles 1 to 2 μm long, were formed in the same manner. Although Cloud believed the bulk of the aragonite to have been chemically precipitated he recognised that similar needles were produced by algae. Studies in the Persian Gulf (Wells and Illing, 1964) also suggested an inorganic origin for part of the carbonate muds, but some later workers (e.g. Stockman et al., 1967; Neumann and Land, 1969) claimed that such muds formed solely from the decomposition of codiacean and dasycladacean algae.

Much of this argument concerning the origin of carbonate muds has little relevance to ancient environments because the conditions required for both inorganic and organic formation are similar and very specific. All the modern aragonite-rich muds described to date are forming in shallow seas (mostly < 30m depth) in subtropical or tropical climates where a high evaporation rate produces water super-satured with respect to $CaCO_3$. Some of this mud is swept into deeper water, but nowhere has it been observed to form deposits comparable in extent to those of its source areas.

Aragonite needles have not been observed in the Kimmeridge Clay in the present work. This could be because they were never formed or because they have subsequently inverted to calcite. Aragonite needles have rarely been described from ancient sediments and none has been recorded from the Jurassic calcareous oolites of the U.K., a lithology that is believed to have formed in a 'Bahama Banks' environment. The absence of calcareous ooliths, oncoliths, pelloids,

coral and shell brash from the Kimmeridge Clay, strongly suggests that the Kimmeridgian sea was too deep and/or insufficiently saline for either carbonate precipitation, or secretion of carbonate by benthonic algae, to occur on a large scale.

It is therefore assumed that the calcite mud in the Kimmeridge Clay that cannot be attributed to particular organisms in electron micrographs, is also biogenic and derived from the breakdown of such organisms. The common occurrence of aragonitic shell material in the Kimmeridge Clay in Norfolk, and the rarity of dissolution or recrystallisation features in even the most fine-grained calcitic debris, suggests that much of this fine-grained material was deposited as calcite. This may be low-magnesian calcite similar to that responsible for the unindurated nature of the Chalk (see Hancock 1976 for review of chalk petrology). The bulk of the unidentified calcite in the Kimmeridge Clay is probably derived from coccoliths, calcispheres and foraminifera and the more calcareous parts of the Kimmeridge Clay are therefore similar in composition to the most argillaceous parts of the Chalk.

2.4.3.3 Phosphate, pyrite, quartz

It has long been recognised that the phosphate in marine muddy sediments is derived partly as a sediment and partly by ion exchange at the sea-water sediment interface. Phosphate-rich, highly oxygenated waters cause insoluble ferriphosphates to accumulate in the sediment; under the action of reducing decomposition processes this can be converted to the more soluble ferrophosphate and may then react with hydrogen sulphide to precipitate pyrite and phosphates. Although the basic chemistry of these reactions is simple, the rôles played by the chemistry of the sediment and its infauna and bacteria, and that played by variations in the salinity, pH, degree of oxygenation, temperature

and rate of circulation of the sea-water, in the formation of the various type of phosphatic nodule are largely unknown. Some of these aspects have been studied but a complete synthesis has yet to emerge.

Heutschel and Wattenberg (1930) were the first to show that the regional distribution of phosphate is related to plankton, high latitudes having higher contents of both phosphate and plankton than low latitudes. Phosphate-rich areas occur in low latitudes but are restricted to local areas of upwelling, notably off the coasts of Peru-Chile (Baturin et al., 1972) and South West Africa (Burnett and Veeh, 1977). There, phosphate formation is associated with organic-rich sediments that may be modern analogues of Kimmeridgian oil shales. Holocene phosphate formation has recently been recorded from the edge of the continental shelf along the east coast of Australia (O'Brien and Veeh, 1980) in an area of only moderate upwelling and such deposits may be more widespread than had previously been thought. In almost all marine examples described to date phosphate, pyrite and high organic contents occur together.

Most of the pyrite in the Kimmeridge Clay occurs as replacement of shells, of sediment in burrows or as concretionary crystals, and is likely to be diagenetic. Tiny pyrite framboids are also present, most abundantly in the organic-rich mudstones. Similar Jurassic occurrences have been assumed to be diagenetic (e.g. Love, 1964), but a suggestion by Degens et al. (1978) that framboids are being formed by anaerobic bacteria within the lower part of the water column in the Black Sea, may indicate that some ancient examples should be regarded as allogenic. No criterion has yet been suggested that would enable the two types of framboid to be distinguished.

Quartz occurs in the Kimmeridge Clay in two forms, as coarse silt

or very fine-grained sand in the basal beds of the Type A rhythms, and as fine silt disseminated throughout the mudstones. The coarser material is presumed to be of fluvial derivation. The finer material probably has a mixed fluvial and aeolian origin. Its ubiquitous distribution throughout the mudstones and its lack of sorting into sizes or shapes suggest sources unrelated to the basin of deposition. Some could have come from the London Platform, but much of it is < 10μm in size and could have come from very distant sources. Silt-grade quartz, lifted into the upper atmosphere by Saharan dust storms, has been recorded in rain falling on the American coast over 3000 miles away (Prospero and Carlson, 1972).

2.4.4 Faunal and floral evidence

2.4.4.1 Introduction

Taken as a whole, the Kimmeridge Clay contains a rich fauna including ammonites, brachiopods, crinoids, serpulids and marine bivalves, foraminifera and ostracods that could have tolerated only minor deviations from normal (c 35‰) marine salinity. Most individual bedding planes, however, carry a predominantly low diversity - high density fauna and at some horizons the diversity is particularly low. Even at these latter levels the fauna remains wholly marine. In general, the most diverse faunas occur at the bases of the Type A and Type B rhythms, and the least diverse in their upper parts. In addition, there is a slow decrease in diversity with time in the Kimmeridge Clay. The floral evidence provided by the coccoliths and dinoflagellates also suggests deposition in a normal-salinity environment in most parts of England, including Norfolk, throughout the Kimmeridgian. Variations in the coccolith diversity (Table 9) at particular levels in the Kimmeridge Clay of the Weald may reflect a local fluviatile influence. None of the fauna or microflora can be

attributed to any specific water depth. All the bivalve and gastropod genera have modern representatives that live on continental shelves; Lingula is commonly quoted as indicative of shallow (< 20m) water, but this may not always have been the case.

2.4.4.2 Origin of the mudstones

It is difficult to assign precise depositional environments to the lithological/faunal associations described in Section 2.2.3, but the environments of the seven mudstone lithologies can be related to one another in terms of probable energy and water depth. The origin of the remaining two associations, oil shales, is discussed in Section 2.4.4.3. The faunal evidence shows all the associations to be fully marine (c 35‰); the possibility of minor salinity variations in response to local conditions cannot be ruled out at some levels.

The presumed environments of the seven mudstone associations shown in Fig. 43 are based on the following evidence:

(i) The coarsest grained lithologies in the Kimmeridge Clay are the phosphatic pebble beds that occur at the bases of the Type A rhythms and the siltstones that overly them. The water-worn nature of the pebbles and shells, the rich, diverse fauna and the intensely bioturbated nature of these deposits indicate deposition in a well-aerated, turbulent environment above the wave-base of storms. The presence of mud and fine silt suggests that wave action was sporadic, and the upward passage of the pebble beds into muddy siltstones suggests that the frequency with which the sediment was affected by strong currents or waves diminished with time.

The next shallowest environment in the Kimmeridge Clay is presumed to be that in which the Pinna-Thracia Mudstone and the Nanogyra

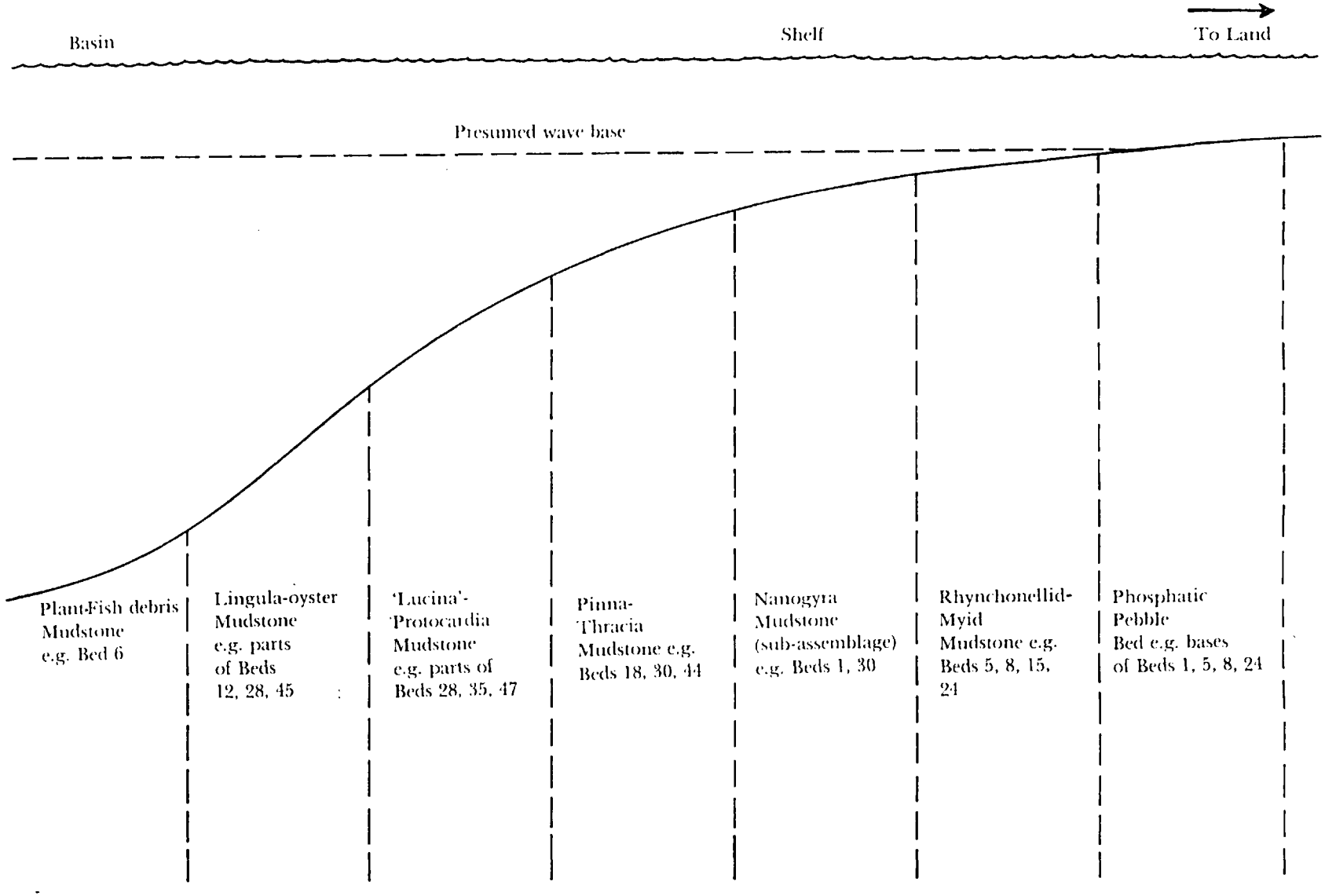


Figure 43. Diagrammatic section showing the relationship of the Kimmeridge Clay mudstone associations to their presumed environments.

Mudstone were deposited. These associations contain a low diversity fauna with, at some levels, a great abundance of individual species that probably indicates an environment that may have been subject to relatively large changes in salinity and/or temperature. The intensely bioturbated nature of the mudstones, the local abundance of serpulids, crustaceans, grazing trails and the presence of local coquinas composed almost entirely of Nanogyra virgula, all suggest deposition in shallow water. The abundance of the deep burrowing Thracia, the only common non-oyster bivalve, may also indicate generally inimical conditions. One modern, but shallower, equivalent of the Nanogyra Mudstone might be the 'mussel scalps' that occur in the intertidal and shallow subtidal parts of The Wash (Wingfield et al., 1979).

Lithological/faunal associations that can be matched in detail with those of the Pinna-Thracia Mudstone, occur in the Oxfordian Corallian Beds and Ampthill Clay. One of these beds, the Ringstead Waxy Clay of Dorset, was interpreted by Talbot (1973) as lagoonal in origin on the basis of its high density-low diversity fauna and its relationship to the adjacent sandstones and limestones of the Corallian Beds. Similar associations in the Ampthill Clay pass laterally in the Bedfordshire-Oxfordshire area into coral reefs and oolites of undoubted shallow-water origin (Wilson, 1968). There is no evidence in the Kimmeridge Clay of either a persistent or an extensive offshore barrier (the Abbotsbury Ironstone and the Elsham Sandstone may have acted as small, temporary shoals) that could have allowed a lagoon to develop. It seems more likely that the restricted nature of the fauna in this lithology in the Kimmeridge Clay was due to minor fluctuations in salinity caused by a combination of evaporation and variable, but inadequate, circulation within a relatively shallow sea that extended over very large areas.

The 'Lucina'-Protocardia Mudstone contains a more diverse benthonic fauna than the Pinna-Thracia mudstone but, even so, is characterized by low diversity and a great abundance of particular species. The presence of abundant ammonites indicates that there was no restriction on their movement into the area, and ubiquitous bioturbation shows that the sea-bed was readily colonised. Most of the preserved fauna of bivalves, gastropods, inarticulate brachiopods and foraminifera lived on or just below the sea-bed. Part of this fauna is also present in the Lingula-oyster Mudstone but there, the benthonic fauna (including bioturbation) is less diverse and less abundant. It therefore seems reasonable to assume that bottom conditions were less favourable in the Lingula-oyster Mudstone than in the Lucina-Protocardia mudstone. The only common benthonic fauna in the former lithology is Lingula and oysters that colonised ammonite shells and were not thereby in contact with the sediment. This paucity of infauna is presumed to indicate anoxic or poorly oxygenated conditions in the top layer of the sediment, a situation that is more likely to develop in relatively deep, still water than in shallow water. The Lingula-oyster Mudstone is therefore assumed to represent a deeper water environment than that of the 'Lucina'-Protocardia Mudstone.

The Plant-fish debris Mudstone is represented by only a few thin bands in the Kimmeridge Clay in Norfolk, but it is better represented in Lincolnshire and is likely to be well developed in the basinal sequences or those most distant from land. The presence of lamination and common fish and plant debris indicate a de-oxygenated sediment with little fauna and conducive to the preservation of organic material. However, bivalves in life position, and burrows lined with fragments of ammonite and bivalve shell in the sediment, and oysters and crinoids

on the sediment surface indicate that the sea-water was aerobic. This is the only association recorded in the Kimmeridge Clay worthy of the description 'black shale' and, by analogy with numerous similar shales, is presumed to have been deposited in still, relatively deep water.

It has been assumed in the above discussion and in Fig. 43 that all the associations observed in the Kimmeridge Clay of Norfolk formed solely in response to differences in water depth. The rhymthmic nature of the sequence suggests that widespread changes in sea level were a major factor, but climatic changes and tectonic events (which may themselves have been related to sea-level changes) must also have been influential. The differences between the Pinna-Thracia Mudstone and the 'Lucina'-Protocardia Mudstone might reflect a change in sea level, a change from an arid to a humid climate, a rejuvenation of the land areas or two or more of these features in combination. In the absence of either lithological or faunal features that are diagnostic of specific water depths these uncertainties must remain unresolved.

It should also be noted that the presumed depths in Fig. 43 are relative to one another. There is no evidence in Norfolk, and little in England as a whole, to suggest that the associations shown in Fig. 43 co-existed. At any particular time almost the whole of the English outcrop and subcrop was occupied by a single lithological/faunal association. Although the thicker sequences (e.g. those of North Yorkshire, the Weald and Dorset) contain proportionately more dark grey mudstone than thinner sequences such as that of Norfolk, the sequence of associations can be used to provide correlations throughout the country. Furthermore, the sequence of environments with time did not follow a regular progression from deep to shallow, or vice versa. The

Type A rhythms, as interpreted in Fig. 43, represent a shallow, turbulent environment (Phosphatic pebble bed and Rhynchonellid-myid siltstone) followed by rapid deepening (Lingula-oyster Mudstone and/or 'Lucina'-Protocardia Mudstone) and then shallowing (Pinna-Thracia Mudstone). The implication of this lateral persistence of the associations is that the Kimmeridge Clay of the present day land area outcrop and subcrop was deposited on a broad shelf; lateral passages from one association to another may be present at the seaward edge of this shelf, in areas such as the North Sea and Western Approaches, but adequate samples are not yet available from these areas.

2.4.4.3 Origin of the oil shales

Because of their potential economic importance as a source of hydrocarbons, naturally and artificially, oil shales have attracted considerable attention in recent years. In north-west Europe, the most extensive and potentially the richest oil shales, occur in the Jurassic, notably in the Lias in England, France and Germany, and the Kimmeridge Clay in England.

Oil shales range in age from Precambrian to Recent, although in Cambrian and older rocks they are uncommon because their organic content has usually been diagenetically altered to graphite. The distribution of oil shales through time shows two marked peaks, in the Permian and early Tertiary, which correspond to periods when proportionately large areas of the Earth were covered by lakes and shallow seas. This relationship is generally thought to be due to the common coincidence in such environments of the two most important requirements for the formation of oil shales, a prolific organic source and a means of preserving organic material in the sediment.

Most of the world's oil shales are thought to have formed from algae in lakes, brackish marine basins and embayments or in shallow shelf seas, in which the organic material has been saved from the destructive action of aerobic bacteria by falling into an anaerobic zone.

The world's largest oil-shale deposit and that which has been most extensively studied, the Green River Formation (Eocene) of the USA, is a well documented example of lacustrine (varying from fresh-water to hypersaline) deposition. Other, less well documented, but nevertheless undisputed, examples of freshwater/brackish marine (lake/lagoon) deposition include the Chattanooga Shale (Devonian-Carboniferous) of the USA, the Lothian oil shales (Carboniferous) of Scotland and the Fushun oil shales (Oligocene) of China. The Liassic and Kimmeridgian oil shales are unusual in the world context in that they are laterally extensive deposits that occur in fully marine sequences and their origin has, therefore, been the subject of some controversy.

According to Trask (1939), few modern typically marine sediments contain more than 10% organic matter; near-shore sediments generally contain between 1% and 8% and open-ocean sediments < 1%. More recently, Ryan and Cita (1977) have suggested that episodes of ocean-wide stagnation have occurred from time to time in the past during which organic-rich sediments accumulated in the open oceans. Kaplan and Rittenberg (1963) state that the highest organic content recorded in any contemporary marine environment is 23.4% in one of the Norwegian fjords. Forsman (1963) recorded up to 40 wt % of organic matter (mostly kerogen) in oil shales from the Kimmeridge Clay of the Dorset coast, and the potential oil yields of the comparable seams in Norfolk indicate that they contain 10 to 30 wt % organic matter.

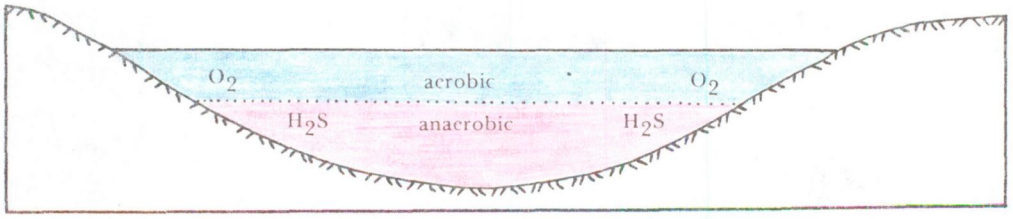
At first sight, the most attractive Holocene analogue of the

Kimmeridgian oil shales are laminated sediments forming on the floor of the Black Sea. They consist of light-coloured carbonate laminae composed largely of the single coccolith Emiliania huxleyi (Lohmann) (Bukry et al., 1970) and dark-coloured organic-rich clay laminae composed largely of land-derived clay minerals and chitinous dinoflagellates (Degens, 1979). The Black Sea is a large (1200 km x 400 km) land-locked,deep (absyssal plain at a depth of 2,200 m), density-stratified water body which has a complex Quaternary history that has included deposition in shallow to deep, and freshwater to hypersaline environments. During the Holocene, sedimentation has been dominated by the development of stable salinity layering in which by far the greater part of the depositional area lies below an O_2 - H_2S interface (Fig. 44, Example 1). This interface has migrated up and down the water column with time (Degens and Stoffers, 1976) and is currently at a depth of about 200 m. Below the interface the water column and bottom sediment is hydrogen-sulphide bearing, anoxic and therefore devoid of either benthonic or pelagic life. The algal content of the sediment is derived from pelagic coccoliths and dinoflagellates (Boon et al., 1979) that form seasonal blooms in the aerobic near-surface waters, largely within the photic zone.

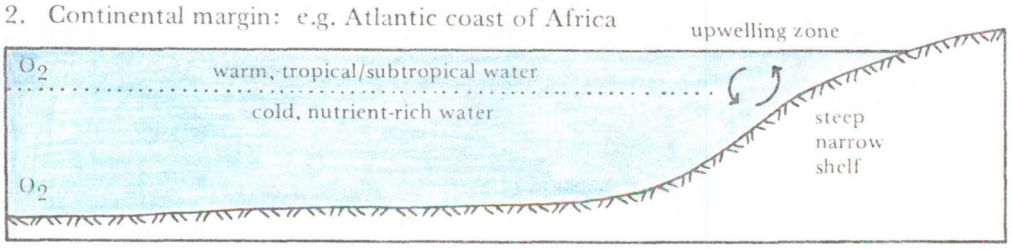
A similar, but more complex, origin has been postulated by Rossignol-Strick et al. (1982) for laminated organic oozes that formed on the floor of the eastern Mediterranean in the late Pleistocene. There, a layered water column is thought to have formed in response to floods of nutrient-rich, freshwater debouching from the River Nile.

Ancient examples of layered water bodies that gave rise to this type of laminated sediment are well known. Bradley (1931) was the

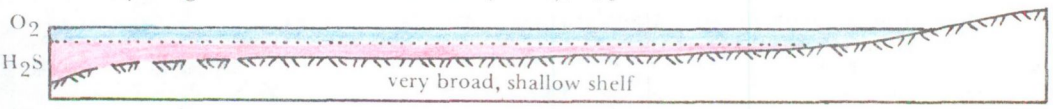
1. Barred basin: e.g. Black Sea, Norwegian fjords



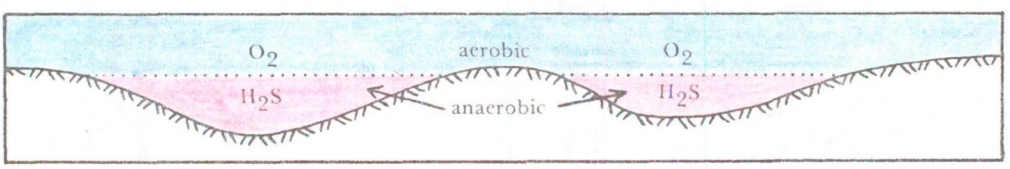
2. Continental margin: e.g. Atlantic coast of Africa



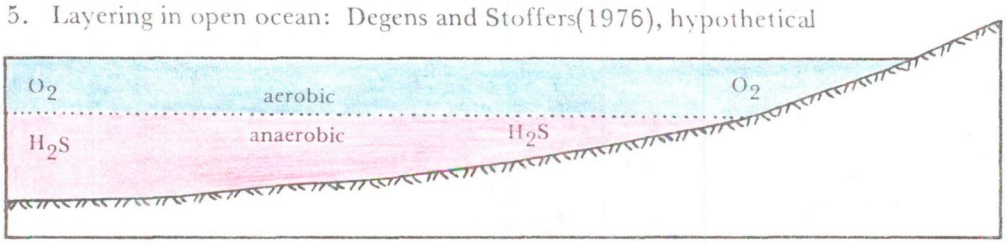
3. Layering on broad shelf: Hallam (1967), hypothetical



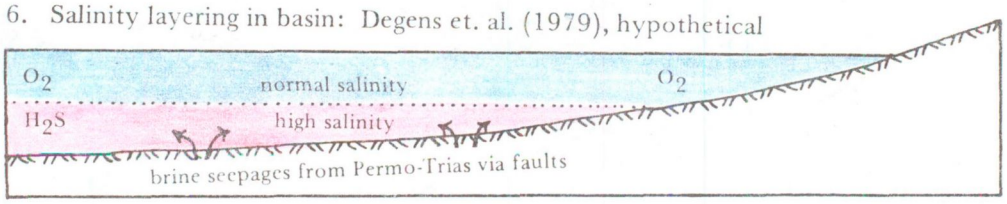
4. Layering in hollows on broad shelf: Hallam and Bradshaw (1979), hypothetical



5. Layering in open ocean: Degens and Stoffers(1976), hypothetical



6. Salinity layering in basin: Degens et. al. (1979), hypothetical



7. Algal blooms on shelf: present account, hypothetical

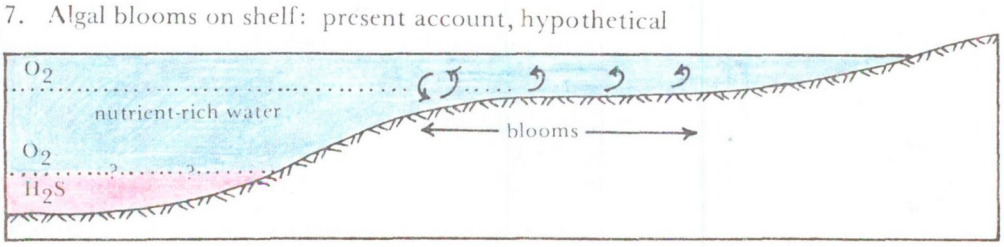


Fig. 44 Possible models for the depositional environment of the oil shales in the Kimmeridge Clay

first to suggest that fine alterations (couplets) of organic matter and mineral matter (mostly dolomite) in the Chattanooga Shale and the Green River Formation were formed from winter phytoplankton blooms and summer chemical precipitation (due to evaporation).

There is a marked similarity in algal composition and lithology between the couplets in the Green River Formation, the Holocene of the Black Sea and the laminated coccolith-rich/kerogen-rich bands that occur in the Kimmeridge Clay, especially those of the Dorset coastal sections where the last named are best developed. This similarity has prompted Tyson et al. (1979) to suggest that the oil shales and coccolith-rich bands in the Kimmeridge Clay were formed in a stratified water column directly analogous to that present in the Black Sea. The problem with this explanation is that it cannot account for all the faunal and sedimentary features that are present in the Kimmeridgian oil shales. Firstly, their observation that the oil shales are virtually devoid of indigenous fauna is true of only selected horizons in Dorset, notably the thickest and richest oil-shale seams (the Blackstone 0.62m thick and a small number of seams 0.10 to 0.4m thick), and is untrue of the majority of oil-shale seams in Dorset and almost all seams elsewhere in England. Secondly, fine coccolith/kerogen lamination is restricted to about six levels in Dorset (totalling less than 2 m of sediment in a succession of 500+ m) and is known only at single horizons at other localities. It is not, therefore, characteristic of the Kimmeridgian oil shales as a whole and cannot be used as an essential part of a rhythm, such as that described by Tyson et al. (1979, Fig. 3), to explain the origin of these oil shales in terms of a fluctuating O_2 - H_2S interface.

The similarity of the laminated bands in the Kimmeridge Clay to those in the Black Sea, or indeed those in the lacustrine Green River Formation, is due largely to the similarity of their planktonic contents and is consequently related more to conditions in the surface waters than those at the sediment/water interface. The presence of benthonic faunas in Kimmeridgian oil shales effectively rules out the Black Sea as an analogue. In detail, even the laminated bands contain differences. Two of the more significant of these are that the Kimmeridgian examples are not uranium-enriched whereas the Black Sea examples are markedly so, and the coccoliths in the Kimmeridgian bands (Plate 10) do not show carbonate dissolution features, whereas those of the Black Sea bands are deeply etched (Degens and Stoffers, 1976). Both these features in the Black Sea are related to the length of time the coccoliths take to fall through the thick, anaerobic part of the water column.

The second modern analogue for the accumulation of organic-rich sediments in a marine environment is that of the edges of continental shelves in areas of upwelling. There, blooms of phytoplankton (usually dinoflagellates) form in the surface waters at certain times of the year in response to the favourable conditions provided where dense, cold-water currents impinge upon the edge of the shelf and bring nutrient-rich waters to the surface (Brongersma-Sanders, 1948) (Fig. 44, Example 2). The abundance and types of plankton present in any given bloom are governed by complex and interacting factors, such as water turbulence, distance from shore, availability and proximity of river effluence and the amount of upwelling (e.g. Davey and Rogers, 1975). Such blooms are generally dominated by one or two species of

pigmented dinoflagellate (commonly species of Gonyoulax or Gymnodium) which occur in such large numbers that they discolour the surface waters red or brown ('red tides') and, on settling out, give rise to organic-rich sediments. Blooms and associated organic-rich sediments have been described from the Atlantic coasts of Africa (e.g. Namibian shelf, 150 km x >500 km) and Europe, and the Pacific coasts of the America's (e.g. Peruvian shelf, 100 km x >1500 km). Similar blooms have been recorded from partially land-locked seas, such as the North Sea, where the effects of upwelling are small or absent but where there is a sudden increase in the supply of land-derived nutrients. This type of bloom occurs in the North Sea in response to large outflows of nutrient-rich water from the Baltic Sea in the early summer.

A secondary effect caused by most types of bloom, and especially those composed of dinoflagellates, is the production of highly toxic waste products. These poisons have been shown (e.g. Adams et al., 1968 describing a toxic bloom in the North Sea) to be capable of killing a large proportion of the benthonic and pelagic fauna in the area in which they settle, and they can even be lethal in distant parts of the food chain (e.g. in birds and man as 'mussel poisoning'). This environmental analogue, which has been used by the present author (Gallois, 1976) to explain the origin of the Kimmeridgian oil shales, is discussed in more detail below.

The apparent paradox of substantial amounts of organic material being preserved in sediments, which on general faunal and sedimentary grounds seem to have been laid down in a shallow marine environment, was first recognised by Hallam (1967) in the Lias. The solution he

suggested (1967, 1975) was that of anaerobic bottom conditions developed beneath a layer of undisturbed, effectively stagnating, seawater on a very broad continental shelf (Fig. 44, Example 3). There are a number of difficulties in applying this suggestion to the oil shales in the Kimmeridge Clay. Firstly, there is evidence of a plentiful benthonic fauna in the oil shales, both in the form of burrows and trails and in situ bivalve and gastropod shells. Secondly, the oil shales are thin seams (generally <0.1m-thick) which occur over a wide area (> 35,000 km^2, preserved in England) apparently independent of both distance from land and the overall shape of the sea-floor (i.e. whether in a slowly or rapidly subsiding area). Thirdly, the oil shales occur in juxtaposition (commonly interburrowed and thinly interbedded) with a variety of lithologies which must represent a variety of different, and presumably rapidly changing, bottom conditions.

The stagnant-bottom-conditions hypothesis could explain local occurrences of oil shale within a single basin of deposition containing variable bottom conditions, or could explain widespread occurrences within a basin containing uniform conditions. It does not, however, explain the widespread occurrences in the Kimmeridge Clay, which embrace more than one depositional basin containing variable conditions. Nor does it explain the characteristic association of these oil shales with the occurrences in flood proportions of the pelagic flora and fauna of coccoliths, foraminifera, ammonites and the crinoid Saccocoma. A modified version of this hypothesis (Fig. 44, Example 4), proposed by Hallam and Bradshaw (1979) to explain the occurrence of the Liassic oil shales, is even less applicable to the oil shales in the Kimmeridge Clay in that it

could not account for their remarkable lateral persistence.

In addition to possible modern analogues, a number of authors (notably Degens and Stoffers, 1976 and Ryan and Cita, 1977) have suggested that, at times in the past, the oceans were density stratified and that anaerobic conditions conducive to the accumulation of organic-rich sediments occurred over large areas of their floors (Fig. 44, Example 5). A variation of this hypothesis, in which brine seepages (due to faulting) from the sea-bed gave rise to a dense, high salinity, anaerobic water layer (Fig. 44, Example 6), has been proposed by Degens and Paluska (1979) to explain the origin of organic-rich Kimmeridgian sediments beneath the northern part of the North Sea.

Jordan (1974) had earlier suggested that salt domes (derived from the Permo-Trias) caused high salinities and 'black shale' development at a number of levels in the Mesozoic of NW Europe. Neither of these hypotheses is compatible with the presence of benthonic faunas in most of the Kimmeridgian oil shales of the English land area. In addition, the second hypothesis is inappropriate because Permo-Triassic rocks are absent beneath much of the onshore outcrop and subcrop of the English Kimmeridge Clay (e.g. the Weald), and no salt deposit has been recorded within much of the remaining area (that lying to the south of the River Humber).

The nearest modern analogies to 'density-stratified anoxic oceans' are parts of oceans where bottom currents are restricted by topography with the result that a stratified water column develops in which a layer of oxygen-depleted water (O_2 <0.5 ml/l) forms in the middle or upper part of the water column. Such layers give rise to laminated (no bioturbation) organic-rich sediments where they impinge

on the sea bed at the edges of the continents (Desmaison and Moore, 1980). The best modern example is the northern part of the Indian Ocean (Bay of Bengal and Arabian Sea) where sediments with 1% to 11% organic carbon are forming over an area of more than 1,000,000 km sq. The presence of common bioturbation and a benthonic fauna in the Kimmeridgian oil shales seem to preclude this mechanism for their origin. In addition, the development of the oxygen-deficient layers is thought to be largely controlled by the effect of the Coriolis force on oceanic currents (Stommel, 1977). It is difficult to envisage how such a mechanism could change sufficiently rapidly to produce thin organic-rich layers such as those in the Kimmeridge Clay.

The unsuitability of layered-water models (Fig. 44, Examples 1, 3, 4, 5 and 6) to explain the faunal and sedimentary features in the Kimmeridgian oil shales has led the present author to suggest that an open-ocean upwelling model, similar to that of many present day continental margins (Fig. 44, Example 2) but modified to take account of the broad continental shelves that are known to have existed in the Jurassic (Fig. 44, Example 7), is more applicable. Such a model requires frequent dinoflagellate blooms and occasional coccolith blooms.

At the present time, seasonal blooms of coccoliths consisting largely of one species occur from time to time over large areas of the North Sea (Braarud et al., 1953). Such blooms characteristically form in seas which are rich in land-derived nutrients and are to some degree landlocked so that, although they remain a fully marine environment, their salinities are slightly lower than those of the open oceans.

The persistence and composition of the thin coccolith-rich beds in the Kimmeridge Clay suggests that they were formed from similar blooms. It is suggested, by analogy with the origin of the coccolith-rich beds with which they are so intimately associated, that the oil shales have resulted from other algal (probably dinoflagellate) blooms and that the organic content of the oil shales is largely derived from such blooms. Furthermore, the blooms themselves, by de-oxygenating and poisoning the water, could have provided temporary anaerobic bottom conditions that ensured the preservation of their organic content and faunal assemblage.

One of the bivalves most affected by the 1968 toxic booom off the East Coast of Britain was Lucinoma borealis Linné (Adams et al., 1968), a modern relative of the bivalve which forms the most extensive plasters in the Kimmeridge Clay oil shales - 'Lucina' minuscula Blake. Other similarities that occur between the Kimmeridgian oil-shale lithological/faunal association and modern continental shelves in upwelling areas include the abundance of phosphatic bone debris and faecal pellets.

The effects of algal blooms on the bottom conditions would have varied from place to place. In areas such as Norfolk, close to the London Platform, aerobic conditions and faunal colonisation were probably rapidly re-established once the poisons from each bloom or group of blooms had become fixed in the sediment with the result that bioturbated, shelly oil shales were produced. In the more rapidly subsiding areas, such as the Weald and south Dorset, where the water is likely to have been deeper and quieter, the organic remains may have lingered in hollows in the sea bed for a sufficient time for almost barren oil shales (such as the Blackstone) to form. Such

beds are exceptional in Kimmeridge Clay as a whole and in the present author's opinion represent a local response to a more widespread mechanism. Even in these almost barren beds there is commonly evidence of bioturbation, suggesting that anaerobic conditions were a temporary phenomenon.

Thick oil-shale seams only occur in the eudoxus to pectinatus zones of the Kimmeridge Clay and their formation may be related to the period of maximum extent of the area of deposition. The highest Kimmeridge Clay, above the Rotunda Nodule Bed (not represented in Norfolk), contains little bituminous matter and was probably deposited in a restricted basin which formed as a result of the Middle Volgian earth movements (Casey, 1971). The Kimmeridge Clay oil shales may therefore have been deposited in an environment which was intermediate between open ocean and restricted marine at a time when the delicate balance between palaeogeographical influences and nutrient supply was particularly favourable to the formation of algal blooms. The palaeogeography in Kimmeridge Clay times was probably not unlike that of the present day North Sea, with a series of subsiding basins linked by relatively narrow straits between land areas of low relief and with oceanic marine currents entering the area from the west and north (Fig. 40). The triggering mechanism for the blooms was nutrient-rich water; whether this was introduced into the depositional area by upwelling, fluvial sources or a combination of the two is not known. The widespread nature of the oil shales could be explained by either source, but their common occurrence in the basal parts of rhythms suggests that they are related to changes in relative sea-level (see 2.4.5 for further discussion), and this would favour an upwelling source.

2.4.5 Rhythmic sedimentation

Few sedimentary sequences are so uniform that they do not contain any repetition of lithology. Where such repetition occurs it may consist simply of an alternation of two lithologies or it may be made up of several lithologies which are arranged in a rhythmic pattern. Such sequences have been described as composed of rhythms, cycles or cyclothems by various authors. In a review of this type of sedimentation Duff et al. (1967) concluded that these three terms were synonyms, but to many authors the term 'cycle' still implies a symmetrical variation (e.g.ABCBA) and 'rhythm' an asymmetrical variation (e.g. ABCABC). The sedimentary variations described in the present account are of the asymmetrical type and the term 'rhythm' is used throughout to avoid possible misunderstanding.

Conybeare and W. Phillips (1822) are generally credited with the first recognition that the Middle and Upper Jurassic in England is composed of large-scale rhythms in which clay is followed by sand and the sand by limestone. Later authors expanded upon the idea and smaller and smaller clay/sand/limestone rhythms were recognised; Arkell (1933, pp. 54 - 55) lists 9 such rhythms within the Jurassic of southern England and although some of these are of doubtful validity (because they are incomplete or only locally present) the majority seem to be real. J. Phillips (1871) believed these rhythms to be epeirogenic in origin.

Small-scale rhythms have been recognised in the clay formations in the Jurassic, notably in the Lias in England and Germany and in the Oxford Clay. Brinkmann (1929), in his classic work on the

ammonite succession of the Oxford Clay of the Peterborough area, recognised two types of rhythm, both of which begin with a condensed deposit resting on an erosion surface. He interpreted this as indicative of prolonged periods of shallow-water deposition followed by relatively rapid deepening of the sea and then by steady sedimentation until the next phase of shallowing. Duff (1975) has recently confirmed Brinkmann's observations. Frebold (1927) observed similar rhythms in the Lower Lias of Germany and France which, because he could correlate them over large distances, he considered to be due to epeirogenic movements.

Klupfel (1917) described rhythms lithologically similar to the Type B rhythms of the Kimmeridge Clay, but on a larger scale, in the Lias of north-west France (Lorraine). There, shales (organic-rich in part) that rest on an eroded surface pass up into calcareous mudstones and calcareous mudstones with thin limestones, or into limestones. He interpreted these rhythms as due to shallowing of the sea to such an extent that the limestones were at times emergent. There are, however, marked differences between these rhythms and those of the Kimmeridge Clay. Firstly, faunal diversity increases with time in the Liassic rhythms, whereas the opposite is the case in the Kimmeridge Clay and, secondly, changes in detrital quartz contents are in opposition (increasing with time in the Lias, decreasing in the Kimmeridge Clay). Hallam (1963) gave further details of the Liassic rhythms and drew attention to the occurrence of oil shales (e.g. the Posidonienschiefer) at the bases of many of the rhythms. He suggested that the presence of glauconite and phosphate at this level might indicate condensed deposition.

Small-scale rhythms occur throughout the Kimmeridge Clay in Norfolk and fall into two types, depending upon the lithology of their basal bed (Type A and Type B of Fig. 5). A third type of small-scale rhythm (Type C) can be recognised in the highest part of the Kimmeridge Clay in Dorset (in the fittoni Zone, a stratigraphical level not represented in Norfolk), in which medium and pale grey calcareous mudstones pass up into pale grey, highly calcareous mudstones (i.e. similar lithologies to the upper parts of the Type A and Type B rhythms).

In addition, larger changes from more to less bituminous and more to less calcareous also occur in the Kimmeridge Clay, and can be regarded as larger scale rhythms (Fig. 10). In south Dorset, where the complete sequence is preserved, the formation itself forms a single, very large rhythm when compared with the other Upper Jurassic clays. The silty rhythms of the lower part of the Kimmeridge Clay pass up into kerogen-rich rhythms which are overlain by a thick sequence of uniformly highly calcareous mudstones. The sandy and silty Kellaways Beds, the kerogen-rich Lower Oxford Clay and the highly calcareous Middle and Upper Oxford Clay show a similar progression from siliciclastic-rich to carbonate-rich muds. So does the sequence formed by the silty West Walton Beds, the dark grey mudstones of the lower part of the Ampthill Clay and the highly calcareous upper part of the Ampthill Clay. Although in this last example no kerogen-rich bed is developed (Fig. 45), a thin bituminous bed (Bed 22 of Gallois and Cox, 1977) is present in the middle part of the Ampthill Clay and this could be interpreted as an attenuated representative of the kerogen-rich part of the other rhythms. In Norfolk, the highest part of the

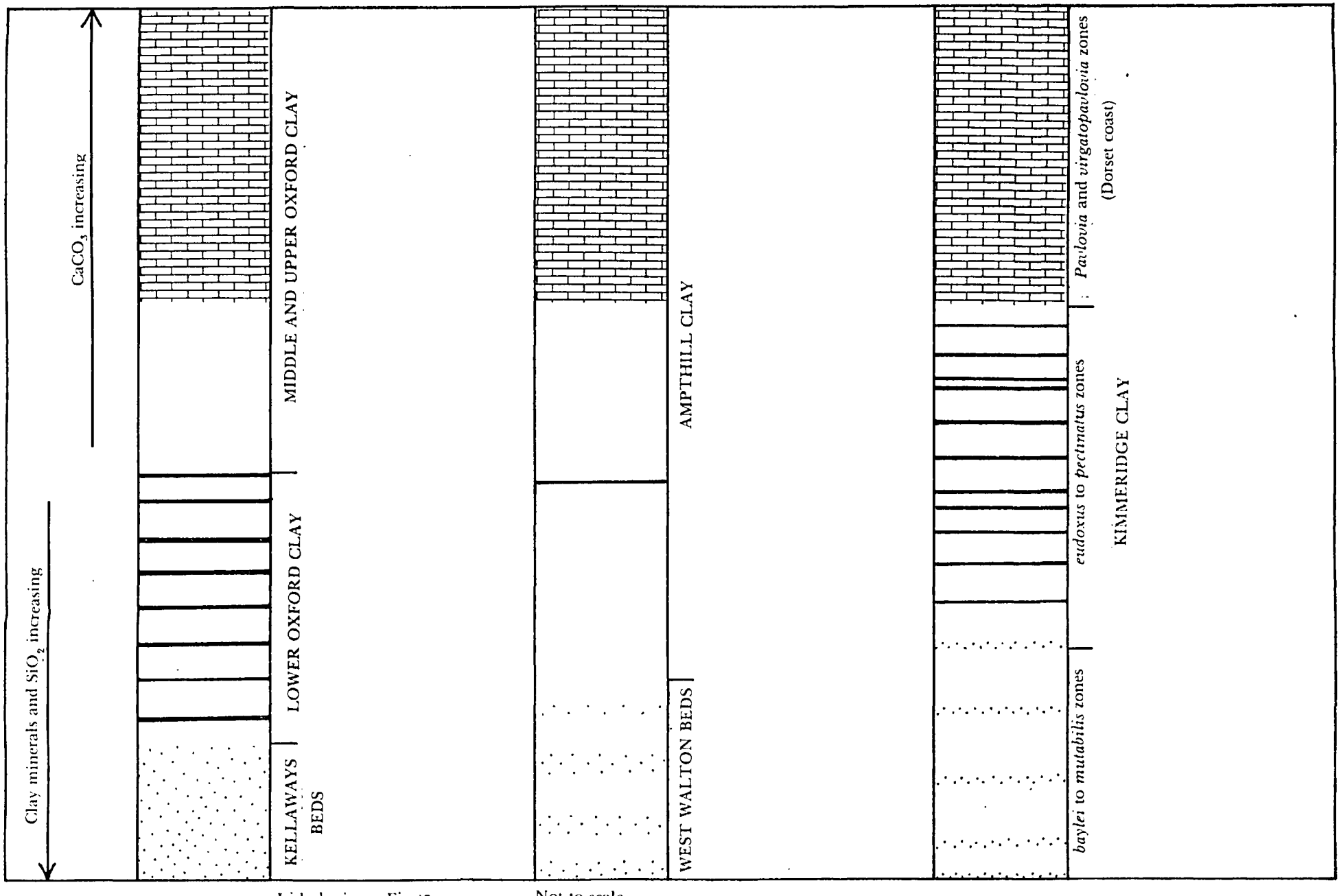


Figure 45. Large-scale argillaceous rhythms in the Upper Jurassic of eastern England.

Kimmeridge Clay is absent because the Sandringham Sands rest on the pectinatus Zone, the upper part of the kerogen-rich beds.

In all three types of small-scale rhythm in the Kimmeridge Clay the final event was the deposition of highly calcareous mud; the same lithology dominates the Upper Oxford Clay, the upper part of the Ampthill Clay and the highest Kimmeridge Clay. It will be seen later (Chapter 4) that sedimentation in the Gault followed much the same pattern.

The lithological similarity of the top part of the Type A, B and C rhythms to one another is reflected in their faunal assemblages. In each type of rhythm the youngest assemblage is rich in pyritized trails and burrows, has a low-diversity bivalve and ammonite fauna in which Thracia and/or Pinna is commonly prominent or in which one bivalve species is especially abundant (the Pinna-Thracia Mudstone of Section 2.2.3), and usually contains faunal elements such as echinoderm and crustacean fragments that are rare elsewhere in the Kimmeridge Clay. Large forms of 'Perisphinctes'-like ammonites are common in this lithology. Examples of this lithological faunal association also occur in the Upper Oxford Clay (Pinna and crustacean debris abundant), and the upper part of the Ampthill Clay (Protocardia and Procerithium abundant, the perisphinctid Ringsteadia common). In the Kimmeridge Clay the Pentacrinus Band, the Supracorallina Bed and Propectinatites?-rich Band all occur in this lithology (Fig. 21).

The low faunal diversity (locally with high density) of this lithology, its high calcium carbonate content (mostly coccoliths, calcispheres and microscopic shell debris), its thoroughly bioturbated nature and its local proximity to the London Platform suggest deposition in an open marine environment, below the action of waves, but with some

degree of restriction of the water circulation.

In contrast to the highly calcareous mudstones, the siltstones and silty mudstones at the bases of the Type A rhythms have a rich and diverse fauna. They rest unconformably on the underlying beds and invariably mark the incoming of new faunal elements. This lithology and assemblage can be likened to the basal beds of a number of other fine-grained formations in the Mesozoic. In each case a silty bed with phosphatic pebbles and a diverse fauna with new elements (the 'pulse faunas' of Jeans, 1973) rests on an erosion surface. Examples include the phosphatic pebble beds that carry successively higher stratigraphical levels of the Lias, Ampthill Clay and Gault onto the London Platform, and the Cambridge Greensand and Totternhoe Stone in the Chalk.

The presence of silt, coarse angular shell debris, traces of cross-bedding and a diverse fauna in the basal bed of the Type A rhythms indicates well-aerated bottom conditions within the range of wave action for at least part of the time. There therefore seems to have been a sudden shallowing followed by a rapid deepening of the sea during each Type A rhythm (Fig. 46). This deepening initially gave rise to dark grey mudstones such as the '*Lucina*'-*Protocardia* Mudstone, but these were slowly replaced by paler grey mudstones of the *Pinna*-*Thracia* Mudstone type. This suggests (Fig. 43) a slow decrease in water depth with time in the later part of the rhythm and implies that the shallowest Kimmeridge Clay lithology, presumed to be a highly calcareous mud with a restricted fauna, has been lost by winnowing and/or erosion prior to deposition of the phosphatic pebble bed that marks the base of the succeeding rhythm (Fig. 46).

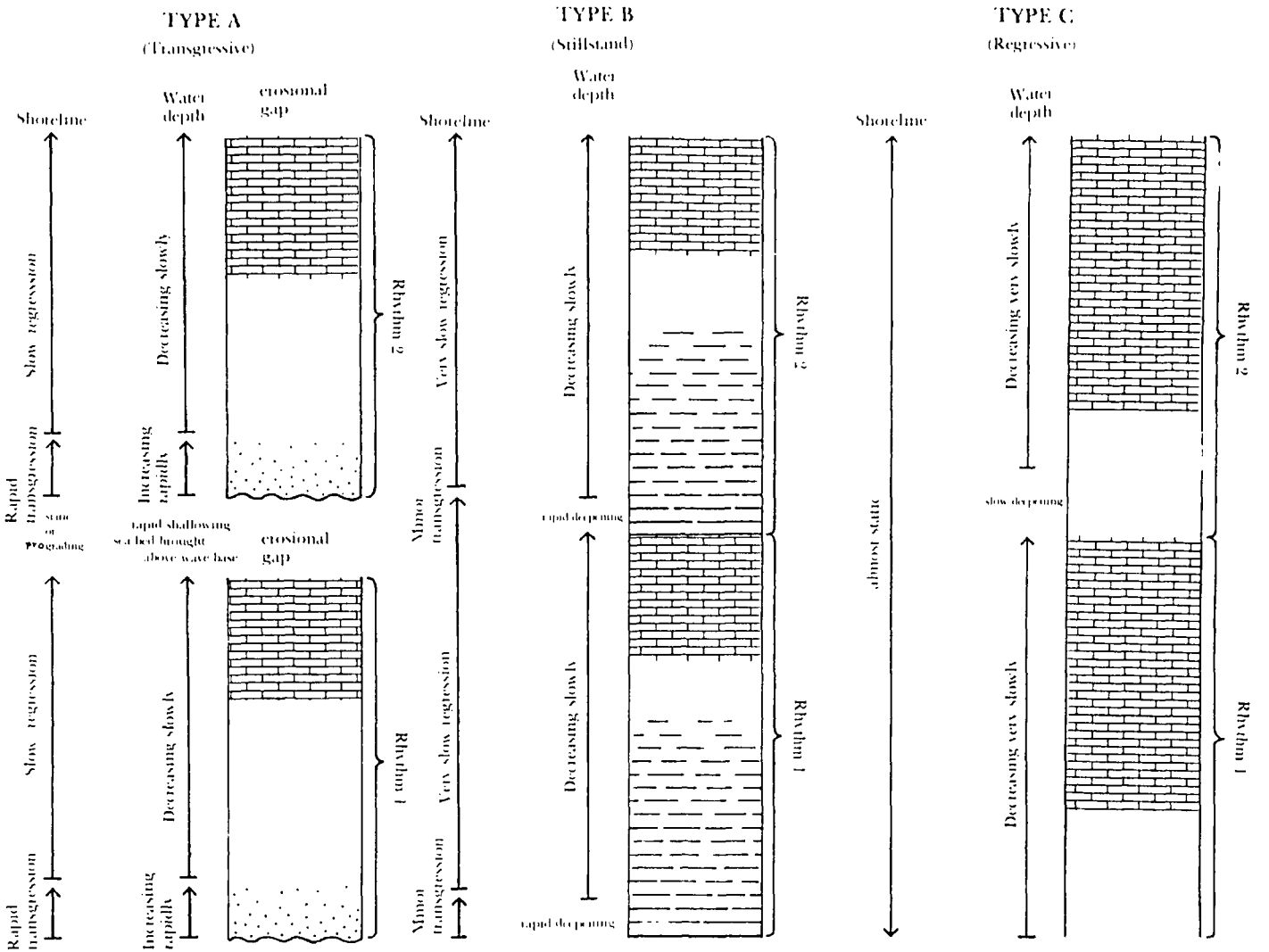


Fig. 46 Hypothetical mechanisms to explain the three types of Kimmeridge Clay rhythm (lithologies as Fig. 10.)

A similar sequence of events can be used to explain the origin of the Type B rhythms, except that there the full sequence is preserved. Oil shales form the bases of the rhythms because, by analogy with the transgressions that introduced new faunas in the Type A rhythms, a rapid deepening of the sea introduced a flood of nutrients into a shallow basin in which water circulation had previously been partially restricted. The net effect of the Type B rhythms is presumed to be one of stillstand (Fig. 46).

The Type C rhythms show little lithological variation with time. They are wholly composed of relatively shallow-water calcareous muds and are presumed to have formed in response to the same mechanism of fluctuating water depth as that which formed the Type A and Type B rhythms (Fig. 46).

Frebold (1927) inferred a similar sequence of events for some of the clay/limestone rhythms in the German Lias as that described here for the Type A rhythms. Stille (1924) suggested this was due to sporadic tectonic uplift of the shallow-water (shelf) margins of the Tethyan geosyncline followed by gradual sinking of the basin and margins as a whole. What is not clear from this explanation, nor from any subsequent interpretation by other authors, is why each transgression and ultimate expansion of the area of deposition should begin with a period of uplift.

Numerous attempts have been made to relate transgressive events to world-wide eustatic rises in sea-level. Many of these are suspect, however, because of the difficulty of distinguishing between the effects of sea-level movements and tectonic events in any one region. Cooper's (1977) postulation of 14 world-wide eustatic rises in the Cretaceous, identified by means of a large number of local trans-

gressions (many of which are poorly defined), is an example of a complex combination of well documented data and speculation. The identification by Hallam (1977) of Jurassic eustatic sea-level movements on the Russian Platform, within the area of a single stable massif, is likely to be more accurate.

Donovan and Jones (1979) concluded that the only two major mechanisms that could cause world-wide changes in sea-level were changes in the volume of land ice (up to 150m change) and changes in the volume of the oceanic ridges (up to 300m change). They considered the sedimentary infilling or desiccation of individual marine basins (e.g. the Mediterranean during the Messinian Stage) to be capable of causing only minor changes world-wide (up to 15m).

There is no evidence of glaciation in the Jurassic and it must therefore be assumed that any large change in sea level was caused by tectonic activity related to sea-floor spreading. In the vicinity of the newly formed Atlantic Ocean, this activity is likely to have been accompanied by tectonic movements on the continental shelf and adjacent land. The origin of the rhythms in the Kimmeridge Clay is therefore probably complex, and due to a combination of interrelated eustatic and epeirogenic movements.

2.4.6 Concluding remarks

The Upper Jurassic in England, beginning with the marine Kellaways Beds and ending with the freshwater Purbeck Beds, is regressive overall but contains several phases of transgression and regression. The Oxford Clay, West Walton Beds - Ampthill Clay and Kimmeridge Clay begin with transgression and probably end with regression. The Kimmeridge Clay rests with minor unconformity on Corallian Beds

(the Ampthill Clay in Norfolk) throughout its English outcrop and subcrop. This might appear to be incompatible with the statement that the lower part of the Kimmeridge Clay was transgressive but it must be borne in mind that the upper part of the Ampthill Clay was regressive and that the Kimmeridge Clay reoccupied a sedimentary basin that had recently contracted.

The present work has shown that the sequence of sedimentary events in the Kimmeridge Clay was complex. The lower part of the formation is characterised by transgressive rhythms; these were replaced by stillstand and then by regressive rhythms so that the overall result was either regression or stillstand (Fig. 47).

Little direct evidence has survived concerning the palaeogeography in Kimmeridgian times. The lithologies, fauna and flora and oxygen isotopes indicate that the Kimmeridge Clay was deposited in a warm shallow sea on a wide continental shelf dotted with vegetated islands under a tropical climate. The distribution of the clay minerals does not enable any palaeo-environmental conclusion to be drawn but it seems likely that they were largely derived from argillaceous Palaeozoic rocks that cropped out in a nearby land area beneath what is now central East Anglia.

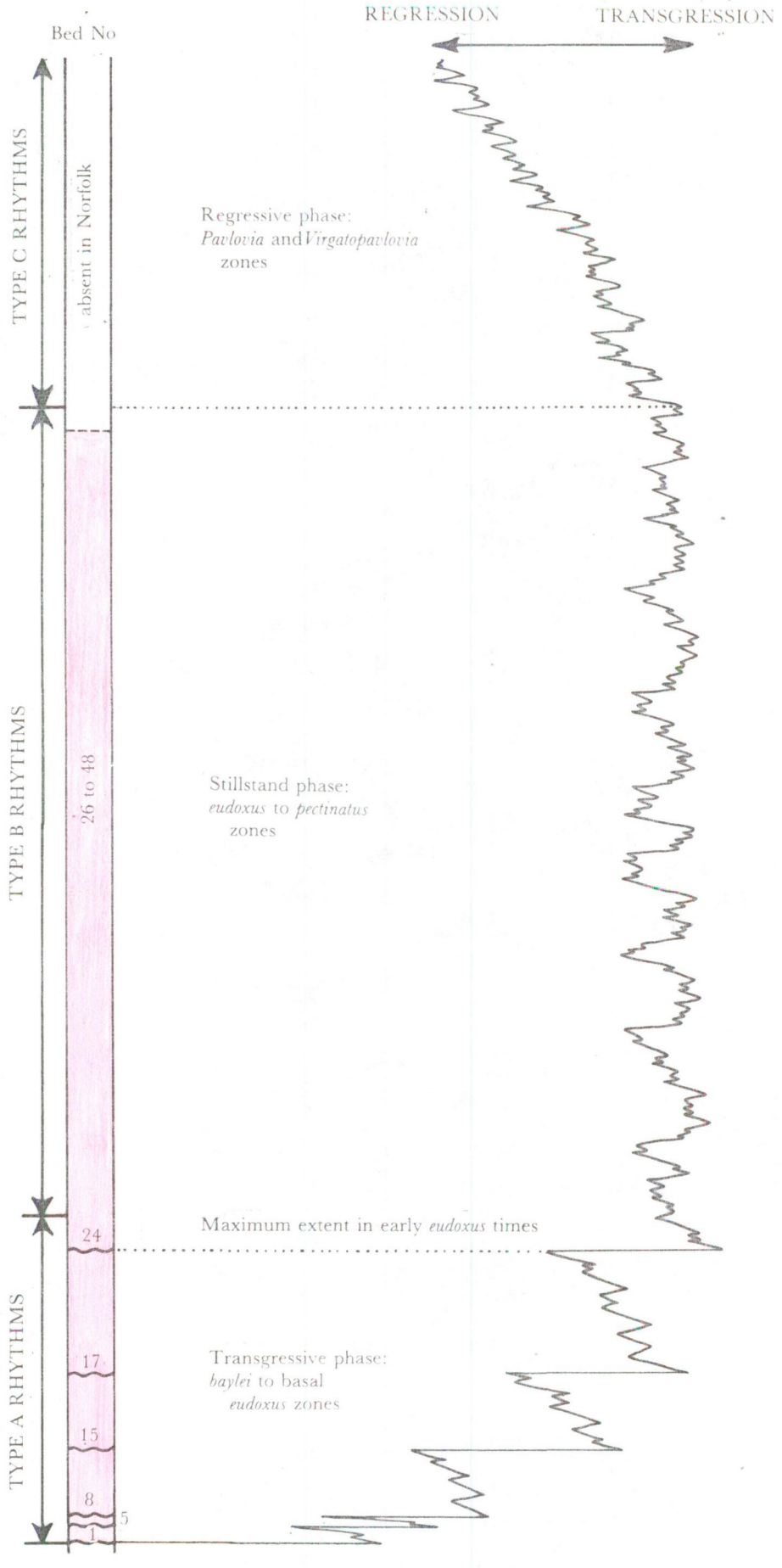


Figure 47. Hypothetical representation of land/sea-level movement during deposition of the Kimmeridge Clay.

CHAPTER 3

LATE JURASSIC EARTH MOVEMENTS

3.1 Introduction

It has become increasingly apparent in recent years, with the general acceptance of the theory of continental drift and the development of that of plate tectonics, that non-sequences in the British Mesozoic which had formerly been regarded as minor events of local importance are the reflection of tectonic phases related to the separation of Europe and Africa from the Americas.

It is now generally believed that the formation of the rift that was to become the Atlantic Ocean began in the early Jurassic (e.g. Hallam, 1971; Smith and Briden, 1977). Sea-floor spreading has continued to the present day, but the process has been erratic with periods of accelerated movement, and consequential intensified tectonic activity, in the late Triassic, early Jurassic, late Jurassic, early Cretaceous and late Cretaceous. These movements were collectively called the Kimmerisch (Cimmerian) orogeny by Stille (1913) after the Cimmerian Mountains in the Crimea. Stille recognised an Older Cimmerian phase represented by an unconformity between the Trias and the Lias, and a Younger Cimmerian phase represented by the unconformity between the Jurassic and the Cretaceous. Whilst these are the two principal phases of the Cimmerian throughout much of Europe numerous other sub-phases are present in many areas.

Arkell (1933, pp. 93 - 96) listed the main transgressions in the British Jurassic and early Cretaceous and drew attention to

those that appeared to have been preceded by tectonic activity. Foremost among these were the folding and faulting that affected the Jurassic rocks, but which preceded the deposition of the Lower Greensand (Aptian) over much of southern England.

In recent years the recognition of the importance of fault-controlled subsidence in early Mesozoic sedimentation in the British onshore and offshore area (Kent, 1975), and the widespread nature of the late Jurassic to mid Cretaceous change from this type of sedimentation to one of simple geosynclinal subsidence (Kent, 1977) has resulted in the term 'late Kimmerian' being widely used in geological descriptions of the North Sea (e.g. Ziegler, P.A., 1975).

The effects of late Jurassic earth movements on the Kimmeridge Clay of East Anglia were indirectly documented by the early stratigraphers who noted the various unconformities* and non-sequences that occur around the edges of the London Platform. These relatively minor breaks in sedimentation were not thought to be associated with any major tectonic event although it was realized that they marked a progressive change in the late Jurassic environment from an extensive marine shelf receiving muds to a series of shallow, isolated basins receiving coarser clastic sediment. It was only comparatively recently that Casey (1971, p. 164) suggested that the Upper Lydite Bed, a pebble bed marking an unconformity at the base of the Portland

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* The term unconformity is used here in its broadest sense (following the International Dictionary of Geology, 1971) to include all erosional breaks between formations. Intraformational breaks are referred to as 'minor erosion surfaces'. The difference between the two is entirely one of scale and could be described by reference to terms such as 'non-sequence', 'minor unconformity' and 'disconformity' if such terms were themselves unambiguous.

Beds at outcrop between Wiltshire and Lincolnshire, might be related to the opening of the North Atlantic. Whilst this suggestion justifiably draws attention to the importance of this bed it oversimplifies the position because the Upper Lydite Bed does not represent a single, isochronous event, but is a composite result of a number of local minor events.

Late Jurassic (Callovian to Portlandian) sedimentation was almost continuous in Dorset, the Hampshire Basin and the Weald. To the north of this area, around the edges of the London Platform in Wiltshire, Buckinghamshire, Oxfordshire, Cambridgeshire and Norfolk, there are numerous minor breaks in the sequence.

3.2 Norfolk

In Norfolk the earliest widespread Upper Jurassic unconformity is that at the base of the West Walton Beds (Middle Oxfordian), which rest on a number of different stratigraphical levels in the Oxford Clay. Minor folding and/or faulting also occurred in the late Oxfordian in Norfolk; this is shown by variations in thickness within the Ampthill Clay. The lower and middle parts of the formation thicken regularly (Fig. 48a) whereas the upper part shows irregular variation (Fig. 48b). Four laterally persistent erosion surfaces occur in Beds 30 to 37 of the Ampthill Clay (Gallois and Cox, 1977) in Norfolk and these, together with an erosion surface at the base of the Kimmeridge Clay, cause the variations in thickness in the upper part of the Ampthill Clay (Fig. 49).

Minor, but widespread, erosion surfaces occur at the bases of the baylei, cymodoce, mutabilis and eudoxus zones in the Kimmeridge Clay in Norfolk; there is no evidence of a break in sedimentation

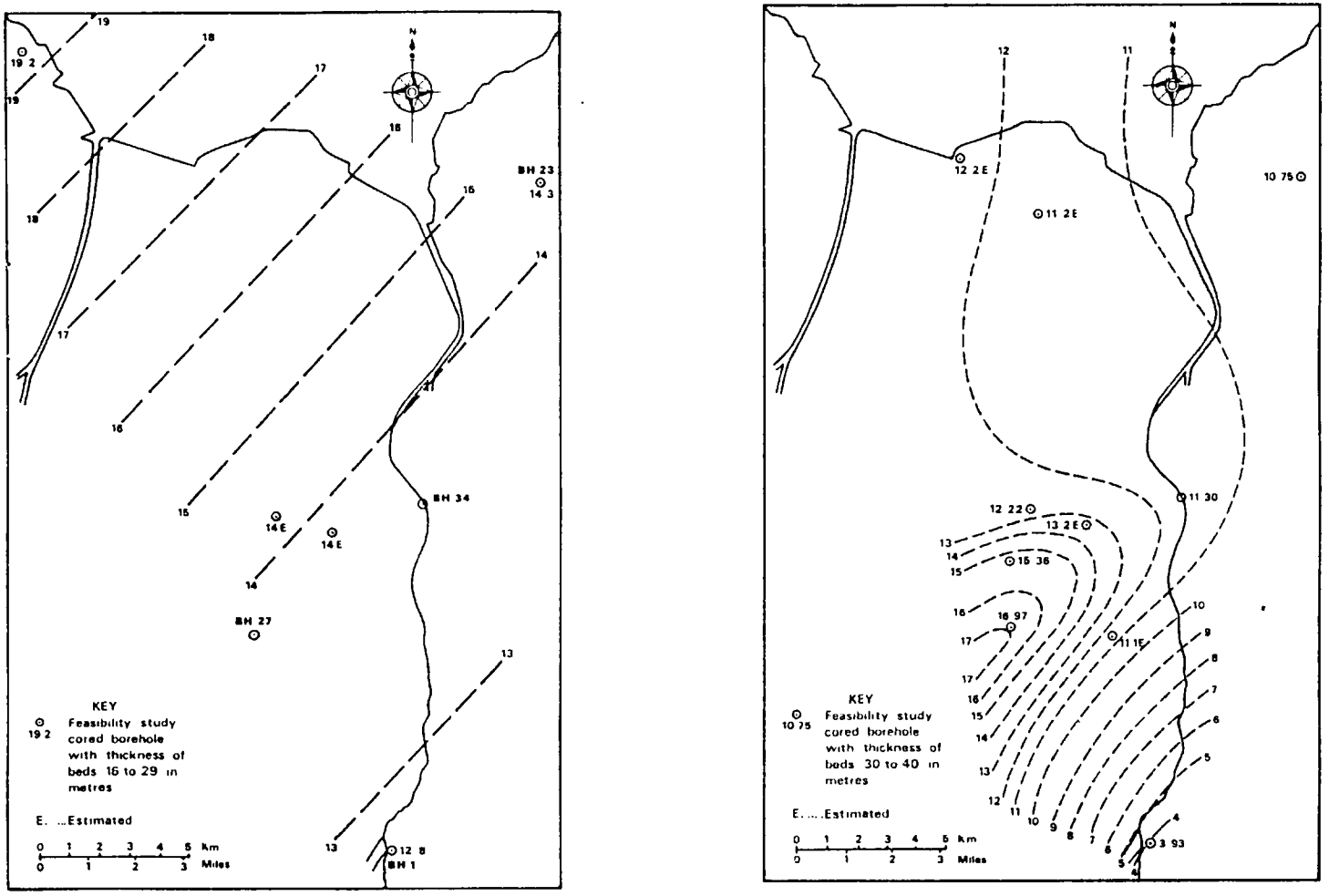


Figure 48. Isopachytes for selected intervals in the Ampthill Clay in west Norfolk (after Gallois and Cox, 1977).

above the eudoxus Zone except for local minor erosion surfaces within the scitulus and hudlestoni zones (bases of Kimmeridge Clay Beds 40 and 44 respectively) in the Gayton, North Runcton and Marham areas.

The Kimmeridge Clay is everywhere unconformably overlain by the Sandringham Sands in Norfolk. The youngest Kimmeridge Clay preserved in the county is pectinatus Zone in age (Bed 48 in The Wash). Southwards along the outcrop the Sandringham Sands progressively rest on lower beds within the Kimmeridge Clay until, near the county boundary at Little Ouse (Temple Farm Bh.), Weeting (Ely-Ouse Bh. 23) and Mundford (Mundford C Bh.), only the Lower Kimmeridge Clay is preserved (Fig. 50). South of the River Little Ouse the Sandringham Sands are themselves overstepped by the Lower Greensand.

Between the River Little Ouse and the vicinity of Caxton, Cambridgeshire, the Lower Greensand (Woburn Sands) rests on a surface cut in gently folded Jurassic rocks. A similar situation could be present in the Kimmeridge Clay subcrop in Norfolk and Suffolk. However, the limited borehole data suggests a slow, regular overstep with no evidence of folding (Fig. 50). Kimmeridge Clay is absent due to this overstep, south-east of a line running from near Soham, Cambridgeshire to the north Norfolk coast in the vicinity of Wells.

In Cambridgeshire, Holmes (in Worssam and Taylor, 1969, p. 72) described folds in the Upper Jurassic rocks that were planed off by a Lower Greensand (Aptian) transgression (Figs. 51 and 52c). Similar, but more subdued, folding affects the Ampthill and Kimmeridge clays of the Ely area (Fig. 52b). These folds appear to die out northwards because it can be inferred from boreholes drilled for the Ely-Ouse tunnel scheme between Hockwold cum Weeting, south-west Norfolk and

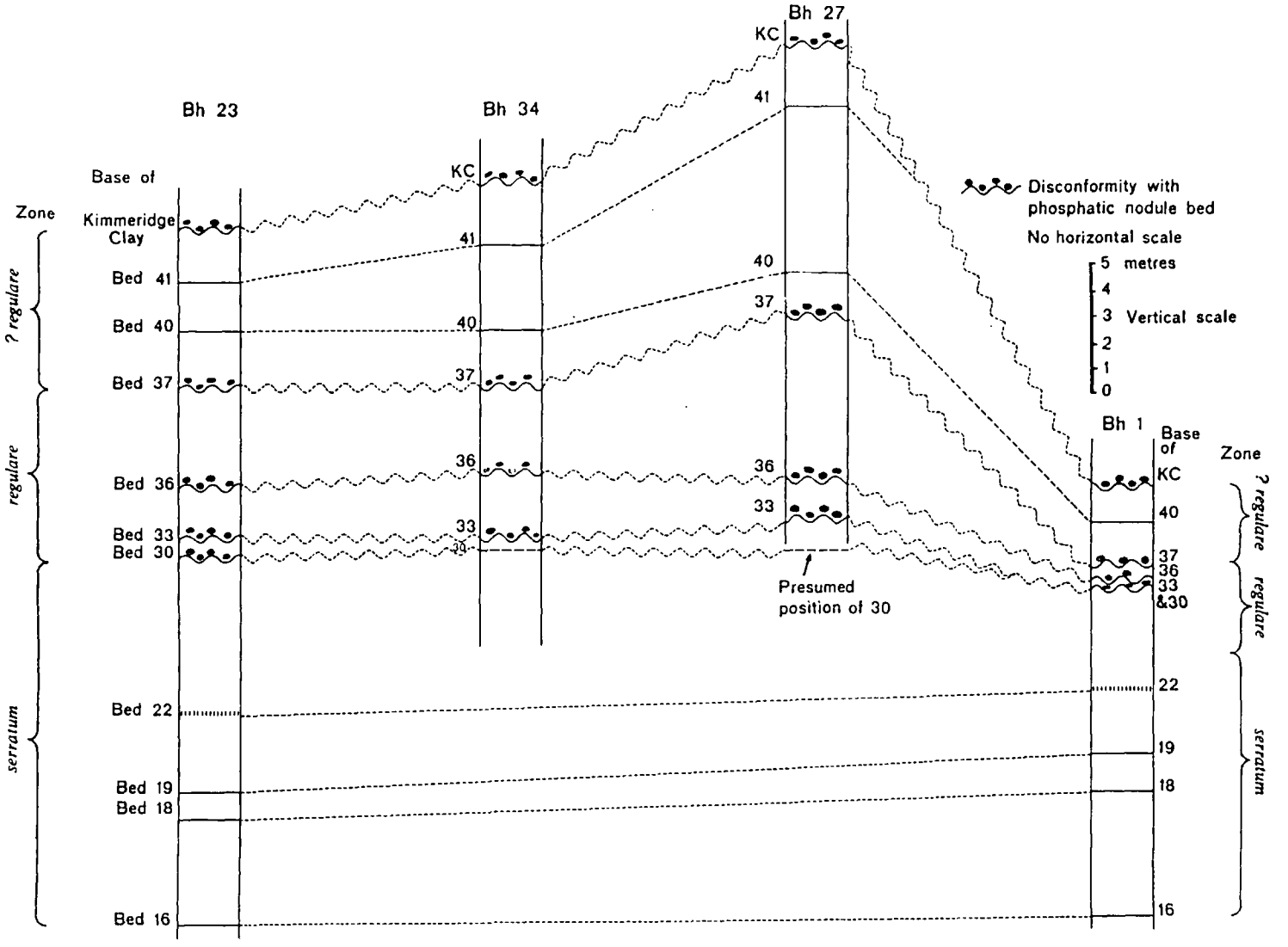


Figure 49. Attenuation in the upper part of the Ampthill Clay and the overstep of the Kimmeridge Clay in west Norfolk (after Gallois and Cox, 1977).

Kentford, Suffolk that the Middle and Upper Jurassic is rapidly but regularly overstepped by the Lower Greensand (Fig. 52a). Each of these three sections (Fig. 52a-c) lies close to the edge of the London Platform and the presence of structures in the Jurassic may be related to boundary structures that control the shape of the platform.

The age of the folding shown in Figure 52 cannot be accurately determined. The youngest folded formation is the Kimmeridge Clay and the oldest unfolded formation the Woburn Sands. Elsewhere in southern England, notably in Jurassic subcrop area around the southern edge of the London Platform in the Swindon to Reading area, the youngest strata beneath the Lower Greensand are Portland or Purbeck beds that are very gently folded. In south Dorset, the Isle of Purbeck monocline and associated folds involve the whole of the Jurassic and Cretaceous, but in parts of the area the intensity of folding can be shown to be greater in the Jurassic rocks than in the post-Aptian Cretaceous rocks (Arkell, 1947). Furthermore, large faults have been recorded in the Jurassic that do not penetrate the Lower Greensand or Gault (e.g. Arkell 1933, pp. 95-96).

Tectonic activity clearly commenced in the late Jurassic and continued into the early or mid Cretaceous in some areas, the intensity and effects of the activity varying from area to area with time.

There is evidence in Norfolk that faulting and possibly folding occurred in the late Jurassic; this was probably re-activated in the early Aptian. Both the Kimmeridge Clay and the Sandringham Sands have very low dips in Norfolk ($< \frac{1}{2}^{o}$) and there is no detectable angular discordance at outcrop between the two formations. A discordance does however exist as demonstrated by the southerly overstep of the younger formation across the older (Fig. 50).

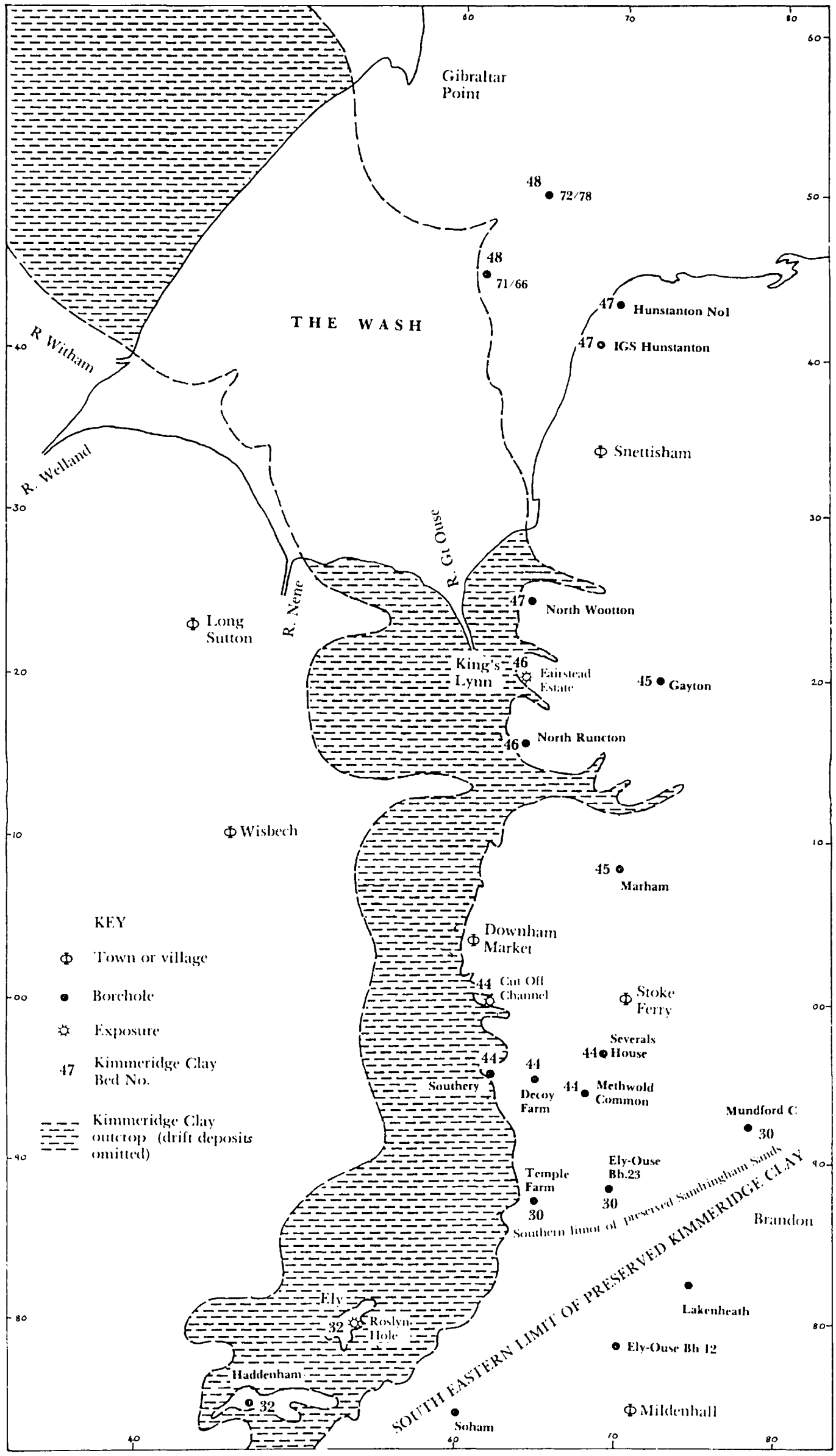


Figure 50. Age of the youngest Kimmeridge Clay preserved beneath the Sandringham Sands, Woburn Sands or Norfolk Carstone.

At one locality in Norfolk there is probable evidence of late Jurassic faulting. At North Runcton, two cored oil-shale exploration boreholes were drilled (the second to provide additional material for analysis) 3m apart. Both proved Sandringham Sands resting on Kimmeridge Clay at closely similar depths, but the first proved a fault (accompanied by disturbed dips, slickensiding and sheared mudstone) within the top part of the Kimmeridge Clay. The beds below this fault can be matched in detail in both boreholes, but those above cannot (Fig. 53). The highest part of the Kimmeridge Clay was disturbed by weathering in both boreholes but was sufficiently fossiliferous for its stratigraphical horizon to be identified. The dip of the fault plane (60°) and the geometry of the boreholes and marker bands strongly suggest that the fault does not displace the base of the Sandringham Sands. Small faults (throws < 5m) were found to be relatively common in the Kimmeridge Clay beneath The Wash, but none was recorded that stopped at the base of the Sandringham Sands (Wingfield et al., 1979; geological sections based a seismic-reflection survey).

The age of the tectonic activity that produced these disturbances can be accurately determined in Norfolk. Beneath The Wash and north-west Norfolk, Kimmeridge Clay with *pectinatus* Zone (Upper Kimmeridgian = Lower Volgian *sensu* Casey, 1967) ammonites is unconformably overlain by Sandringham Sands with *Paracraspedites oppressus* Zone (Upper Portlandian = Middle Volgian *sensu* Casey, 1967) ammonites. *Pavlovia spp.* derived from the youngest Kimmeridgian zones (= Middle Volgian *sensu* Casey, 1967) are abundant as phosphatic pebbles in the basal bed of the Sandringham Sands and suggest that the Kimmeridge Clay was formerly more complete in Norfolk. The tectonic activity that

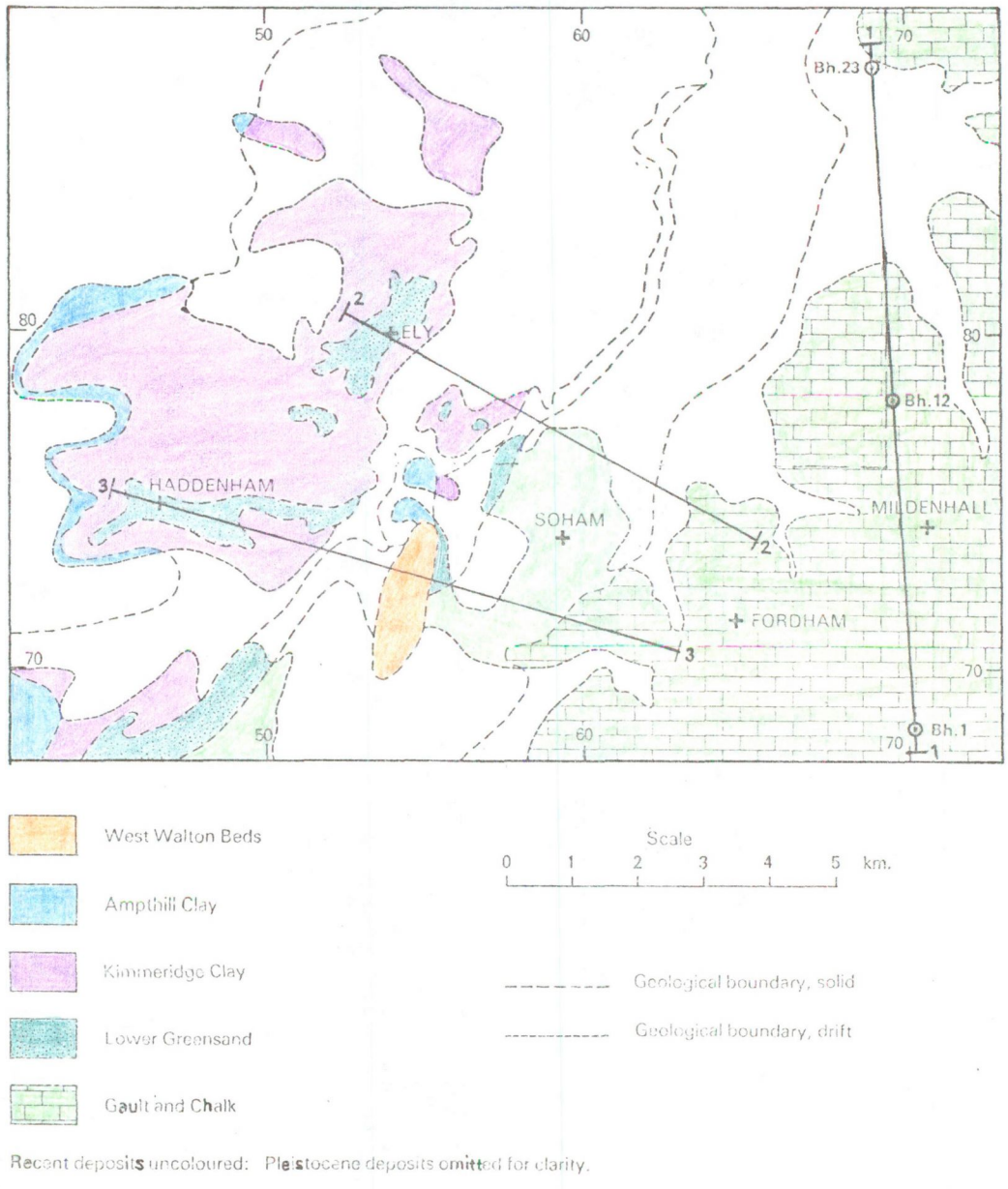
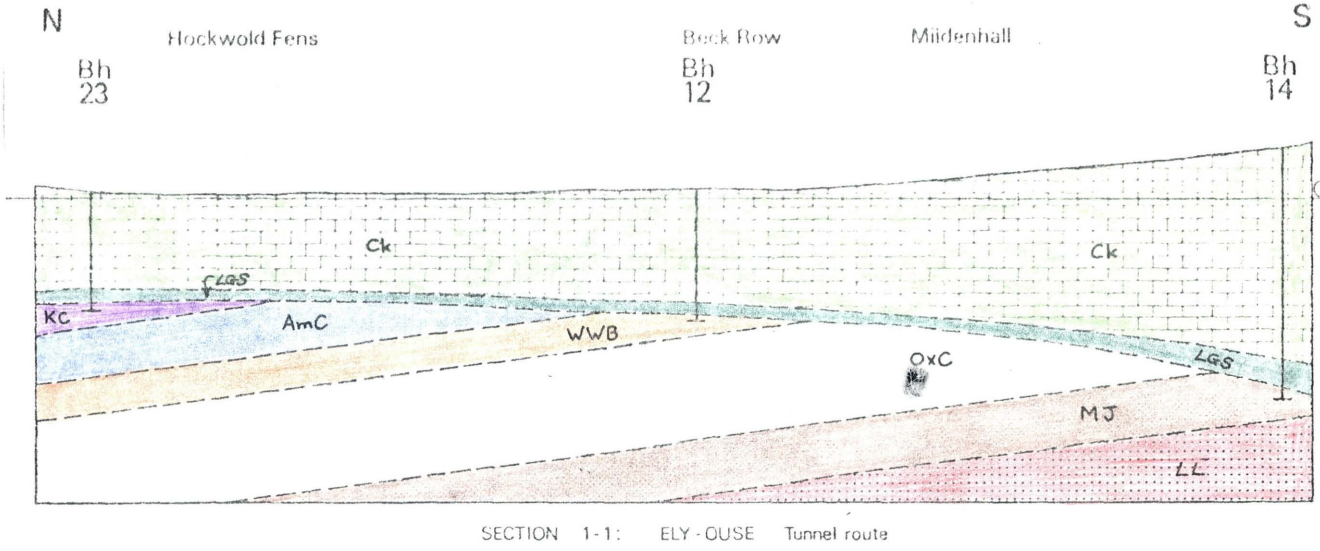
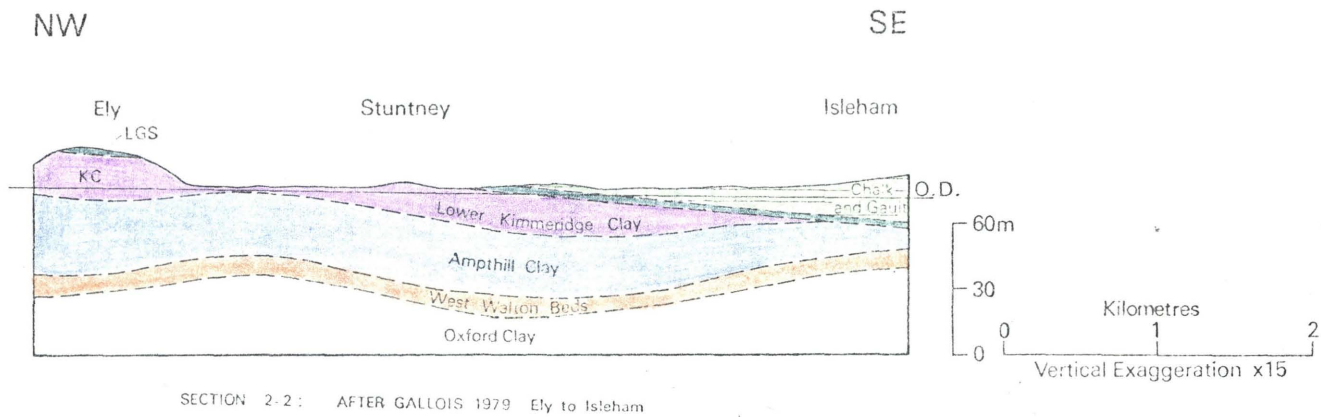


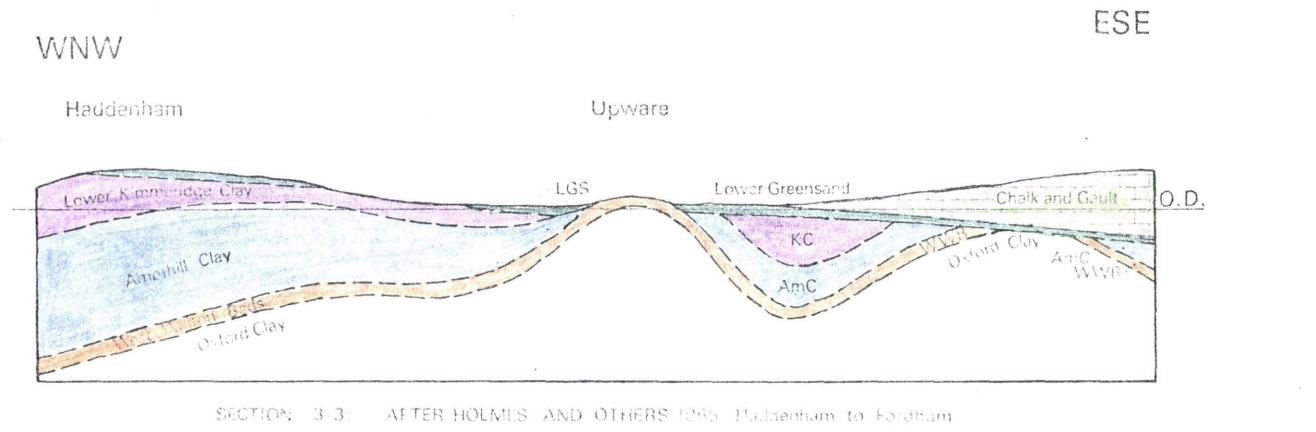
Figure 51. Geological sketch map of south-west Norfolk showing the lines of section in Fig. 52.



SECTION 1-1: ELY - OUSE Tunnel route



SECTION 2-2: AFTER GALLOIS 1979 Ely to Isleham



SECTION 3-3: AFTER HOLMES AND OTHERS 1965 Haddenham to Fordham

Ck	Gault and Chalk	WWB	West Walton Beds
LGS	Lower Greensand	OxC	Oxford Clay, Kellaways Beds and Cornbrash
KC	Kimmeridge Clay	MJ	Middle Jurassic
AmC	Ampthill Clay	LL	Lower Lias

Figure 52. Geological sections showing the overstep of the Woburn Sands and the Norfolk Carstone across folded Upper Jurassic strata in south-west Norfolk, west Suffolk and north Cambridgeshire.

gave rise to the basal Sandringham Sands unconformity probably therefore began and ended in the Middle Volgian, hence the reference by Casey (1967) to the 'Middle Volgian earth movements'.

Although that part of the 'late Kimmerian' tectonic activity which can be attributed to the late Jurassic is small in Norfolk, it had a widespread effect around the edges of the London Platform. In Norfolk it caused a marked change in sedimentation from the quiet, argillaceous deposition of the Kimmeridge Clay to the predominantly arenaceous turbulent sedimentation of the Sandringham Sands.

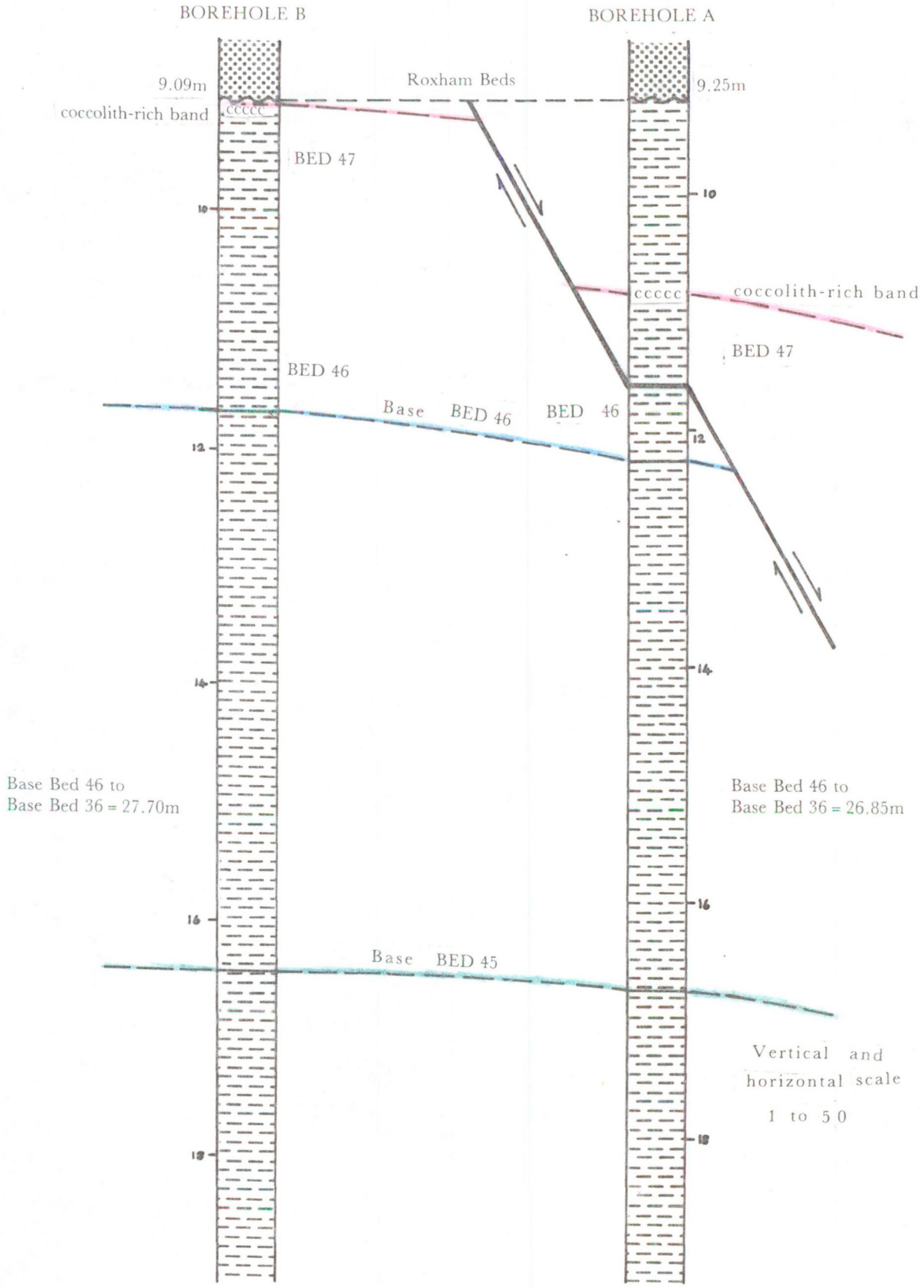


Figure 53. A possible late Jurassic fault at North Runcton.

CHAPTER 4

TOP JURASSIC - LOWER CRETACEOUS

4.1 Introduction and history of research

The top Jurassic - Lower Cretaceous rocks of Norfolk are the most complete sequence of marine strata in Britain for the study of the late Jurassic to mid Cretaceous interval. Their relationship to other English sequences is shown diagrammatically in Fig. 54. They crop out in a series of low escarpments running south from Hunstanton, via the eastern part of King's Lynn to Denver, a distance of about 40 km. Farther south, the outcrop is concealed by Recent deposits between Denver and the county boundary at the River Little Ouse except for two small outliers which cap the Fenland islands of Hilgay and Southery. At its maximum, between King's Lynn and Gayton, the outcrop has a width of about 10 km (Fig. 55).

Much of the top Jurassic - Lower Cretaceous sequence is composed of alternations of loose sand and sandy clay that give rise to low, gently rounded features with few natural exposures (Plate 19). Between Hunstanton and the Babingley River these features are well displayed and provide considerable aid in geological surveying. South of the Babingley River the outcrop is overlain by extensive tracts of Quaternary deposits and features are less well developed.

As with many other parts of England, William Smith, in his pioneer geological maps of the counties, was the first to recognize the main divisions of the Jurassic and Cretaceous rocks of East Anglia. On his geological map of Norfolk (1819) he delineated the "Oaktree Clay" [Kimmeridge Clay] and the "Golt Brick Earth" [Gault] separated by "Sand" (Table 13). Rose (1835, p. 175) noted that the sand was referred to as

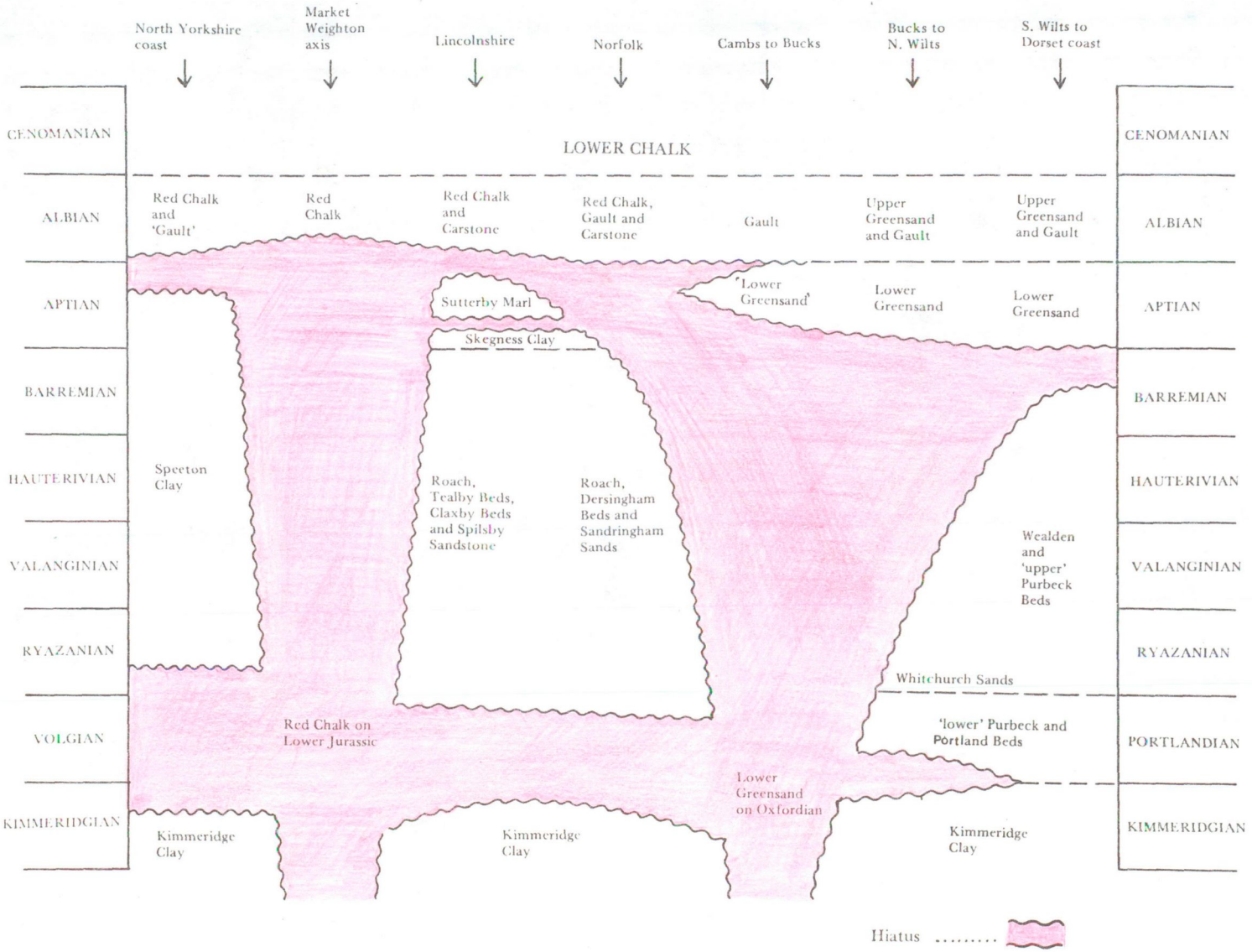


Figure 54. Correlation of the late Jurassic to mid Cretaceous sequences of Norfolk and Lincolnshire with those elsewhere in England.

<table>
<tr><th>Wm Smith
1819</th><th>Rose
1835, 1862</th><th>Teall
1875</th><th>Whitaker and
Jukes-Browne
1899</th><th>Present
Work</th><th>Modern
Stages</th><th></th></tr>
<tr><td>Chalk</td><td>Chalk</td><td>Chalk</td><td>Chalk</td><td>Chalk</td><td>Maastrichtian
to
Cenomanian</td><td>Upper Cretaceous</td></tr>
<tr><td>Golt Brick
Earth</td><td>Red Chalk
Gault</td><td>Red Chalk
Gault</td><td>Red Chalk
Gault</td><td>Red Chalk
Gault</td><td>Albian</td><td rowspan="8">Lower Cretaceous</td></tr>
<tr><td rowspan="7">Sand beneath
the Golt</td><td rowspan="7">'breccia'
Carstone
'loose white
sand'</td><td rowspan="7">Carstone
'clay'
'white sands'</td><td>Carstone</td><td>Carstone</td><td></td></tr>
<tr><td rowspan="2">erosional
gap</td><td>Sutterby Marl[1]</td><td rowspan="2">Aptian</td></tr>
<tr><td>Skegness Clay[1]</td></tr>
<tr><td>Roach</td><td rowspan="2">Barremian</td></tr>
<tr><td>Snettisham
Clay</td><td>Snettisham
Clay</td></tr>
<tr><td rowspan="2">Sandringham
Sands</td><td>Dersingham Beds</td><td>Hauterivian</td></tr>
<tr><td>Sandringham
Sands[2]</td><td>Valanginian
to
Volgian (pars)</td><td rowspan="2">Upper Jurassic (pars)</td></tr>
<tr><td>Oaktree
Clay</td><td>Kimmeridge
Clay</td><td>Kimmeridge
Clay</td><td>Kimmeridge
Clay</td><td>Kimmeridge
Clay</td><td>Kimmeridgian</td></tr>
</table>

[1] Submarine outcrops beneath The Wash only. [2] See Table 14 for subdivisions of Sandringham Sands.

Table 13. Evolution of the nomenclature of the top Jurassic-Lower Cretaceous rocks of Norfolk. Discussion of the ages of the various formations is given in the text.

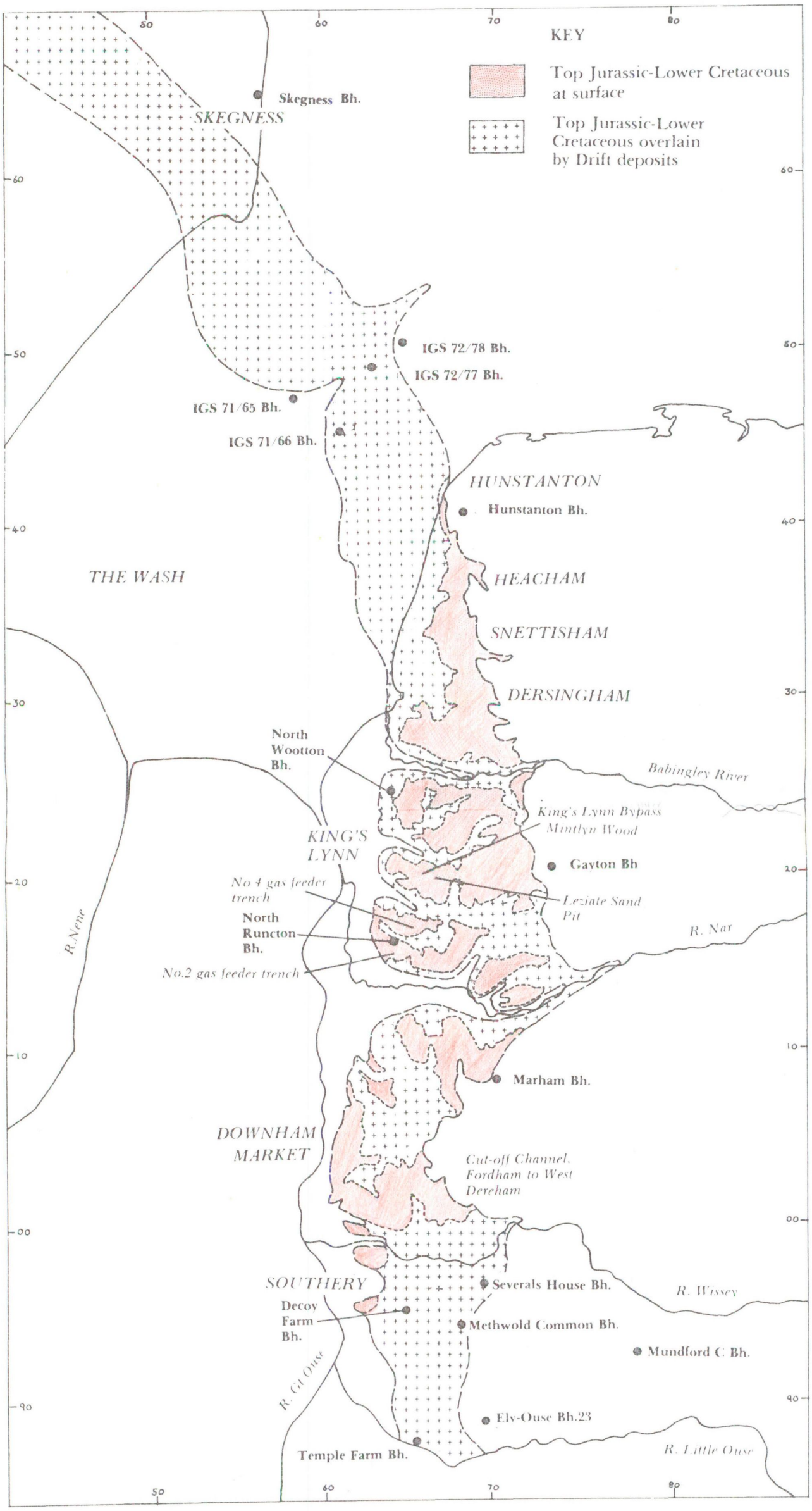


Fig.55 Key localites and boreholes in the top Jurassic – Lower Cretaceous of Norfolk and The Wash

Carstone in Norfolk but that it presented "little interest to the naturalist, being a mere mechanical deposit, and, as far as it has at present been explored, affording no animal remains."

Rose subsequently noted (1862, pp. 234-6) that the beds between the Kimmeridge Clay and the Gault (in south-west Norfolk) and between the Kimmeridge Clay and the Red Chalk (in north-west Norfolk) could be divided into three parts, "loose white sand" that was worked in large quantities for glassmaking at Dersingham, Shouldham and Downham Market, a ferruginous sandstone known locally as "Carstone" (or "Car Stone" = Fen Stone) and a "breccia" (the Carstone of Hunstanton cliffs).

Teall (1875, pp. 16-19) recognized three slightly different divisions, comprising the white sands and the Carstone, but with an intervening clay. These latter divisions were confirmed by the Geological Survey for those parts of Old Series Sheets 65 and 69 (published 1883 and 1885 respectively) between Hunstanton and King's Lynn and the names Sandringham Sands and Snettisham Beds were added to that of the Carstone (Whitaker and Jukes-Browne, 1899, p. 6). In a later addition to the same memoir, Lamplugh (in Whitaker and Jukes-Browne, 1889, p. 16) replaced Snettisham Beds with Snettisham Clay.

In proposing the name Sandringham Sands for the lowest of their three divisions, Whitaker and Jukes-Browne adopted with slight modification a term that had been suggested by Harmer (1877, pl. 1) for the whole of the 'Lower Greensand' of Norfolk. Whitaker and Jukes-Browne (1899, pp. 5 and 8) described the Sandringham Sands as being probably over 100 ft (30m) thick, consisting mostly of light-coloured, sharp and silvery sands, but in their upper part iron-stained and in places cemented into a flaggy brown stone. The overlying Snettisham Clay, although poorly exposed, was recognised as a continuous bed from

Hunstanton (where it had been mistakenly identified by Rose and other early workers as Kimmeridge Clay) as far south as Ashwicken.

The clean white and green glauconitic sands of the Sandringham Sands invited natural lithological comparison with parts of the Lower Greensand of southern England and all the early workers except William Smith appear to have assumed the two formations to be of similar age. Smith noted in the marginal comments on his 1819 map that the 'Portland Rock' was occasionally found in the sand beneath the 'Golt Brick Earth', but the significance of this perceptive observation was overlooked for almost 150 years.

Lamplugh (in Whitaker and Jukes-Browne, 1899, p. 22) was clearly aware that the Sandringham Sands were older than the Atherfield Clay (the basal bed of the Lower Greensand in southern England), but it was not until Spath (1924, p. 79) assigned the overlying Snettisham Clay to the Lower Barremian, on the basis of its crioceratid ammonite fauna, that the Sandringham Sands became universally recognised as early Cretaceous in age and were tentatively assigned to the Berriasian (≈ Ryazanian but see below for discussion) to Hauterivian stages. At that time few fossils, other than the rare bivalves and bits of wood recorded by Rose (1862, p. 230), had been found in the Sandringham Sands and it was generally assumed that the basal beds of the formation were the earliest Cretaceous rocks in Norfolk.

In 1961, when the first good sections became available through the lower part of the Sandringham Sands (in the Cut-Off Channel at West Dereham), ammonites indicative of a late Jurassic to early Cretaceous age were obtained from the basal beds (Casey 1961a, 1963). Subsequent exposures in the cuttings for the King's Lynn Bypass (1964-5) provided additional faunal and lithological details of the lower part of the

Sandringham Sands and showed that this part of the formation underwent rapid lateral variation at outcrop. Important additional sections through parts of the basal beds were provided by the No. 2 and No. 4 Gas Feeder Main trenches dug for the Gas Council through the West Winch area in 1967 and 1968 respectively to carry North Sea gas to the Midlands.

The earlier sections showed the one-inch geological maps of the area to be inadequate and the present author therefore began the primary six-inch survey of the Norfolk Lower Cretaceous in 1965. Continuously-cored boreholes were drilled for stratigraphical purposes through the complete Top Jurassic - Lower Cretaceous sequences at Skegness, Hunstanton, Gayton and Marham in 1970, to supplement the survey. The boreholes at Skegness and Hunstanton were sited to provide data on the Lower Cretaceous outcrop beneath The Wash because serious interest was expressed at that time in the possibility of constructing a barrage from Lincolnshire to Norfolk to impound fresh water. The rapidity of the lateral lithological changes within the Lower Cretaceous of the area is such that these boreholes could not be correlated in detail and two additional cored boreholes (IGS 72/77 and IGS 72/78) were subsequently drilled within The Wash by the drilling ship m.v. Whitehorn in 1972. These various sections and boreholes and the survey enabled new lithological (Casey and Gallois, 1973) and palaeontological (Casey, 1973) classifications to be devised for the Sandringham Sands.

The recognition by Casey (1961a) that the Jurassic-Cretaceous boundary lay within a relatively complete, ammonite-bearing sequence in Norfolk and Lincolnshire stimulated much discussion concerning the position of this boundary in other sequences in the Boreal province. The nomenclature for the youngest Jurassic and the oldest Cretaceous

stages followed here is that given in a review of the evidence from a large number of sections in Europe by Casey et al. (1977) in which the system boundary is placed at the junction of the Volgian and Ryazanian stages. A more recent suggestion by Sasonova and Sasonov (1979) that the system boundary should fall within the Volgian Stage (which would itself be divided into two new stages - a Jurassic Gorodischian Stage and a Cretaceous Kashpurian Stage) has not been used because much of the correlation data quoted in its support is based on published work that had already been refuted by Casey et al. (1977).

The term Ryasanian was proposed by Sasonov (1951) for the basal Cretaceous stage of the Boreal faunal province because at that time no ammonite indicative of the Berriasian Stage, the basal Cretaceous stage of the Tethyan province, had been recorded in the Cretaceous of north-west Europe and large areas of Russia. The type section of the Ryazanian is in river cliffs in the banks of the Oka, a tributary of the Volga, at Ryazan (about 180 km south east of Moscow). More recent evidence has shown that it is ill chosen because it is a condensed and incomplete sequence consisting of glauconitic sands with phosphatic nodule and pebble beds. Casey (1973) drew attention to the similarity, both in lithology and fauna, of the basal Cretaceous sequences of eastern England to that of Ryazan and consequently used the term Ryazanian when describing the English succession. However, some Russian workers (e.g. Saks and Sasonova 1972, translated 1975), have questioned the usefulness of a separately defined Ryazanian Stage and have attempted to define the Berriasian Stage in terms of boreal ammonite genera. In an attempt at compromise Casey, Mesezhnikov and Shulgina (1977) have used the term 'Ryazanian-Berriasian'. For simplicity the term Ryazanian is used in this account except in Table 14 (which quotes Casey et al. 1977).

Whitaker and Jukes-Browne's original definition of the Sandringham Sands included all the beds between the Kimmeridge Clay and the Snettisham Clay. Lamplugh (in Whitaker and Jukes-Browne, pp. 16-17) drew attention to a bed of ferruginous, thin-bedded sandstone, in places "slaggy" or "cindery", in the upper part of the Sandringham Sands that had been quarried at Sandringham, which he thought appeared to pass northwards into the lower part of the Snettisham Clay. This observation was not confirmed by the present survey, but the sandstone has been shown to be part of a complex rhythmic sequence of clays and sands that includes the Snettisham Clay in its upper part. These beds have therefore been grouped together under the name Dersingham Beds (Casey and Gallois, 1973). Kent (1947, p. 17) suggested that the disappearance of the Snettisham Clay southwards from the Snettisham area was due to truncation by higher beds of transgressive Cretaceous strata rather than a lateral change in lithology. The present work suggests that the distribution of the Snettisham Clay results from a complex situation involving both overstep and facies change along the outcrop.

The stratigraphical results of the Hunstanton Borehole and the field survey suggested that the Snettisham Clay was not unconformably overlain by the Carstone throughout its outcrop (as had previously been supposed) but, in the Hunstanton area, that it was conformably overlain by an equivalent of the Lincolnshire Roach (sensu Swinnerton, 1935). The presence of the Roach (Middle or Upper Barremian in age) in Norfolk was subsequently confirmed by trenches dug on Hunstanton beach in 1972 and 1974. The nomenclature used for the Lincolnshire succession in this thesis is given in Table 14; individual formations are discussed in the text.

The Lower Cretaceous sequence in south-east Lincolnshire has long

SWINNERTON 1935		PRESENT WORK	STAGE
Chalk		Chalk	Cenomanian
Red Chalk		Red Chalk	Albian
Carstone Grit		Carstone	
Carstone Sand			
Sutterby Marl		Sutterby Marl	Aptian
		Skegness Clay	
Upper Roach Roach Stone Lower Roach	Fulletby Beds	Roach	Barremian
Upper Tealby Clay Tealby Limestone Lower Tealby Clay	Tealby Beds	Tealby Beds	
Upper Ironstone Hundleby Clay Lower Ironstone	Claxby Beds	Claxby Beds	Hauterivian Valanginian
Ferruginous Grit Glauconitic Sands Basement Beds	Spilsby Beds	Upper / Lower Spilsby Sandstone	Ryazanian Volgian
Kimmeridge Clay		Kimmeridge Clay	Kimmeridgian

Table 14. Comparison of Swinnerton's (1935) nomenclature for the Top Jurassic-Lower Cretaceous rocks of Lincolnshire with that used in the present work.

been known, from the work of Swinnerton (1935), to be more complete than that in Norfolk because of the southerly overstep of the Carstone. In the Skegness Borehole the Roach is separated from the Carstone by two Aptian formations, the Skegness Clay and the Sutterby Marl. Thin representatives of both formations are also present in boreholes in the central part of The Wash, but both have been removed by the unconformity at the base of the Carstone before the Norfolk coast is reached. At Hunstanton, the Carstone rests on the Roach. The stratigraphical relationships of the top Jurassic-Lower Cretaceous formations between Skegness and West Dereham are shown diagrammatically in Fig. 56 (see Fig. 55 for borehole sites).

For many years the relationship of the Carstone to the 'Lower Greensand' (= Woburn Sands) of the Buckinghamshire to Cambridgeshire area was poorly understood. The 19th-century geological maps of Norfolk classified both deposits as 'Lower Greensand' and it was generally assumed that they were contemporaneous. A number of authors noted that the two distinctive lithologies appeared to occupy mutually exclusive areas, the Carstone being confined to Norfolk and the Woburn Sands to more southerly counties. Recent work in the Ely district (Gallois, in press) has shown that there is a considerable area of overlap between the outcrops of the Woburn Sands and the Carstone and that the Woburn Sands (Aptian) are overstepped by the Carstone (Albian) in such a way that the most northerly exposure of Woburn Sands straddles the Norfolk-Suffolk county boundary.

Because of its striking lithology and colour and its excellent exposure in the cliffs at Hunstanton the youngest Lower Cretaceous formation in the district, the Red Chalk, has attracted much attention in the past. It was first recorded by William Smith (1816, p. 10), and

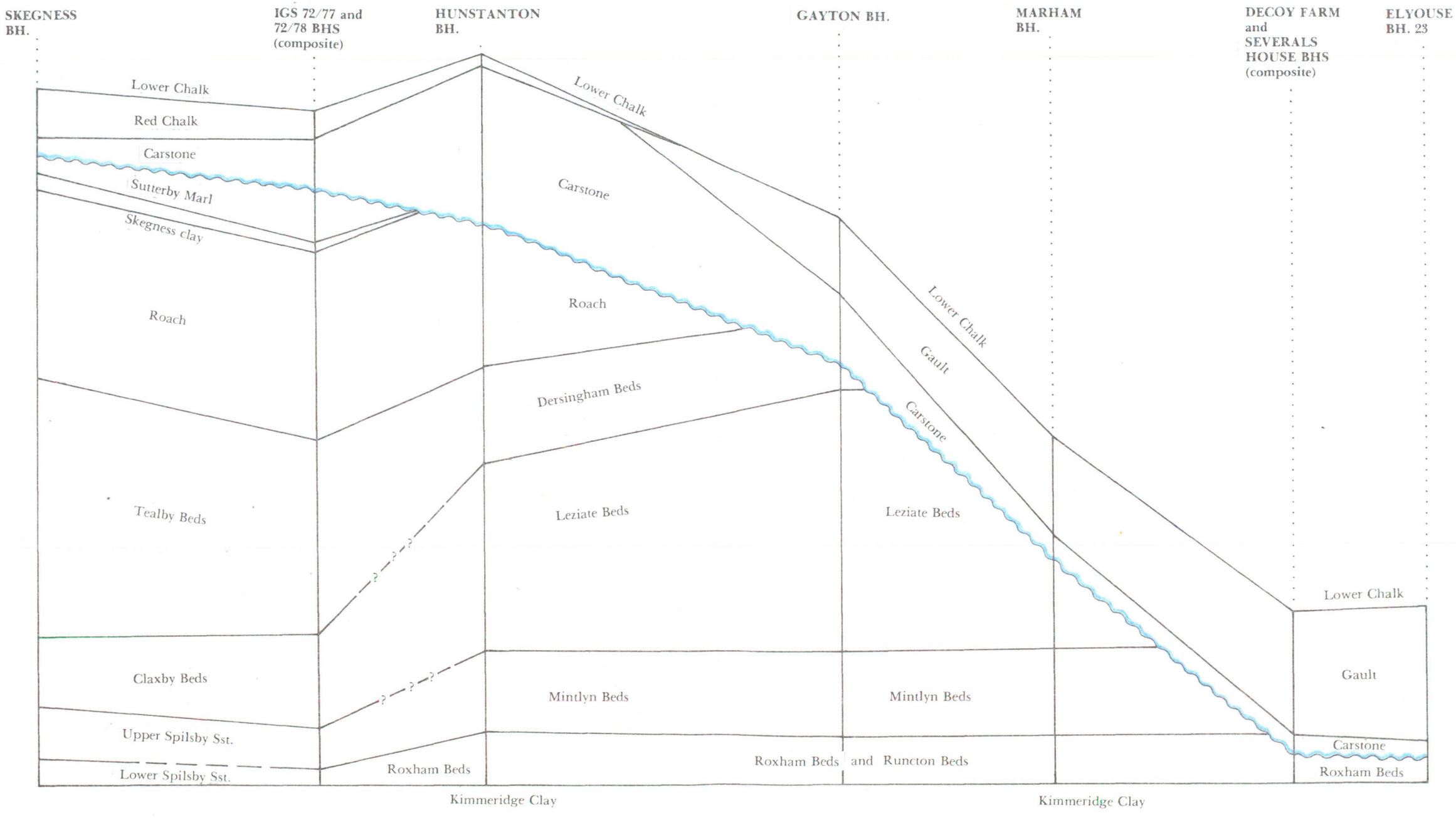


Figure 56. Stratigraphical relationships of the top Jurassic - Lower Cretaceous formations of Norfolk to one another. Top of Kimmeridge Clay taken as arbitrary datum. See Fig. 55 for borehole sites.

its stratigraphical relationship as the lateral equivalent of part of the Cambridgeshire Gault was appreciated as early as 1826 by Sedgwick (p. 342).

Southwards from Hunstanton the Red Chalk becomes progressively more argillaceous until in the vicinity of Sandringham it is partially replaced, and in the area south of the Babingley River it is wholly replaced, by the Gault. Little has been written about this last-named formation in Norfolk and the Geological Survey memoir (Whitaker et al., 1893) describing the Norfolk part of Old Series Sheet 65, and Jukes-Browne's review in the Cretaceous rocks of Britain (Vol. 1, 1900) remain the most comprehensive accounts. Jukes-Browne and Hill (1887) had earlier described a small number of sections in the Gault in the county.

The stratigraphy of the late Jurassic-early Cretaceous rocks of Norfolk has been reviewed by Larwood (1961) and their general stratigraphical relationships to Lower Cretaceous rocks elsewhere in England have been discussed by Boswell (1929), Kirkaldy (1939, 1963) and Rawson et al. (1978).

The positions of the more important exposures, temporary sections and borehole sections in the top Jurassic-Lower Cretaceous formations of Norfolk and The Wash are shown in Fig. 55. A detailed map of the land and submarine outcrops in the area between Hunstanton and the River Nar has been published on 1 to 50,000-scale Sheet 129/145: King's Lynn and The Wash (Gallois et al., 1978) and that for the area between Southery and Ely on 1 to 50,000-scale Sheet 173: Ely (Gallois, 1980). 1 to 10,000 - scale maps of the land area covered by Sheet 129/145 are on open file at IGS and are available as dyeline prints. A 1 to 25,000 - scale map of the formation boundaries for most of the submarine area of The Wash has also been published (Wingfield et al.,

1979). Geological maps of the area between the River Nar and Southery (Sheet 159: Wisbech) are in preparation.

4.2 Sandringham Sands

4.2.1 Introduction

The Sandringham Sands comprise a maximum of about fifty metres of predominantly arenaceous sediments which rise from the fringing marshes of The Wash near Heacham and form an almost continuous narrow outcrop from there to Downham Market (Fig. 55). The formation can be traced beneath the Holocene deposits of Fenland, by means of boreholes, to two small outliers at Hilgay and Southery and from there to its disappearance beneath the Lower Greensand overstep at Little Ouse [TL 630 880]. Much of the outcrop is covered by Pleistocene deposits and, as the sediments are poorly consolidated, natural exposures are rare, small and generally deeply weathered.

At outcrop between Heacham and Ashwicken the Sandringham Sands are conformably overlain by the Dersingham Beds(Fig. 56). To the south of Ashwicken the Carstone rests directly on the Sandringham Sands and the unconformity at its base progressively cuts out the Sandringham Sands in a southerly direction.

The Sandringham Sands have a relatively small subcrop that does not extend far beyond their outcrop. They were proved in deep hydrocarbon boreholes at Hunstanton, North Creake and South Creake and are probably present at Lexham. Sandringham Sands were absent from the Breckles, Great Ellingham, Lakenheath, Rocklands, and IGS Soham boreholes and from the more southerly boreholes (Nos. 1 to 20) drilled for the site investigation of the Ely-Ouse Water Transfer Scheme tunnels. When traced northwestwards from their outcrop into The Wash the bulk of the Sandringham

Sands become rapidly more clayey and pebbly. At most stratigraphical levels the lithologies that characterize the Norfolk outcrop can no longer be recognised by the time the IGS Boreholes 72/77 and 72/78 (8.5 and 9.0 km from the Hunstanton respectively) are reached. The Sandringham Sands can therefore be regarded as a mass of predominantly sandy sediment with a maximum proven area of distribution of about 12 km (The Wash to the South Creake Borehole) by 55 km (Hunstanton to the River Little Ouse). The extent of the subcrop north of Hunstanton beneath the North Sea is not known. Thick sandy Lower Cretaceous sequences were proved in many of the hydrocarbon boreholes in the offshore area but no core is available at this stratigraphical level and the palaeontological data available from the rock cuttings is inadequate to enable the sequences to be classified in detail.

The original extent of the Sandringham Sands, even on the land area can no longer be determined because of their later erosion by younger formations. Patches of sand, which may in part be correlatives of the Sandringham Sands, occur along the western margin of the London Platform as far south as Buckinghamshire. Only in The Wash, where the formation passes laterally into the more argillaceous Lincolnshire sequence, can the original depositional limit be determined with confidence.

The Sandringham Sands have been divided in the present survey into four formations, in ascending order the Roxham Beds, Runcton Beds, Mintlyn Beds and Leziate Beds (Table 15), on the basis of lithological characters that can be recognised in the field by means of exposures (mostly temporary excavations), soil fragments and topographical features. The outcrop of the formation is mostly drift-free in the area between Heacham and the River Nar and although the relief is low (5 to 30m above O.D.) features are well developed (Plate 19). Within that area soil fragments of the

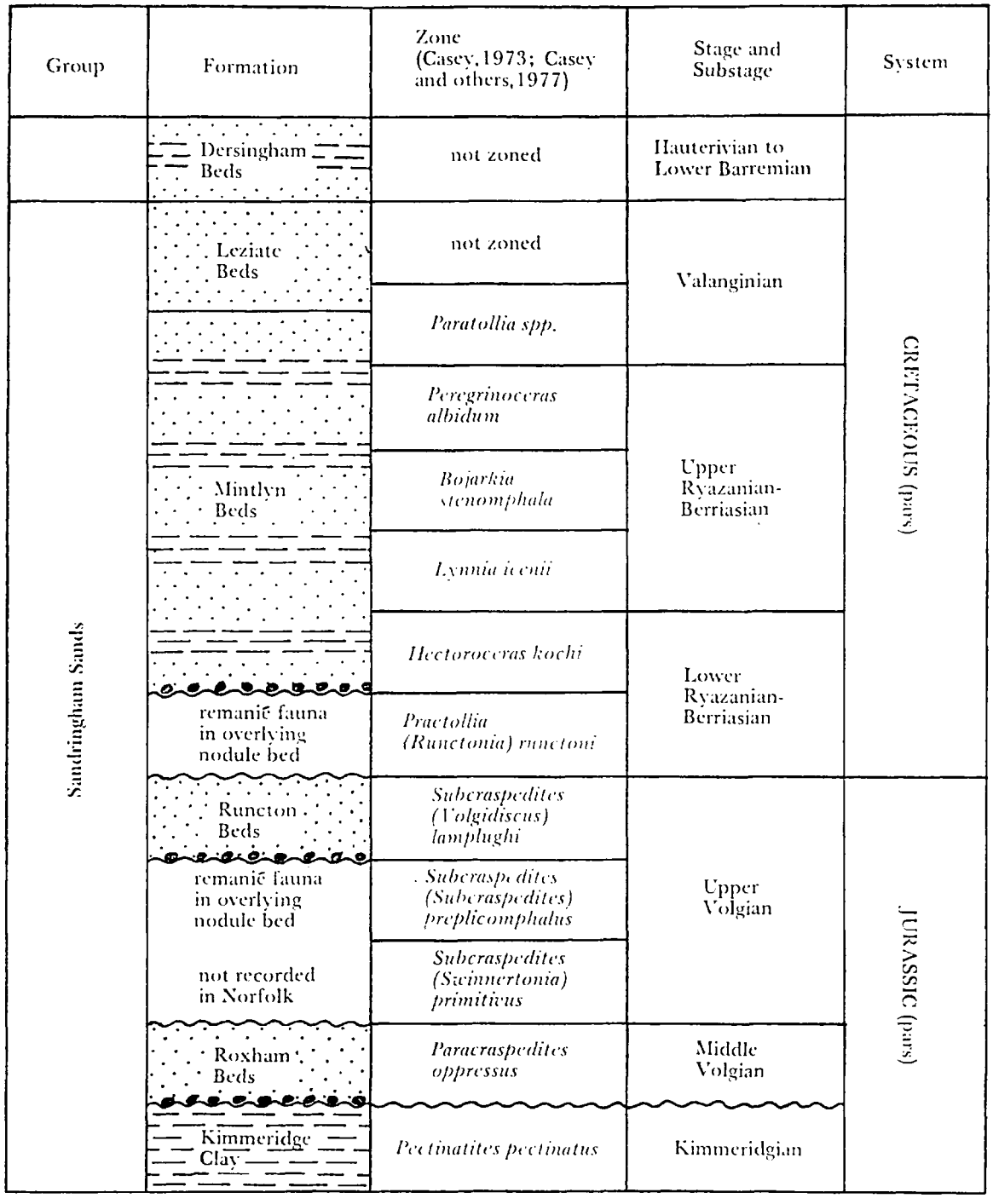


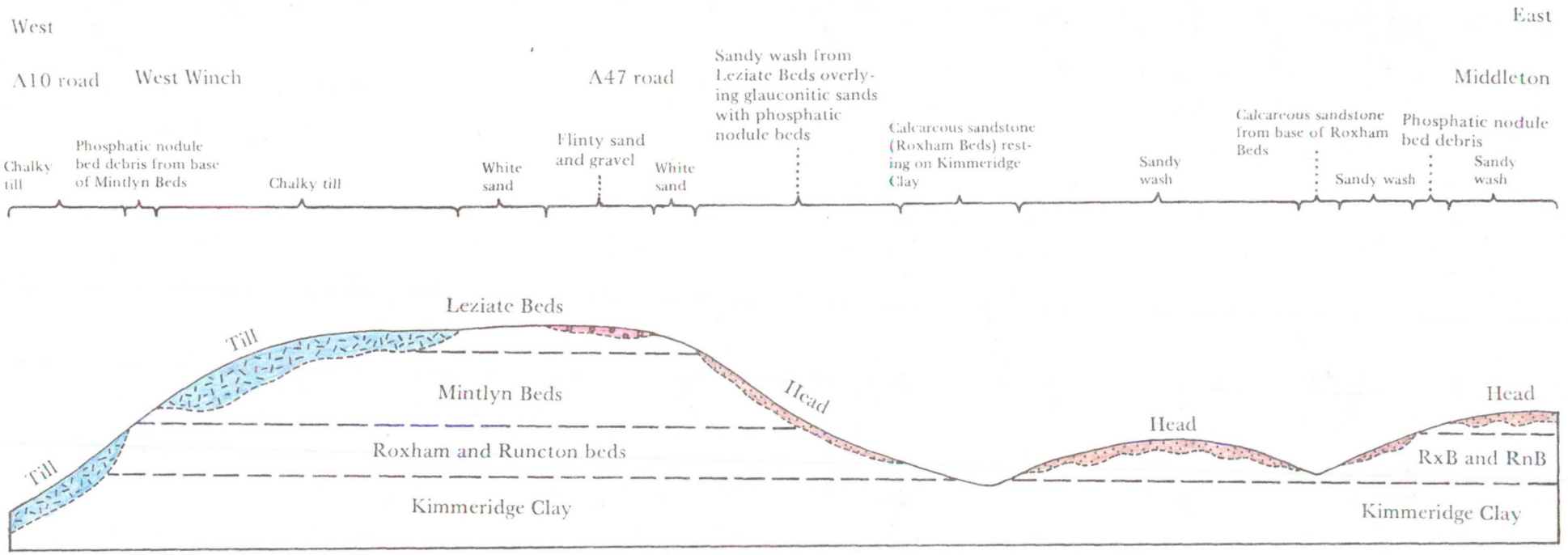
Table 15 The subdivisions and zones of the Sandringham Sands

more durable lithologies, notably phosphatic pebbles, ironstones and thin clays, are commonly exposed in drainage ditches.

The interpretation of such data needs, however, to be treated with caution because the effects of late Pleistocene cryoturbation and solifluction are widespread in the area, there being little or no protective cover of glacial deposits. Fortunately, the geological structure is extremely simple; dips are mostly < $\frac{1}{2}^{o}$ eastwards to north-eastwards and no faulting has been recorded, with the result that the features can usually be interpreted with confidence. A typical section through part of the Sandringham Sands outcrop between West Winch [631 167]* and Middleton [658 175], based on the field survey and a gas pipeline trench, is shown in Fig. 57.

A continuous section through the lower part of the Sandringham Sands became availabe for study in 1961 when the Cut-Off Channel of the Fenland Flood Relief Scheme was cut through the full preserved thickness of the formation between Fordham [TL 639 995] and West Dereham [TL 662 996]. The stratigraphy revealed was more complex than had hitherto been described. The 'loose white sands' that Rose (1835, p. 177-8) had recorded as characteristic of the formation that later came to be called the Sandringham Sands, and which give rise to the heathland scenery of the Sandringham area from which the formation takes its name, were absent through erosion and the Carstone rested on glauconitic sands and clays with crushed pyritized fossils and thin beds of fossiliferous clay ironstone. Similar clays and ironstones had been recorded in the King's Lynn area during the Victorian survey, but had been mistaken for Snettisham Clay (e.g. Whitaker et al., 1893, p. 18). The fauna of the basal bed of the Sandringham Sands (resting on Kimmeridge Clay) showed it to be Portlandian

* Except where otherwise stated all grid references in Chapter 4 fall in 100-km square TF.



Notes refer to strata exposed in trench Horizontal scale: 6 in to 1 mile Vertical scale: 1 in to 50 ft Vertical exaggeration x 18 approx.

Figure 57. Geological sketch section along the line of the No. 4 gas-feeder-main trench between West Winch and Middleton.

(Middle Volgian) in age as originally implied by William Smith (1819). That of higher beds showed that the Jurassic-Cretaceous boundary lay within a complex sequence of erosion surfaces and phosphatic pebble beds in the lower part of the Sandringham Sands. The rich ammonite faunas obtained from this section, together with material from the basal beds of the Sandringham Sands in the King's Lynn district and from the Spilsby Sandstone of Lincolnshire, enabled Casey (1973) to establish the first British zonal scheme for the beds at this (Volgian and Ryazanian) stratigraphical level. The zonation and nomenclature of the Sandringham Sands is summarised in Table 15.

The availability of unweathered material from marine, fossiliferous sands that straddle the Jurassic-Cretaceous boundary prompted palaeontological studies of particular aspects of the fauna and flora. Ager (1971) described the brachiopods from the basal bed of the Sandringham Sands and Creber (1972) compared gymnospermous wood from the Sandringham Sands of the Cut-Off Channel with similar material from the Kimmeridgian of Sutherland. More recently, Kelly (1977) and Pinckney (1978) have completed studies of the bivalves and belemnites respectively of the lower part of the Sandringham Sands and the Spilsby Sandstone.

Pringle (1920, 1923) recorded details of the Sandringham Sands in boreholes in west and south-west Norfolk. Kent (1947) described the lithology of the formation in the North Creake Borehole and noted the similarity of its basal bed to the basal bed of the Spilsby Sandstone of Lincolnshire. Rastall (1919, 1925) and Boswell (1927) compared the heavy mineral assemblages of samples of Sandringham Sands with those from the 'Lower Greensand' (Woburn Sands) of Bedfordshire and Cambridgeshire and Schwarzacher (1953) made a comparison of sedimentary features

Plate 19. Sandringham Sands sections and scenery.

A. The Jurassic-Cretaceous boundary is marked by a band of phosphatic pebbles and nodules within a highly glauconitic clayey sand sequence. No. 4 Gas Feeder Main Trench, Manor Farm, North Runcton, 1968. Photo. no. MN 26163.

B. The type section of the Runcton Beds and the Jurassic-Cretaceous boundary in Norfolk. View eastwards down the gentle dip; the trench is mostly cut in Runcton Beds, the junction with the overlying Mintlyn Beds being marked by Dr R. Casey. The low ridge in the distance is a small but prominent feature formed by thin tabular ironstones in the lower part of the Mintlyn Beds. No. 4 Gas Feeder Main Trench, Manor Farm, North Runcton, 1968. Photo. no. MN 26164.

C. The type-section of the Mintlyn Beds, exposed during excavation of the King's Lynn Bypass, January 1965. Strike section in which the harder, tabular beds of shelly ironstone can just be made out. Photo. no. A 10291.

D. The prominent feature, middle and far distance, is made by ferruginous sandstones at the base of the Dersingham Beds; these overly the soft sands of the Leziate Beds. View south from Dersingham Fen to Sandringham Warren. Photo. no. A 10897.

E. Lodge Hill, Snettisham, viewed from the south. The highest part of the ridge is capped by Carstone; the mixed lithologies of the underlying Dersingham Beds form the middle and upper slopes. The ferruginous sandstones at the base of the Dersingham Beds form a small subsidiary feature where they rest on soft Leziate Beds sands in the lowest part of the escarpment. Photo no. A. 10872.

A
B
C
D
E

(grain size, cross-bedding, etc.) in the same formations.

4.2.2 Roxham Beds

The basal formation of the Sandringham Sands consists of 3m to 6m of poorly consolidated grey and yellowish-green, locally glauconitic sands with disseminated pyrite and, at some levels, pyritic nodules. The formation takes its name from the section in the Cut-Off Channel at Roxham Farm [TL 638 995], West Dereham where Casey (in Casey and Gallois, 1973) recorded 3.5m of glauconitic slightly clayey sand with a basal pebbly sandstone. A typical section through the Roxham Beds, that proved in the Gayton Borehole, is shown in Fig. 58.

The Roxham Beds have been mapped out from their most northerly occurrence on the banks of the Babingley River [652 255] to their disappearance beneath Methwold Fens, near Southery. Temporary sections in a borrow-pit at Hardwick, King's Lynn [635 174], in foundation trenches at Fairstead Estate, King's Lynn [6430 1945], in purpose dug trenches at Brook Farm, North Runcton [6370 1630], in the No. 4 Gas Feeder Main trench near Middleton [6505 1710], in the No. 2 Gas Feeder Main trench at Manor Farm, North Runcton [6515 1555] (Fig. 59), in a drainage ditch at Castles Farm, Wormegay [655 119] and in the Cut-Off Channel at West Dereham have exposed parts of the formation and have suggested that it remains lithologically uniform at outcrop in Norfolk. This uniformity has been further confirmed by the IGS boreholes at Hunstanton, North Wootton, Gayton, Marham, Mundford, Southery and Little Ouse (Fig. 59). When traced north-westwards from the Babingley River into The Wash the thickness of the Roxham Beds is reduced by erosion at the base of the Mintlyn Beds (IGS Bh 72/77); they continue into Lincolnshire (e.g. Skegness Borehole) as the lower part of the Spilsby Sandstone (Fig. 60).

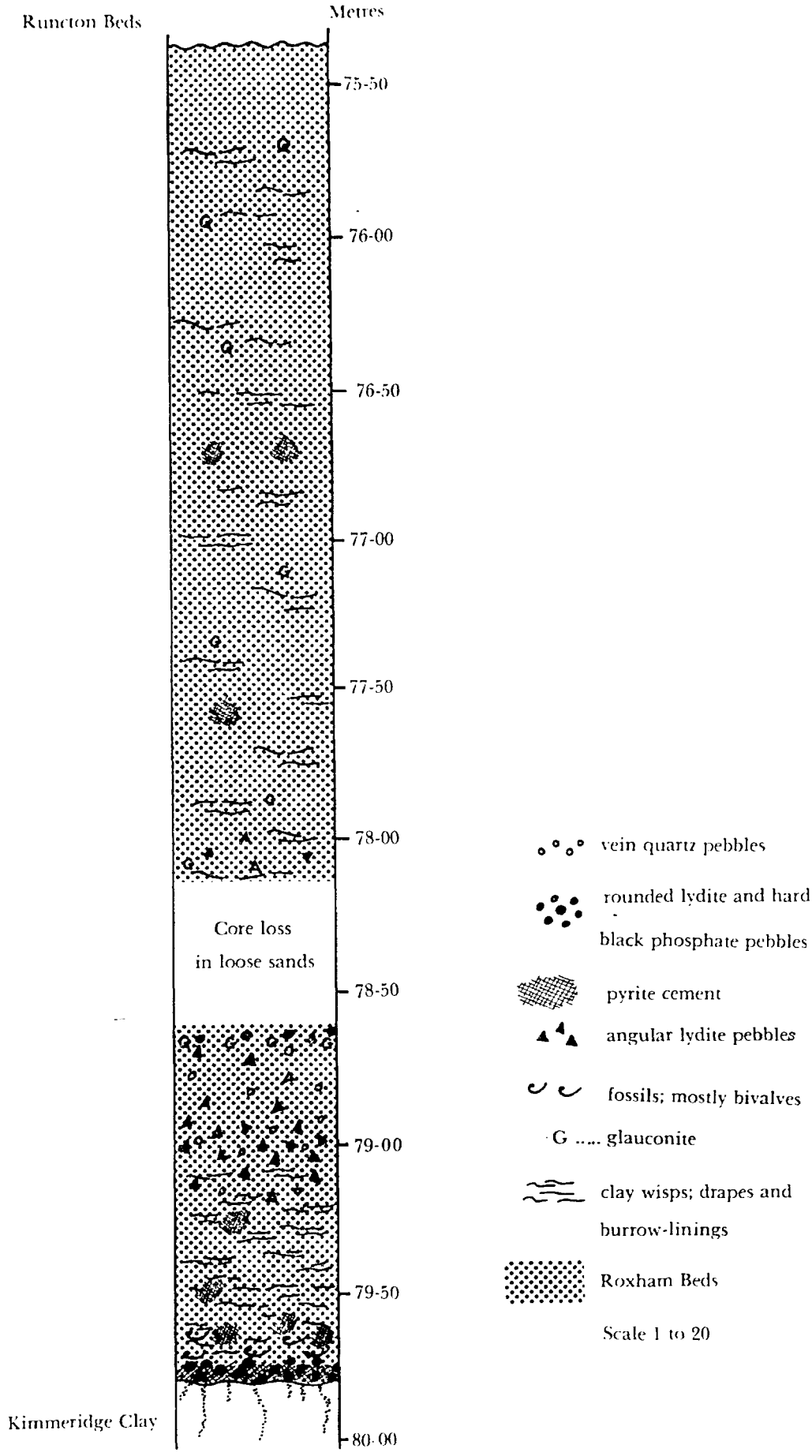


Figure 58. Graphic section of the Roxham Beds sequence in the Gayton Borehole.

In south-west Norfolk the Roxham Beds outcrop is mostly obscured by drift and the formation is only known from shallow research boreholes (percussion samples only) at Upgate Street, Southery [TL 6208 9483], Decoy Farm, Southery [TL 6490 9463], and Temple Farm, Little Ouse [TL 6292 8685]. There, the formation consists of up to 3.6m of fine-grained glauconitic sand with several beds of very dark, purplish brown carbonaceous clay up to 10 cm thick. This clay appears to be more fluviatile in aspect than the adjacent sands and may indicate a change in facies in the Roxham Beds as the London Platform is approached. The most southerly known occurrence of the formation is that at Temple Farm where 2.5m of deeply weathered Roxham Beds sands was recorded beneath Woburn Sands.

At the base of the formation the junction with the Kimmeridge Clay is marked by an erosion surface overlain by up to 1m of densely calcite-cemented, fine-grained, grey sandstone crowded in its lower part with pebbles of black chert (lydite) and black phosphate. Many of the latter are water-worn moulds of pavlovid ammonites and myid bivalves derived from the Kimmeridge Clay (Plate 20). Vein quartz and other pebbles occur less frequently.

Where observed in temporary sections in Norfolk the contact with the overlying Runcton Beds is erosional and is marked by either a phosphatic nodule-bed* that rests on an irregular burrowed surface

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* The distinction between phosphatic nodules and phosphatic pebbles is commonly overlooked in the description of Mesozoic strata. In argillaceous formations such as the Ampthill Clay, Kimmeridge Clay and Gault phosphatic nodules occur <u>in situ</u> as accretions around fossils and trace fossils (e.g. Plate 4). When intraformational erosion occurs such nodules commonly become incorporated in younger strata as water-worn pebbles or simply as exhumed masses from which the adjacent soft sediment has been removed by winnowing. Additional phosphatisation can occur during this process but its effects are generally slight and the difference between <u>in situ</u> phosphatic <u>nodules</u> and derived phosphatic <u>pebbles</u> is usually obvious. In the Sandringham Sands the situation is more complex. Phosphatisation and winnowing by currents appear to have occurred almost continuously so that, whilst individual phosphatic nodules and pebbles can be recognized, much of the phosphatic material in the sands has a complex origin. Irregular phosphatic masses up to 10 cm across are common at some levels and these may contain several generations of pebble and more than one phase of phosphatisation of the matrix. Materials of composite origin such as this are described as 'pebble/nodule beds' in the present account. Where recognisable, 'pebbles' and 'nodules' are distinguished separately.

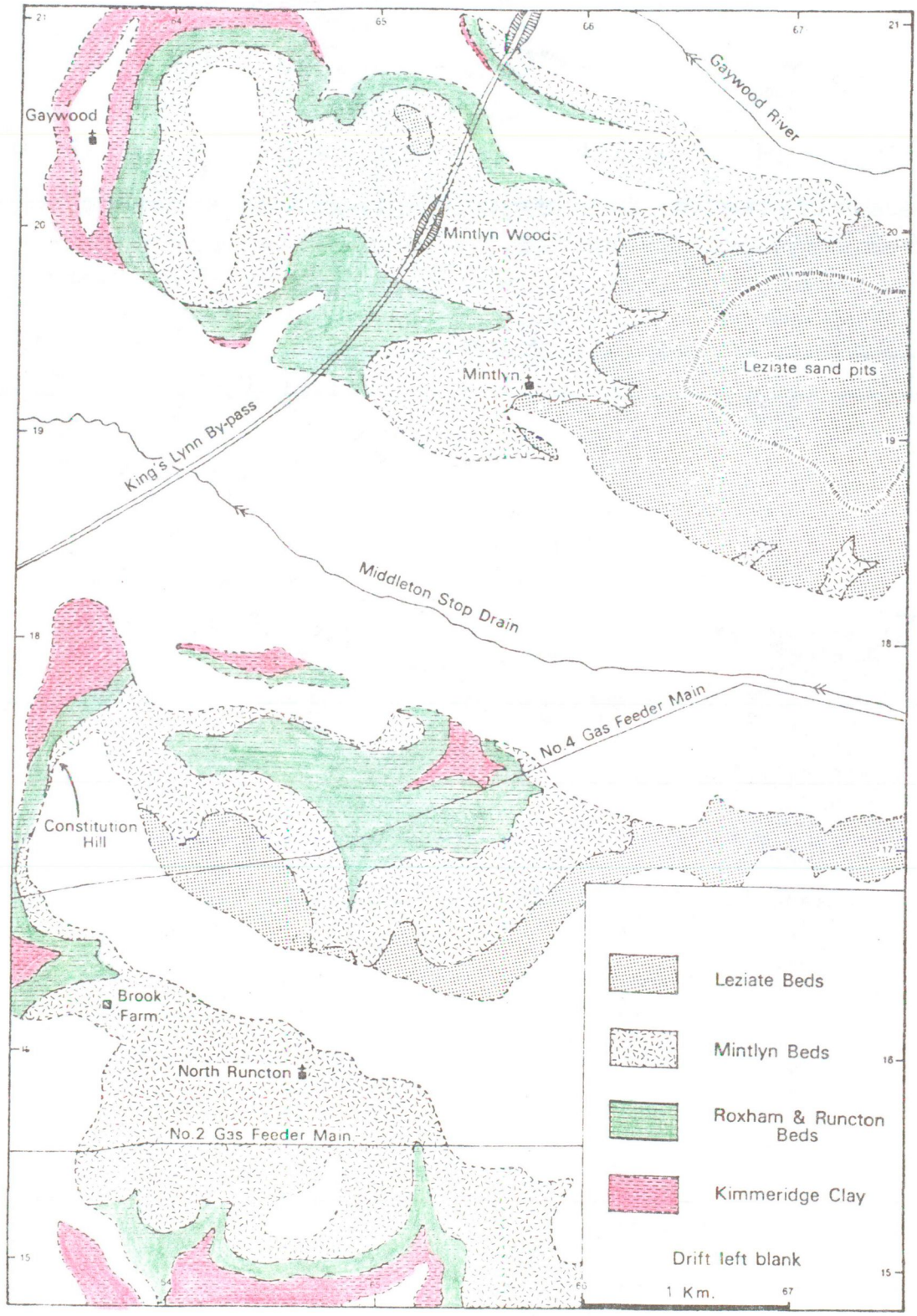


Figure 59. Geological sketch map of the Sandringham Sands outcrop in the King's Lynn area showing the positions of key sections referred to in the text.

Plate 20. Details of the basal cemented bed of the Roxham Beds (Sandringham Sands).

A. Partially rounded to well rounded boulders of the basal bed of the Roxham Beds within chalky boulder clay, close to the junction of the till and the Roxham Beds - Kimmeridge Clay junction. Similar boulders occur in large numbers in the till everywhere in Norfolk close to this junction; because of their durability, scattered examples are known from the till throughout Norfolk and Suffolk and as far south as Essex. Wereham Bypass, 1978.

B./C. Almost complete section through the cemented basal bed (about one third true scale) showing concentration of phosphatic and other pebbles at base, and gradation upward into well sorted bioturbated sand. C. Detail of Ophiomorpha burrows in upper part of bed shown in B; approximately true scale. Wereham Bypass, 1978.

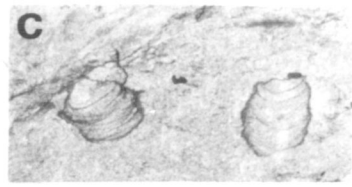
D. Section normal to bedding through the basal Roxham Beds pebble bed showing the rich calcareous fauna (usually largely dissolved at outcrop) in which belemnites (be) and bivalves are dominant. The pebbles contain derived bivalves (bi), foraminifera and other small fossils. North Runcton Borehole 8.90 m.

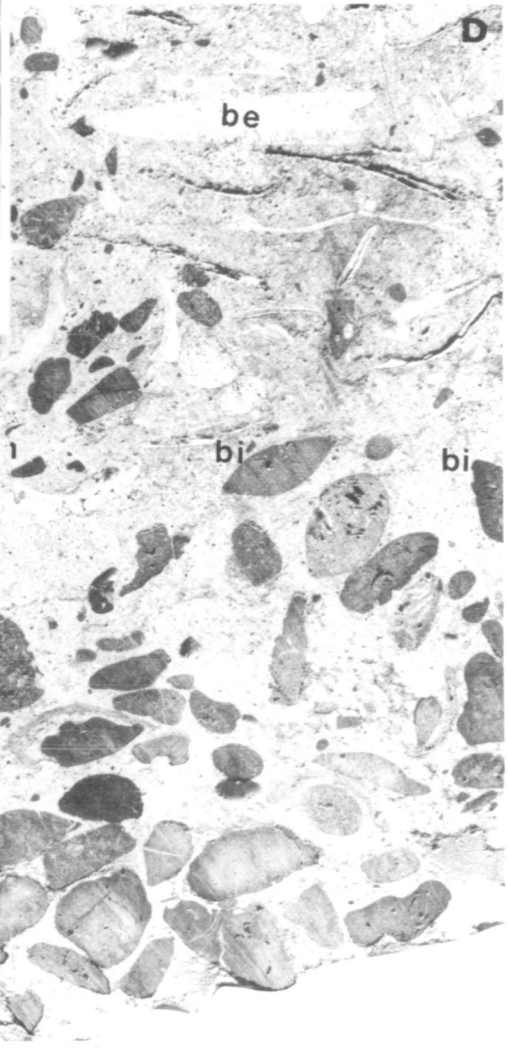
E. Phosphatised pavlovid ammonites within the basal bed of the Roxham Beds. Wereham Bypass, 1978.

F. Detail of basal pebble bed showing graded bedding, shelly fossils, and (upper right) a large bivalve shell that has acted as a trap for small phosphatic pebbles. Wereham Bypass, 1978.

Plate 20

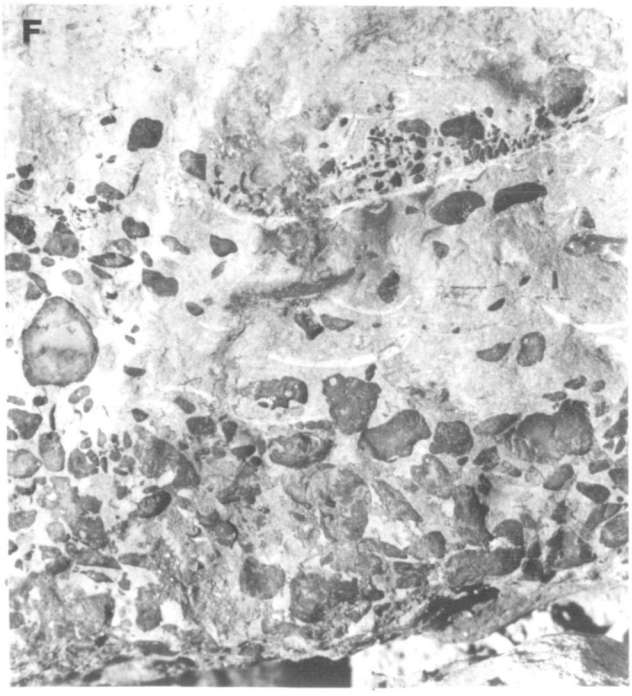












(e.g. at North Runcton) or by channelling (e.g. at West Dereham). The basal sandstone is intensely bioturbated throughout with Ophiomorpha and other burrows common, and with Ophiomorpha and Skolithos burrows filled with sand penetrating several tens of centimetres into the underlying Kimmeridge Clay (Plate 20). It forms a single fining-upward unit in which very pebbly sand passes up into shelly sand and then into sparsely shelly sand with abundant Ophiomorpha (Plate 20) and probably reflects a rapid reduction in the energy of the environment with time.

No large-scale sedimentary feature has been recorded in the Runcton Beds at outcrop, but this may be partly due to the deeply weathered nature of the sections recorded. In unweathered material in boreholes, bioturbation is present throughout and there is little evidence of bedding. Ophiomorpha burrows are abundant in the upper part of the basal sandstone where they are picked out by a lining of carbonaceous sand. Vague carbonaceous and clayey wisps, and mottling picked out by variations in sand grade and colour, occur at other levels and these probably indicate the presence of Ophiomorpha and similar burrows. Body fossils are rare except in the calcareously cemented basal bed and, replaced by pyrite, at a few higher levels.

The basal sandstone is persistent throughout the Roxham Beds outcrop and subcrop in the district (e.g. Hunstanton, Gayton and Marham boreholes) and forms a marked feature and spring line at outcrop. Its thickness is variable, up to 1.5m thick, and the cement may locally be patchy. The common occurrence of large rounded masses (up to 2m across) of it in the Chalky-Jurassic till throughout East Anglia suggests that it may, in places, have originally occurred as concretionary masses. The same bed has been traced as a prominent seismic reflection marker beneath The Wash (Reflector KO of Wingfield et al., 1979) and is present at the base of the Spilsby Sandstone on the Lincolnshire side of The Wash (e.g. Skegness Borehole).

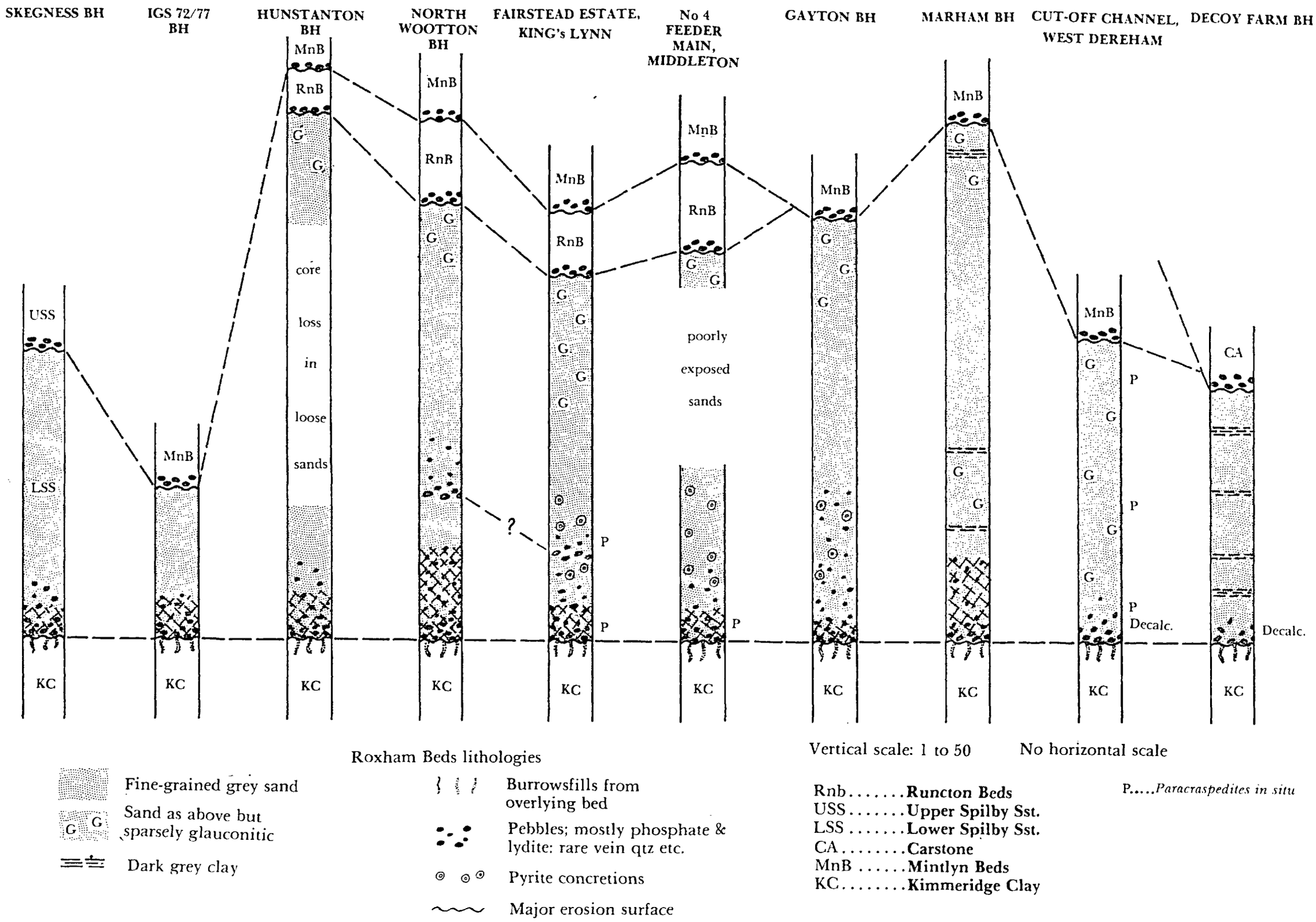


Figure 60. Correlations between the Roxham Beds sequences in Norfolk.

The geographical source of the sandstone erratics is not entirely clear. Casey (1963, p. 13) noted that the basal bed of the Sandringham Sands could be closely matched in lithology with the basement bed of the Spilsby Sandstone at outcrop in Lincolnshire (Beds A and B of Swinnerton, 1935) and the erratics could have come from either or both counties. The presence in the till of west Norfolk of large amounts of Lower Cretaceous material which, from its lithologies, could only have been derived from Norfolk (Gallois, 1978), suggests that the Roxham Beds erratics are largely derived from the Norfolk outcrop. To the north of the Babingley River, former outcrops on the floor of The Wash and eastern side of The Wash that are now overlain by Recent deposits, probably also contributed much material. Calcareous sandstone erratics of a similar lithology, but of undoubted Lincolnshire origin, have also been recorded in the drift of the district. Casey (1973, Plate 3, Fig. 4) has collected preplicomphalus Zone ammonites from erratic boulders at Leziate, and has recorded the same fauna in calcareous sandstone doggers in the Lower Spilsby Sandstone in the Fordington Borehole, Lincolnshire (1973, p. 203). Sandstone of this age has not been recorded in situ in Norfolk.

The basal phosphatic pebble bed of the Roxham Beds was correlated by Casey (1973) on the basis of its distinctive lydite cherts and derived phosphatized pavlovid ammonites with the Upper Lydite Bed, a phosphatic pebble bed that marks the base of the Portland Beds in the Aylesbury to Swindon area. This correlation is possibly misleading because the Upper Lydite Bed is not a marker bed in the chronostratigraphical sense. Its age varies from kerberus to oppressus Zone (early to late Middle Volgian) between Wiltshire and Norfolk and from oppressus to primitivus Zone between Norfolk and north Lincolnshire (Fig. 61).

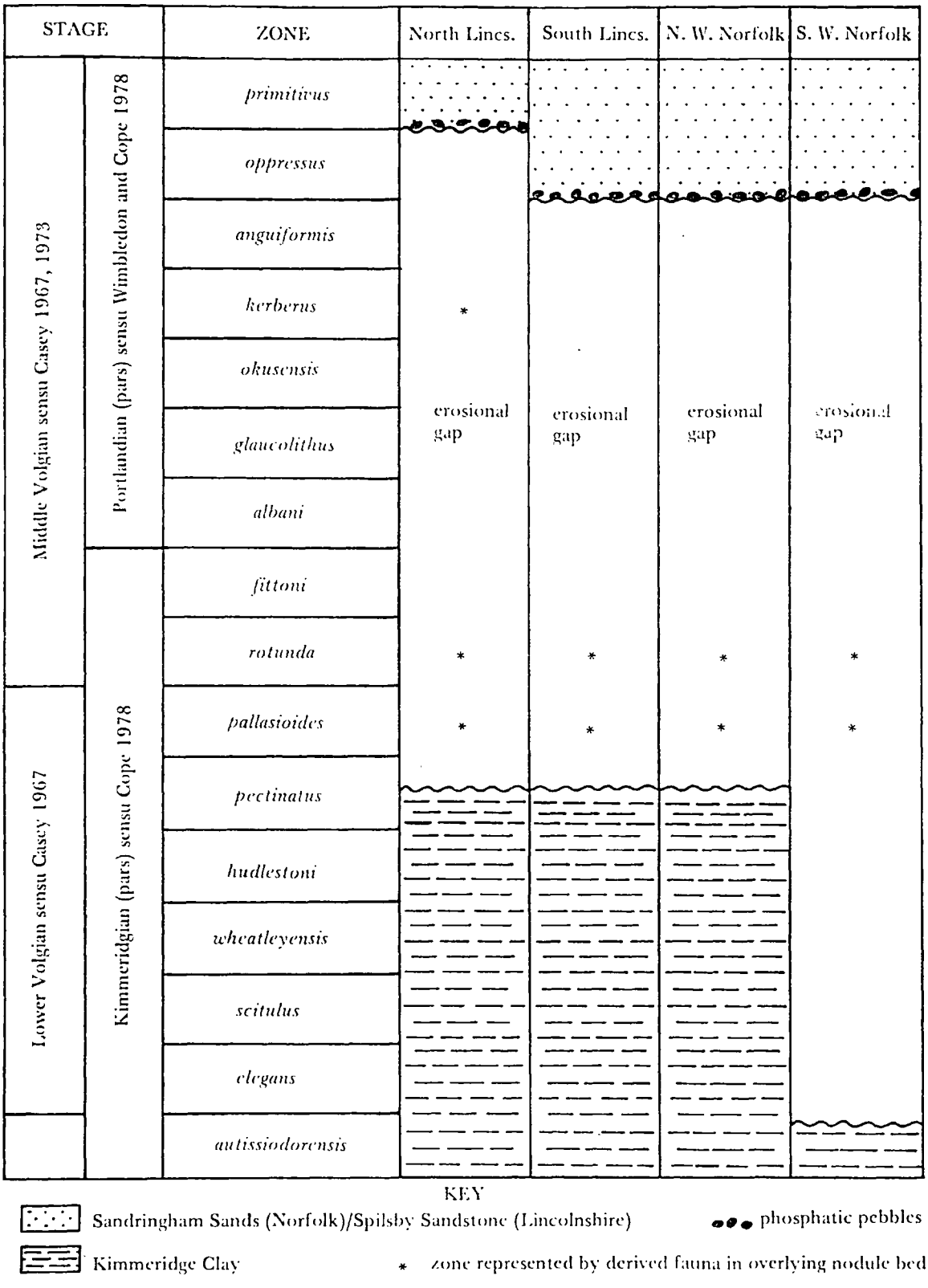


Figure 61. Comparative sections showing the time occupied by the late Jurassic erosional gap in Lincolnshire and Norfolk.

There is no evidence of diachroneity in the Roxham Beds in Norfolk.

The most prolific source of indigenous fossils from the Roxham Beds has been the basal sandstone. At Roxham Farm the sandstone was decalcified by weathering to a loose pebbly sand with pyritic nodules containing moulds of bivalves and ammonites. These were identified by Casey (1973, p. 199) as including the Middle Volgian zonal index ammonite Paracraspedites oppressus Casey, together with P. cf. bifurcatus Swinnerton, P. stenomphaloides Swinnerton and Glottoptychinites? trifurcatus Swinnerton. The Roxham Beds sands in the spoil from the trenches at Fairstead Estate also yielded pyritized, but poorly preserved, Paracraspedites. Elsewhere at outcrop in Norfolk the pyritic nodules at higher stratigraphical levels within the Roxham Beds crop out above the water-table and have been destroyed by oxidation so that the only consistently fossiliferous horizon in the formation is the basal sandstone. This was recorded in situ below the water-table in the No. 4 Gas Feeder Main trench near Manor Farm, Middleton [6507 1709], where it had retained its calcite cement and contained abundant Paracraspedites spp., the belemnite Acroteuthis, the large terebratulid brachiopod Rouillieria ovoides (J. Sowerby) (Terebratula rex auctt.) and numerous bivalves including common Entolium, Oxytoma and Modiolus. The same bed was also recorded in drainage trenches at Wormegay [655 119] but was decalcified and much of its fauna destroyed. Unweathered basal Roxham Beds sandstone is also present in the Hunstanton, Gayton and Marham boreholes and some of the oil-shale exploration boreholes recorded by Pringle (1923), but the core diameters were too small for much of the fauna to have been preserved.

Many of the erratic boulders of the sandstone that were discovered in the till in the cuttings of the King's Lynn Bypass and in the overburden

at Leziate Sand Pits yielded a prolific fauna of ammonites (Casey, 1973), bivalves (Kelly, 1977), belemnites (Pinckney, 1978; Pinckney and Rawson, 1974) and brachiopods (Ager, 1971). The fauna of these boulders presumed to have been derived from outcrops in Norfolk and beneath The Wash can be summarized as follows: Rhynchonella aff. subvariabilis (Davidson), Rouillieria ovoides (J. Sowerby), Anisocardia sp. nov., Arctotis cf. intermedia Bodylevsky, Camptonectes morini (de Loriol), Cucullaea (Dicranodonta) vagans Keeping, Codakia? crassa (J. Sowerby), Corbicellopsis claxbiensis (Woods), Entolium orbiculare (J. Sowerby), Falcimytilus suprajurensis Cox, Grammatodon sp., Iotrigonia sp. nov., Isognomon cf. cuneatum Zakharov, Liostrea plastica (Trautoskhold), lucinid, Mesomiltha kostromensis (Gerasimov), Modiolus sp., Musculus (M.) fischerianus (d'Orbigny), Myophorella (M.) intermedia (Fahrenkohl), Myophorella sp., Nanogyra thurmanni (Etallon), Neocrassina (Lyapinella) asiatica Zakharov, N. (Pressastarte) sp. nov., Nicaniella claxbiensis (Woods), N. mnewnikensis (Milaschwitch), N. sp., ostreid, Oxytoma octavia (d'Orbigny), Pinna cf. constantini de Loriol, Pinna sp., Plagiostoma sp., Pleuromya cf. uniformis (J. Sowerby), Pleuromya sp., Plicatula, Protocardia (P.) concinna (von Buch), Pseudolimea arctica Zakharov, Senis aff. petschorae (Keyserling), gastropods indet., Paracraspedites spp. and Acroteuthis sp.

4.2.3 Runcton Beds

The Runcton Beds consist of highly glauconitic sands with phosphatic nodule/pebble beds at several levels. They are intensely bioturbated throughout and no other sedimentary structure has been recorded in them either at outcrop or in boreholes. The base of the formation rests unconformably, and with slight irregularity, on the Roxham Beds; the

Runcton Beds are themselves overlain unconformably by the Mintlyn Beds. The Runcton Beds have been mapped out almost continuously between North Wootton and Downham Market but because of the narrowness of their outcrop they have been combined for convenience with the Roxham Beds (with which they have Jurassic affinities) on the geological maps. Phosphatic debris from the pebble beds that bound the Runcton Beds occurs as persistent soil fragments and drain spoil and the boundaries are relatively easy to trace. The basal Runcton Beds pebble bed can be differentiated from that which marks the base of the Mintlyn Beds on lithology (see below).

The present-day distribution of the Runcton Beds appears to be that of a narrow subcrop elongated parallel to the outcrop. The outcrop runs from the Babingley River to Downham Market; to the north it is overlain by the Recent deposits of Wolferton Marshes and The Wash and presumably continues as far north as the latitude of Hunstanton (proved in the Hunstanton Bh.), but does not extend much further northwards (absent in IGS Borehole 72/77) (Fig. 62). To the south (West Dereham) and east (Gayton and Marham boreholes) the formation is absent due to overstep by the Mintlyn Beds and the subcrop is narrow.

The Runcton Beds attain their maximum thickness of about 1.5 metres, estimated from the geological survey, at outcrop in the North Runcton area. The thickest observed sequence recorded to date occurred in the No. 2 Gas Feeder Main trench at Manor Farm, North Runcton [6515 1555] where the formation consisted of 1.15m of dark green, glauconite clayey sand with bivalves and ammonites in clay-cast and phosphatic preservation. The following section (after Casey and Gallois 1973, p. 6) is a composite based on sections

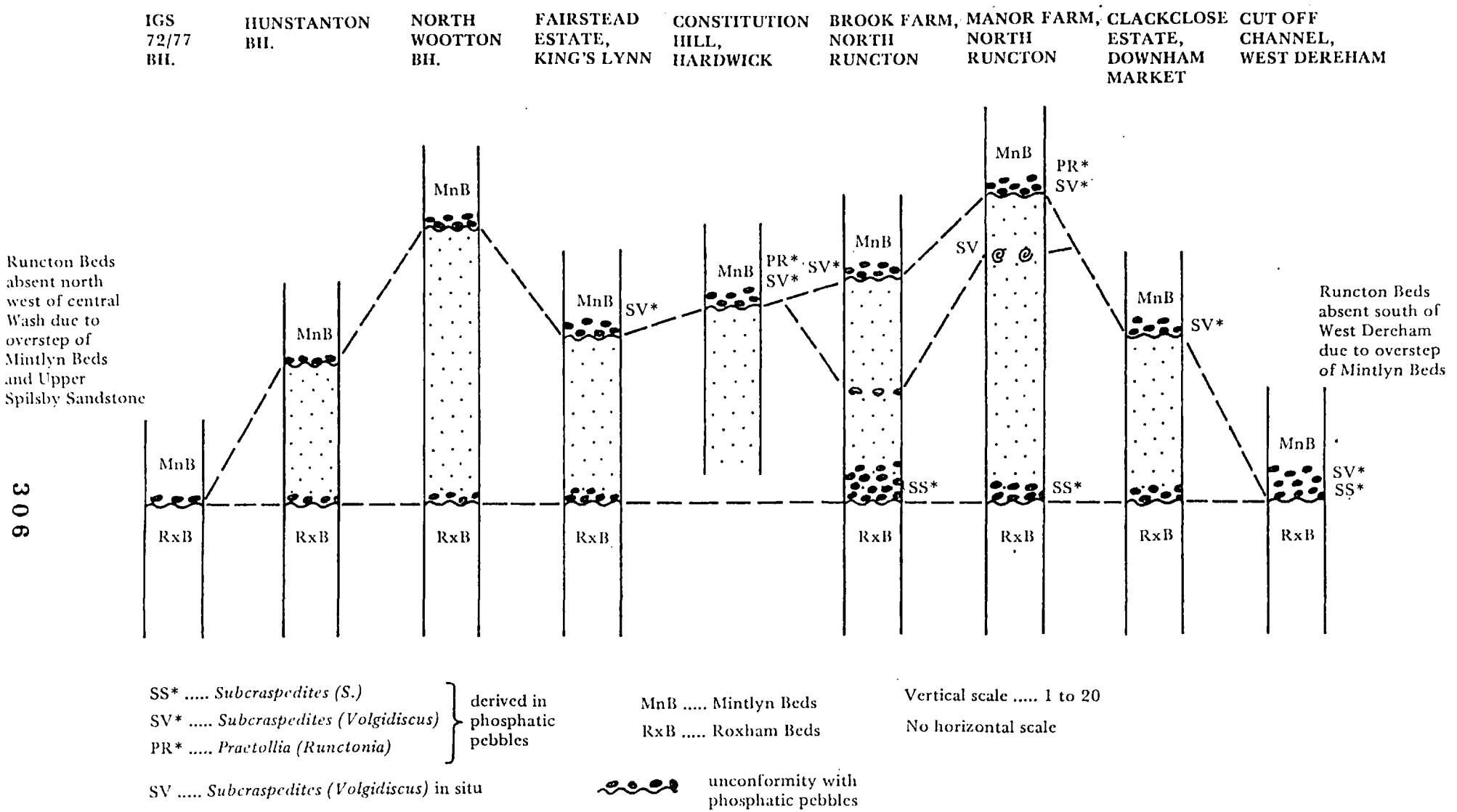


Figure 62. Correlations between the Runcton Beds sequences in Norfolk.

recorded over about 100m of trench; the lowest nodule bed was measured and collected *in situ* by touch below the water-table:

Mintlyn Beds

Basal phosphatic nodule/pebble bed .. .. .. 0.10 to 0.15m

Runcton Beds

Sand, bright green, glauconitic, clayey with brown clay and phosphatized clay wisps, clay casts and 'ghosts' of fossils 0.15m

Phosphatic nodule bed; brown fragile phosphate, mostly moulds of ammonites and bivalves in matrix as above; the ammonites include *Subcraspedites* spp., tending to fall apart at the sutures.. .. 0.3 to 0.10m

Sand, dark green, clayey glauconitic 0.75m

Black, rough, phosphatic nodules/pebbles, some in clotted masses; *in situ* but below water level in trench; *Subcraspedites* in this mode of preservation loose on tip 0.15m

Roxham Beds (part only)

Sand, grey-green, faintly glauconitic, slightly clayey, loose; collected from below water level in trench.

A similar, but laterally more variable section was recorded in three closely spaced (about 5m apart) trenches made to examine the sequence at nearby Brook Farm [6370 1630] ; these showed the non-sequences bounding and within the Runcton Beds to be complex and impersistent over short distances (Fig. 63). The following composite section was measured:

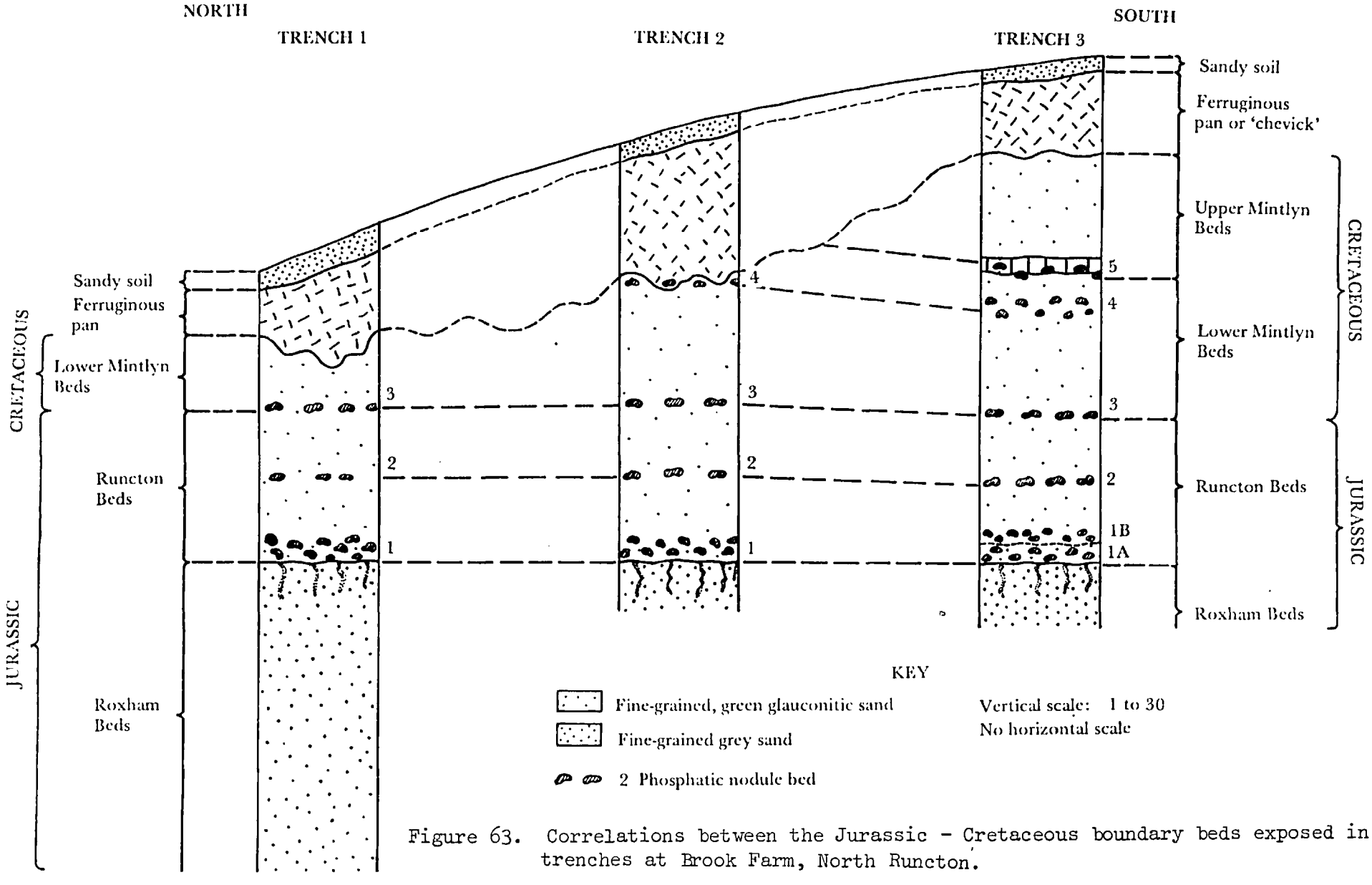


Figure 63. Correlations between the Jurassic - Cretaceous boundary beds exposed in trenches at Brook Farm, North Runcton.

Quaternary on Mintlyn Beds with phosphatic nodule/pebble bed at base; resting on irregular surface of .. .. see Fig. 63

Runcton Beds

Sand, fine-grained, greenish-grey weathering to brownish grey, glauconitic, slightly clayey .. 0.33m

Phosphatic nodule bed; impersistent band of widely spaced, soft, medium brown phosphatic nodules with casts of small bivalves and rare Subcraspedites .. .. up to 0.02m

Sand, fine-grained, dark green, glauconitic; clayey throughout with wisps of glauconitic clay; small patches of secondary ferruginous cement 0.33m

Phosphatic nodule/pebble bed; composite bed, ferruginously cemented in part, consisting of an upper (0.08m thick) and a lower (0.10m thick) band separated by a secondary ferruginous pan; upper band composed of large, irregular dark bluish grey phosphatic nodules mixed with aragonitic shell debris and soft, crumbly, medium brown phosphatic nodules; lower band composed of dark bluish grey irregular nodules, irregular base .. .. 0.12 to 0.18m

Roxham Beds

Sand, dark grey (pale above water-table), fine-grained, faintly glauconite-speckled with prominent burrowfills of dark green clayey sand extending down from overlying bed; well sorted, clean faintly purplish black in part due to communuted plant debris .. .. 1.16m seen

These same beds were probably briefly exposed in the trench for the No. 4 Gas Feeder Main between the Lynn to Norwich road [643 169] and Middleton [650 171] (Fig. 57). Because of the loose, water-logged nature of the sands the pipeline was emplaced shortly after excavation and no section was recorded. The spoil included glauconitic greenish grey, fine-grained, clayey sands with phosphatic nodule beds within and at their base including, in the middle part of the bed, a band of soft, medium brown phosphatized bivalves (as seen at Brook Farm and Manor Farm).

At all three localities, Manor Farm, Brook Farm and Middleton, the base of the Runcton Beds is marked by a phosphatic pebble bed that rests on a slightly irregular, burrowed surface of Roxham Beds. The green, glauconitic sands of the Runcton Beds form a marked colour contrast with the uniformly grey Roxham Beds; a change of permeability between the slightly clayey Runcton Beds and the relatively clean Roxham Beds causes a line of seepage to form at their junction.

About 1 km north of Brook Farm, at Constitution Hill, Hardwick [635 174] the overlying basal Mintlyn Beds pebble bed has removed the top part of the Runcton Beds and the formation is less than 1m thick. Northwards from Hardwick the formation continues as about 1m of glauconitic sand with phosphatic pebble/nodule beds at several levels. It was proved as loose debris in the excavations at Fairstead Estate, King's Lynn, in ditch sections at North Wootton Common [638 250] and in the North Wootton Borehole (at 12.30 to 13.80m).

In Borehole IGS 72/77, in the central part of The Wash, the Runcton Beds are absent and the basal Mintlyn Beds pebble bed rests on Roxham Beds (Fig. 60). On the Lincolnshire side of The Wash, Casey (1973, Fig. 2) has correlated the Runcton Beds with the bulk

of the Lower Spilsby Sandstone of Lincolnshire on faunal evidence.

To the south of North Runcton, the Runcton Beds have been recorded as loose debris in the temporary sections referred to above and as weathered spoil in ditches at Wormegay [655 119], Wimbotsham [609 057], Downham Market [607 047], Denver [613 007] and in the Cut-Off Channel at West Dereham. At this last locality the Runcton Beds occur as remanié phosphatic pebbles within a thick pebble/nodule bed complex at the base of Mintlyn Beds.

The fauna of the Runcton Beds is sparse. Derived Subcraspedites (S.) cf. sowerbyi Swinnerton, indicative of the former presence of the Upper Volgian Subcraspedites (S.) preplicomphalus Zone, occur in the basal pebble bed of the formation at North Runcton (Casey 1973, p. 200) (Fig. 62). No evidence of the underlying Subcraspedites (Swinnertonia) primitivus Zone has yet been recorded in Norfolk. Subcraspedites (Volgidiscus) lamplughi Spath, the zonal index of the lamplughi Zone, the youngest Jurassic zone in Britain, occurred in a soft brown phosphatic preservation (clearly indigenous) in the trenches at Manor Farm and Brook Farm (Casey in Casey and Gallois, 1973). The same ammonite is commonly a derived component of the Basal Cretaceous (= basal Mintlyn Beds) pebble bed in Norfolk and Lincolnshire indicating that beds of lamplughi Zone age were formerly widespread.

4.2.4 Mintlyn Beds

The Mintlyn Beds consist of grey, greyish green and green glauconitic sands and clayey sands with thin beds and lines of doggers of clay ironstone (siderite mudstone) and thin (mostly < 15 cm) beds of green glauconitic clay. Erosion surfaces marked by phosphatic pebble beds occur at two or more levels in the lower part of the formation. The

high iron content and low permeability of the Mintlyn Beds cause them to weather to poorly drained, dirty orange-brown sand with much secondary limonite (commonly in the form of iron-pan).

In the few large expsoures recorded in the Mintlyn Beds, the ironstone bands and clay seams appear to be even and parallel bedded over long distances. Small-scale sedimentary structures are rare at outcrop because of the deep weathering, but in borehole cores bioturbation, planar lamination and rarer cross-lamination are picked out by clay wisps and concentrations of glauconite, shell debris, carbonaceous sand and clean white sand. Most of the clay seams occur as the basal members of small coarsening-upwards rhythms in which the clay rests with sharp lithological contrast on relatively clean sand.

Indeterminate burrow mottling occurs throughout the formation; Chondrites and Rhizocorallium are common at several levels. Minor erosion surfaces with cf. Skolithos and other burrows commonly mark the junctions of two lithologies,and several of the ironstones are partially phosphatized and form a hardground with a burrowed and bored upper surface that carries a concentration of shells and, in a few instances, phosphatic pebbles. Body fossils are rare except in the ironstones and a few pyritic concretions, and as casts in some of the thicker clay seams. Plant scraps and bits of coalified wood are common throughout.

The formation crops out almost continuously between Wolferton and West Dereham, mostly on low ground at the foot of an escarpment formed by the Leziate Beds and Dersingham Beds. In most areas, the higher part of the Mintlyn Beds is largely covered by loose sandy wash derived from the Leziate Beds. Only on the interfluves at the widest part of their outcrop, between the Babingley River and the

River Nar, can they be readily studied; even there, they are deeply weathered and give rise to poorly drained soils rich in secondary iron. The formation takes its name from this area, from the former parish of Mintlyn near King's Lynn, where much of the sequence was exposed in the Mintlyn Wood cutting of the King's Lynn Bypass (Plate 19).

Eastwards from their outcrop the Mintlyn Beds are present in the same lithologies in the Hunstanton, Gayton and Marham boreholes; the original depositional thickness of the formation appears to have been somewhat variable in its known area of preservation. The northerly and westerly limits of the formation are poorly known. A thin (5.2m) representative of it, overlain by Claxby Beds, was recorded in the central part of The Wash in IGS Borehole 72/77. The formation thins slightly northwards and eastwards from an estimated thickness of about 20m at King's Lynn to 11.4m in the Hunstanton Borehole, 12.9m in the Gayton Borehole and 14.0m in the Marham Borehole. At outcrop, the progressive southerly overstep of the Carstone across the Sandringham Sands brings the Carstone to rest on the Mintlyn Beds at Ryston Park, Denver [624 014], and then cuts out the formation between there and Southery (Fig. 56). Only the lowest 6.5m of the formation is present in the Cut-Off Channel at West Dereham.

Throughout their outcrop the Mintlyn Beds rest unconformably on the Runcton Beds or, between the Cut-Off Channel and Hilgay, on the Roxham Beds. In most sections the erosive nature of the basal pebble bed of the Mintlyn Beds is clearly demonstrated by its irregular, commonly channelled, contact with the underlying beds. The phosphatic pebbles of both the basal Runcton Beds pebble bed and the basal Mintlyn Beds pebble bed occur as gritty, glauconitic, irregular masses cemented

by secondary phosphate, and both contain derived Subcraspedites. However, the pebbles from the two horizons can be distinguished in soil fragments because they differ in colour and texture. The Runcton Beds pebbles/nodules are dense, uniformly black or bluish black (and remain so on weathering) with very rare worn Subcraspedites fragments, whereas the basal Mintlyn Beds pebbles/nodules are commonly dark brown or black but contain paler and darker patches (due to the incorporation of earlier pebbles), have a creamy white weathering patina that accentuates the colour of the glauconite grains, yield relatively common Subcraspedites and other ammonites, and commonly contain iridescent shell debris.

The largest and most stratigraphically revealing section yet recorded in the Mintlyn Beds is that in the cutting [6508 1987 to 6530 2010] dug for the King's Lynn Bypass at the western end of Mintlyn Wood. The beds dip north-eastwards at less than 1°. The following composite section is based on that recorded by Casey (in Casey and Gallois, 1973, pp. 13 - 14):

Mintlyn Beds

Clay ironstone, buff, sandy, slightly glauconitic with bivalve fragments; limonitic "box-stone" weathering	0.10m seen
Sand, buff, slightly clayey	0.55m
Clay-ironstone "box-stones", as above	0.10m
Sand, buff and brown, slightly clayey, passing down into	1.50m
Sand, grey clayey, passing down into	1.80m
Clay, dark grey, glauconitic, sandy with vivid green sandy bands	1.60m

Clay-ironstone, buff-putty-coloured, sandy with grains of glauconite; shrinkage cracks; splintery fracture; limonitic crust where near surface; a few bivalves and ammonites .. .. 0.15 to 0.20m

Sand and sandy clay, blue-green, glauconitic, very clayey with bits of carbonized wood .. .. 0.45 to 0.60m

Clay-ironstone, lenses (up to 1m long), putty-coloured, full of moulds of fossils and bits of carbonized wood; some pyrite; shrinkage cracks; breaks up easily under hammer; common bivalves and ammonites .. .. 0.15 to 0.20m

Sand, grey-green, glauconitic, very clayey with bits of black wood and Chondrites burrows infilled with pale coloured sand; 200mm band of green laminated sand 300mm above base .. .. 1.00 to 1.15m

Clay-ironstone, tabular bed, putty-coloured; fewer fossils than in bed above; shrinkage cracks.. .. .. 0.15 to 0.20m

Sandy clay and clayey sand; blue-green and dark grey, glauconitic, bottom 150mm stiff clay with line of black, pyrite-coated wood at base; beds become sandy upwards, interlaminated sand increasing until top is essentially sand with clay laminae; clay-ironstone "doggers" 0.6m and 1.45m from bottom; Chondrites; ammonite "ghosts" in bottom 150mm 3.50m

Line of black, rolled, phosphatic nodules resting on irregular surface of bed below; ammonites common 0.05m

Clay-ironstone, tabular bed, putty-coloured, sandy, patchily fossiliferous, Ophiomorphia burrows; knobs of semi-phosphatized, sandy and glauconitic clay-ironstone cemented to upper surface, in places enveloping nodules of the bed above; moulds of bivalves in same material lie on upper surface; a few ammonites	0.10 to 0.15m
Sand, blue-green, glauconitic, clayey	0.40m
Band of small, black and brown, phosphatic nodules, well rolled, crowded in dark green, clayey sand, indurated in places; fragments of ammonites	0.15 to 0.20m
Sand, hard, brown, clayey	0.15m
Sand, buff and green, clayey, becoming greener and more clayey below	0.50m

Spoil from the trenches at nearby Fairstead Estate subsequently showed the basal nodule bed of the Mintlyn Beds to be about 3m below the lowest bed proved in the cutting. A second cutting [6563 2089] on the Bypass, 800m NNE of Mintlyn Wood cutting and estimated from the field survey to be stratigraphically about 2m to 3m higher, showed about 0.6m of weathered yellowish green clayey sand overlain by 0.3m of fossiliferous clay ironstone. The highest part of the formation, including the junction with the Leziate Beds has been exposed at times in the most westerly part [6663 1962] of Leziate sand-pits, adjacent to Mintlyn Wood, but is below the water-table and the Mintlyn Beds have been seen only as green glauconitic clay and sand spoil.

The best exposure of the basal beds of the Mintlyn Beds recorded to date is that in the No. 2 Gas Feeder Main trench [6515 1555] near Manor Farm, North Runcton. The following composite section was measured (after Casey and Gallois, 1973, pp. 8 - 9):

Mintlyn Beds

Clay, lilac-grey with glauconite-rich lenses, some iron-staining	1.00m seen
Phosphatic nodules (up to 100mm diameter), buff and grey in grey-green, brown-weathering, glauconitic, sandy clay; some glauconitic, loosely-cemented, gritty nodules at base; ammonites fairly common	0.05 to 0.10m
Clay-ironstone, buff, sandy, glauconite speckled, in lenses; ochreous ferruginous crust; a few ammonites	up to 0.10m
Clay, grey sandy with lenses of green glauconitic clayey sand	0.25m
Clay-ironstone, buff-brown, sandy, glauconitic ..	0.20 to 0.30m
Clusters of small phosphatic nodules, dark inside, pale outside, in brown-weathering, glauconitic, clayey sand; ammonites in nodules; material on tip suggests clay-ironstone "doggers" in this bed ..	0.05 to 0.10m
Sand, dark green, glauconitic clayey	1.00m
Basal nodule bed; black and dark brown, gritty, phosphatic nodules in matrix of dark green (with drab brown wisps) glauconitic, clayey sand; much iridescent shell debris (phosphatized) from broken ammonites, trigoniids and other shells; many of the	

nodules pyritic; nodules shatter without regard to planes of separation from fossils; ammonites tend to be concentrated in lower part of the bed, some traces of iridescent test, mostly in black phosphate; irregular base .. .. 0.10 to 0.15m

Runcton Beds, fine-grained glauconitic sands 1.15m

The Mintlyn Beds are covered by thick drift deposits between Wolferton and the Babingley River; their most northerly outcrop is on the south side of the river valley where brown and green glauconitic clayey sands with much secondary ironstone pan give rise to poorly drained land between North Wootton and Castle Rising. Phosphatic nodules from the basal bed have been thrown out from excavations near North Wootton [e.g. 6524 2536 and 6380 2429], and green glauconitic sands and clays and slabs of fossiliferous ironstone have been revealed from time to time in the deeper excavations in the built up areas of North Wootton, South Wootton, Gaywood and Fairstead Estate, King's Lynn. In most of these areas the Mintlyn Beds are deeply oxidised and commonly covered by weathered brown clayey sands and bleached white sand. Spoil from several trenches at Fairstead Estate [643 197] included phosphatic nodules from the basal bed and several rotted ironstone bands, one with phosphatic pebbles, within a sequence of grey and green glauconitic sands and clays.

The basal beds of the Mintlyn Beds were exposed in the floor of a large borrow-pit [635 174] at Constitution Hill, Hardwick, at Brook Farm, North Runcton (Fig. 63), and, briefly, in the No. 4 Gas Feeder Main trench at West Winch [6325 1674] and near Fair Green [6480 1697 and 6573 1738]. No section was seen in the gas pipeline trench but the spoil at all three sites consisted of glauconitic greenish grey,

fine-grained clayey sands with thin beds of dark green glauconitic clay and thin tabular beds of clay ironstone. The sections proved at Constitution Hill and Brook Farm are given in Appendix D. Phosphatic debris from the basal nodule bed, and slabs of weathered ironstone are common as soil brash throughout this area. Several local walls and barns have been built from the ironstone and the secondary ferruginous pan derived from it.

The Mintlyn Beds can be traced southwards from North Runcton by means of a soil brash of green clayey sands, phosphatic nodules and ironstone slabs, to Blackborough End where they disappear beneath the thick drift deposits of the Nar valley. They re-emerge on the south side of the valley to crop out as low, poorly drained ground around Wormegay, but are then again overlain by drift deposits southwards as far as Stow Bardolph. Between there and Denver the Mintlyn Beds, together with the Roxham Beds, Runcton Beds and Leziate Beds, crop out on a low escarpment that forms the eastern limit of Fenland. The only exposures recorded in this area were in trenches at Wormegay, Wimbotsham, Downham Market and Denver. All were deeply weathered and disturbed by cryoturbation and showed the basal phosphatic nodule bed with derived Subcraspedites spp. overlain by brown and green glauconitic clayey sands with clay-ironstone bands at several levels. They were too deeply weathered to yield an indigenous fauna.

Between Denver and West Dereham the Mintlyn Beds again crop out as low, poorly drained ground with much ironstone and secondary iron-pan occurring as debris in the deeper ditches.

A continuous section through the Mintlyn Beds, unconformably overlain by the Carstone, was exposed at the southern limit of this area of outcrop in the Cut-Off Channel [TL 639 995 to 662 996] near

Roxham Farm. To the south of the Cut-Off Channel the Sandringham Sands crop out only as two small outliers on the Fenland 'islands' on which the villages of Hilgay and Southery are built. Mintlyn Beds are preserved on the more northerly of these. The Southery area is close to their estimated southern limit, because of the overstep of the Carstone, and only the basal beds are likely to be present there. A deep ditch [TL 6204 9772] at Hilgay yielded off-white phosphatic nodules from the basal nodule bed, but the formation is otherwise poorly exposed on the outlier. An abundance of Mintlyn Beds debris, mostly the basal nodule bed and ironstones, in the till that partly clothes the Southery outlier suggests that the lower part of the Mintlyn Beds formerly cropped out nearby.

The full thickness of the formation was cored in the IGS boreholes in The Wash (72/77) and at Hunstanton, Gayton and Marham. The lithological and faunal sequences proved at Gayton and Marham are similar to those proved at outcrop, but the offshore and Hunstanton sequences, although lithologically similar to these, have marked faunal differences and either correlate with the highest (poorly exposed) part of the Mintlyn Beds at outcrop or are entirely younger than them. In either case, the basal Mintlyn Beds nodule bed in the north seems to be a highly condensed deposit that represents much of the Mintlyn Beds of the south.

When allowance is made for the loss of detail due to weathering at outcrop, the sequence proved in the Gayton Borehole is similar to that proved in the Mintlyn Wood cutting and can probably be correlated with it at several levels (Fig. 64). The Marham sequence, although similar in thickness (13.97m compared to 12.86m) to that at Gayton, cannot be matched in the same detail. In the absence of faunal

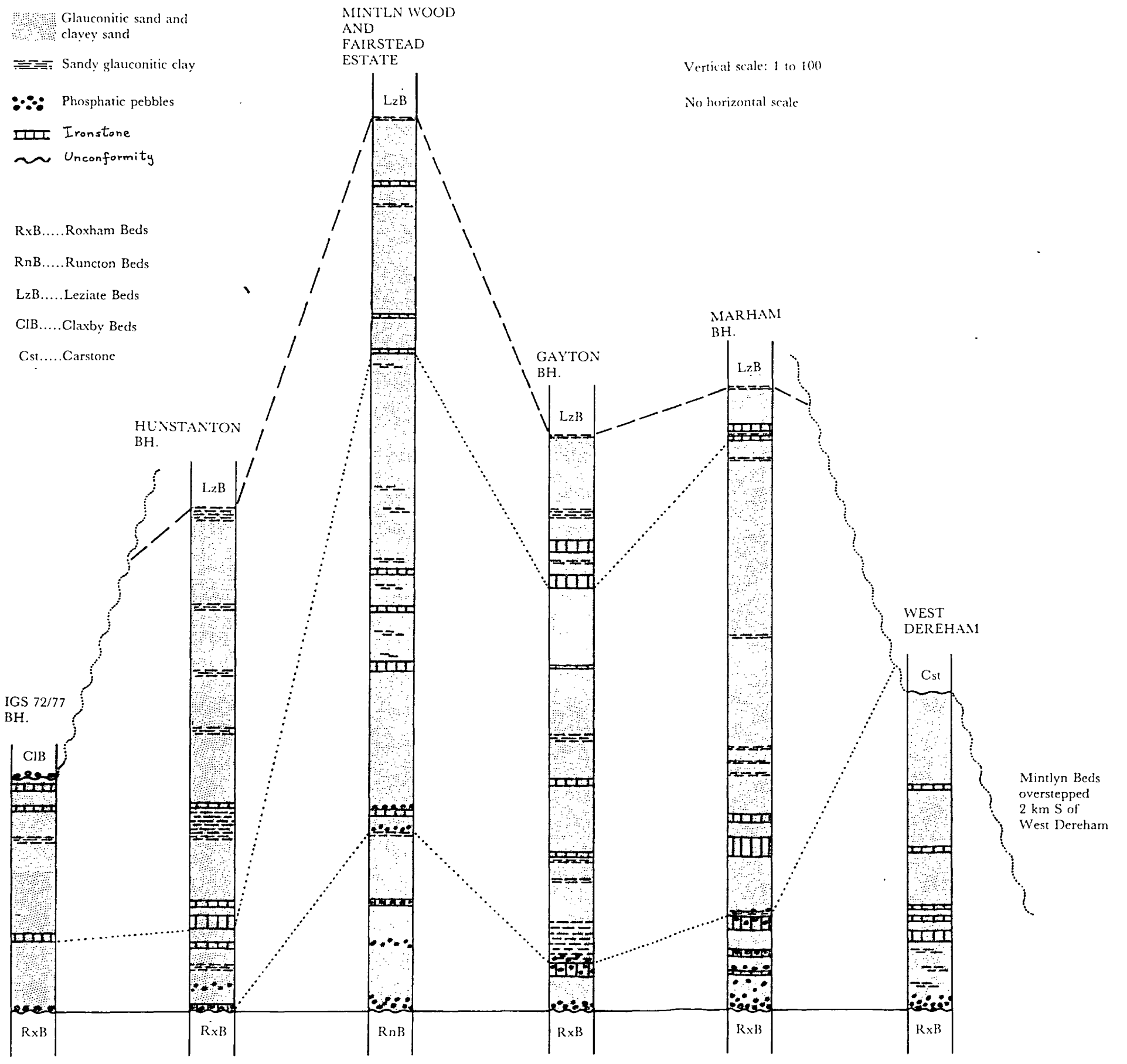


Figure 64. Correlations between the more complete Mintlyn Beds sequences in Norfolk.

evidence, the lateral persistence of the ironstones used for correlation in Fig. 64 cannot be established.

In the North Runcton and Hardwick areas the basal nodule bed of the Mintlyn Beds yielded fragments of phosphatized ammonites that Casey (1973, p. 242) considered to have affinities with both the Jurassic (Upper Volgian) genus Subcraspedites (Volgidiscus) and the Cretaceous (Lower Ryazanian) genus Hectoroceras. He has named these Runctonia gen. nov. 1973; (subsequently, in Casey et al. 1977, p. 16, re-named Praetollia (Runctonia)) and has suggested, on the basis of comparison with the late Jurassic to early Cretaceous faunas of NW Europe, the Russian Platform, the Subarctic Urals, Northern Siberia and Greenland, that they are the oldest Cretaceous fauna yet recognized in Britain. The basal Mintlyn Beds pebble bed in Norfolk (and its equivalent in Lincolnshire - the mid-Spilsby nodule bed) has therefore been taken to mark the base of the Cretaceous in eastern England (Casey, 1963; 1973).

The fossiliferous ironstones in the Mintlyn Wood cutting yielded a rich ammonite and bivalve fauna. The ammonites include, in ascending order, species of Praetollia (Runctonia), Hectoroceras and Borealites, Lynnia (formerly Surites (Lynnia)) and Bojarkia (formerly Surites (Bojarkia)) indicative of the kochi, icenii and stenomphalus zones (Table 15) of the Ryazanian (Casey, 1973; Casey et al., 1977). Phosphatic nodules accompanied by evidence of erosion occur at two levels, in the kochi and icenii zones, and the sequence is clearly condensed.

The bivalves have been identified by Kelly (1977); they include Anisocardia sp. nov., Camptonectes (Boreionectes) cinctus (J. Sowerby), Camptonectes morini (de Loriol), Corbicellopsis claxbiensis (Woods), Corbula sp., Cucullaea (Dicranodonta) vagans Keeping, Discoloripes

sp. nov., Girardotia sp. nov., Myophorella keepingi (Lycett), Neocrassina (Lyapinella) sp. nov. [Astarte cf. saemanni Spath non de Loriol], Neocrassina (Pressastarte) sp. nov., Nicaniella claxbiensis (Woods), Nicaniella sp., ostreids indet., Pinna sp., Pleuromya cf. uniformis (J. Sowerby), Protocardia sp., and Thracia phillipsii (Roemer). None of these species is diagnostic of any particular bed within the Mintlyn Beds. Indeterminate gastropods and wood fragments are also present.

The fossiliferous part of the sequence is overlain by about 4m of sparsely fossiliferous sand, clayey sand and clay ironstone that did not yield any ammonite. The cutting to the NNE, yielded Peregrinoceras spp. indicative of the albidum Zone (Casey, 1973). The highest part of the Mintlyn Beds is poorly exposed and has not yielded any fauna at outcrop. A specimen of Paratollia, indicative of a Valanginian age, was recorded in the upper part of the formation in IGS Borehole 72/77 in The Wash (Morter in Gallois and Morter, 1979, p. 25), thereby suggesting that the Ryazanian-Valanginian boundary falls within the top part of the Mintlyn Beds in that area. Ammonites are so rare in the Valanginian rocks in Norfolk and Lincolnshire that no attempt has yet been made to zone this stage. Elsewhere in the Boreal Province zones have been established at this stratigraphical level largely on the basis of species of Platylenticeras, Polyptychites and Dichotomites.

The age of the preserved Mintlyn Beds varies throughout the length of their outcrop. At West Dereham, the formation consists of 6.5m of glauconitic and pyritic sands and fossiliferous clay ironstones unconformably overlain by the Carstone. The ironstones contain a fauna rich in Hectoroceras and includes over 25 species of bivalve, lignite

logs up to 1m long and bones and teeth of large marine reptiles (Casey, 1971). They were assigned by Casey (1973) to the Hectoroceras kochi Zone. When traced northwards this lower part of the Mintlyn Beds (the Hectoroceras Beds) becomes strikingly attenuated due to erosion at the base of the overlying bed. At North Runcton, Hardwick and Mintlyn Wood the Hectoroceras Beds are 1m to about 4m thick and are overlain with minor unconformity by sands with Lynnia.

There is no exposure of these beds between Mintlyn Wood and North Wootton, but drainage ditches at North Wootton [6524 2536] which yielded large, off-white phosphatic nodules with worn Subcraspedites (basal Mintlyn Beds nodule bed) in the present survey, probably provided the phosphatized Hectoroceras cf. kochi Spath collected by Whitaker during the original (1883) geological survey. This suggests (Casey, 1973, p. 201) that at this last locality the Hectoroceras Beds are represented only by a remanié fauna at the base of the Mintlyn Beds. As yet the Hectoroceras Beds are unknown in England outside Norfolk. They are absent beneath The Wash and in Lincolnshire. Other records of Hectoroceras are widespread in the Boreal province and include East Greenland (Spath, 1947), Western Siberia (Klimova, 1969), the Sub-arctic Urals (Golbert et al., in Saks, 1972) and Canada (Wiedmann, 1968).

Northwards from North Wootton the Mintlyn Beds are known only from the Hunstanton and IGS 72/77 boreholes. At both these localities the small amount of ammonite and bivalve evidence suggests that the sequences are younger than those at outcrop. The formation may therefore be diachronous and young steadily northwards in Norfolk.

4.2.5 Leziate Beds

The Leziate Beds consist of loose, fine-grained, cross-bedded quartz sands, yellow, green, orange-brown or red in places, but mostly clean grey or white, with subordinate bands of silt and clay. Locally the sands are sufficiently lithified to form a friable sandrock. Pyrite nodules are common throughout the formation, but above the water-table these become oxidised to form limonitic concretions, geodes or merely ferruginous stains. Glauconite is abundant in some areas and at some stratigraphical levels in the Leziate Beds, but is rare in others. Phosphatic nodules or other signs of erosion and condensed deposition appear to be absent. At outcrop, the clay and ferromagnesian minerals are commonly weathered and leached to give a clean white sand with a little patchy yellow staining.

The sands rise from beneath The Wash at Heacham and can be traced from there southwards to Denver (Fig. 65). From Heacham to King's Lynn they crop out on the face of a steep feature that is capped by the basal ferruginous sandstones of the overlying Dersingham Beds. South of King's Lynn they form a more subdued feature capped by Carstone. Much of the heathland of west Norfolk that is regarded as typical Sandringham Sands scenery, including Dersingham Heath (Plate 19), Sandringham Warren, Roydon Common, Leziate Heath and Shouldham Warren, is underlain by the free-draining Leziate Beds, basal Dersingham Beds and, at the foot of the Leziate Beds feature, by thick sandy wash derived from the Leziate Beds. The formation underlies much of west Norfolk and was proved in the Hunstanton and Gayton boreholes. When traced north-westwards into The Wash the sands pass laterally into the argillaceous Claxby Beds.

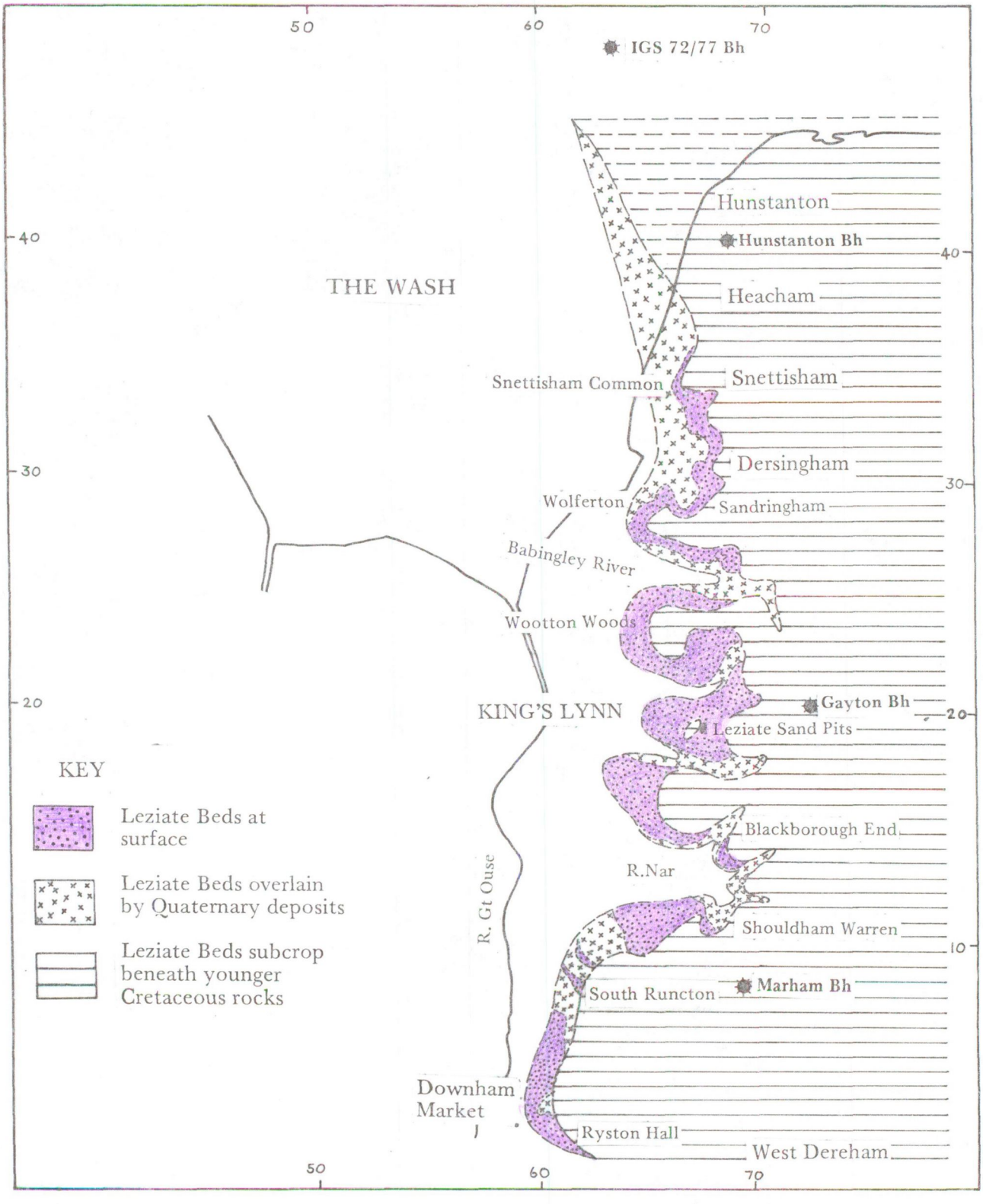


Figure 65. Sketch map of the Leziate Beds outcrop and subcrop showing the positions of localities referred to in the text.

The formation is 20.4m thick at Hunstanton but thickens steadily southwards from there to an estimated maximum of about 30m in the Leziate-Middleton area. It is represented in IGS Borehole 72/77 by only 2.5m of fine-grained sand in the top part of the Claxby Beds sequence. The absence of marker beds within the Leziate Beds makes it impossible to determine whether the variation in their thickness is due to overstep by the Dersingham Beds or to original differences in the depositional thickness. Their rapid attenuation beneath The Wash strongly suggests an original depositional variation. Southwards from Middleton [660 160], the Carstone rests on the Leziate Beds and between there, and their disappearance at Ryston Hall, Denver [628 012], they are progressively cut out in a southerly direction (Fig. 56).

The type section of the formation is the huge complex of pits dug for glass and foundry sands at Leziate Heath [675 193], about 5 km east of King's Lynn (Plate 21). The junction with the underlying Mintlyn Beds has been well exposed from time to time in the most westerly part [665 195] of the pits. There, and in the Hunstanton, Gayton and Marham boreholes, the base of the Leziate Beds has been taken at the top of a thin bed of dark green glauconitic clay; the overlying lithologically uniform sands differ from the Mintlyn Beds in that they contain rare clay seams but no clay ironstone. This junction effectively marks the lower limit of the economically useful sands. It has been proved relatively easy to map because it is marked by a spring-line and a prominent feature. Throughout most of their outcrop the beds close to the junction are obscured by thick sandy downwash derived from the Leziate Beds, but the feature remains persistent.

The sand-pits at Leziate are the most extensive workings of their kind in Britain. They were probably begun in the early part of the 19th century as small pits for glass sand. In recent years they have

Plate 21. Type section of the Leziate Beds.

A. General view of Leziate Sand Pits from the Lynn-Gayton road southwards towards Brow-of-the-Hill. An overburden of Snettisham Clay unconformably overlaid by Carstone, and by Chalky Boulder Clay has been stripped off the area behind the distant face. Almost the full thickness of the Leziate Beds is exposed in the two faces seen here. The lower face, close above the water-table, exposes grey sand with some glauconite and ferrous-iron staining. The upper face is in oxidised and bleached white, yellow and brown sands.

B. Detail of the upper face seen in A. Parallel and large scale planar cross-bedding is faintly visible. Dark brown and orange patches mark the sites of pyritic concretions and cemented sands, now wholly oxidised.

C. Junction of the Mintlyn Beds and Leziate Beds. The glauconitic clayey sands of the Mintlyn Beds pass rapidly up into the clean quartzose sands of the Leziate Beds. Ferruginous seepages, in which the iron minerals are derived from the oxidation of glauconite and pyrite in the sands, are emitted at the junction of the two formations, and mark the lower limit of economic sand working. Leziate Sand Pits, north-east corner.

D, E. Pyrite concretions from the basal beds of the Leziate Beds, locality as C. Similar concretions to these, commonly enclosing bits of wood and poorly preserved bivalves as seen here, occur throughout the Leziate Beds but are rapidly oxidised to form ferruginous stains above the water-table. Natural size.

Plate 21







D





been worked by British Industrial Sands Ltd. for glass and foundry moulding sands and they now extend over about 2 km square. The full thickness of the Leziate Beds has been worked in the pits. The sands are mostly clean, well sorted and fine-grained with patchy irregular ferruginous staining present above the water-table and the iron-bearing minerals glauconite and pyrite present below. The degree of staining, and hence the iron content, varies considerably over short distances, but the bulk of the sand above the water-table is white, grey or pale yellow and relatively free from iron due to leaching by meteoric water (Plate 21). The chemical requirements of the glass industry vary in detail with the product to be made but, in general, the dry sand feed must contain > 96% (for coloured containers) to > 99% (for colourless containers and flat glass) of silica (SiO_2) and < 0.04% (for colourless glass) to < 0.45% (for coloured glasses) or iron. The raw sand can be upgraded by acid leaching and froth flotation to reduce the iron content. The bulk of the glass sand produced at Leziate is used to make clear glass. The other major product at Leziate is resin-coated foundry sand, well sorted fine- and medium-grained silica-rich sands, that is extensively used for making moulds and cores.

In the past (mostly in the 19th century), the Leziate Beds were worked for glass sand in the Snettisham, Dersingham, Roydon, Castle Rising, Blackborough, Shouldham and Downham Market areas. Rose (1835, p. 177) noted that large quantities of "colourless, nearly pure silica" were shipped to northern glass furnaces from quarries at Dersingham. Much of this industry must have been defunct before the end of the 19th century because Whitaker and Jukes-Browne (1899) refer to sections in the sand-pits, but did not record any active working. At least one

quarry [682 293] and an associated adit-mine [6821 2914] was worked at Dersingham as late as the 1890's when sand was directly loaded onto shallow-draught boats to be exported to glass works at Jarrow-on-Tyne (pers. comm., venerable Dersingham resident). Details of the workings and descriptions of the sections are given on open file.

The most complete, unweathered section of Leziate Beds recorded to date is that in the Gayton Borehole which proved the following sequence:

Dersingham Beds (Snettisham Clay), clay with pebble bed at base

Leziate Beds

Sand, fine-grained, greyish white, well sorted; very poorly cemented; composed almost entirely (> 99% at most levels) of angular to sub-rounded clear quartz; traces of grey clay drapes and burrow linings at several levels; faintly glauconitic in part	2.36m
Core lost in soft sand	0.30m
Sand, as above but more glauconitic and clayey at several levels and with wisps of grey clay and green glauconitic clay	2.29m
Core lost in soft sand	6.53m
Sand, as above; becoming more clayey and less well-sorted with depth; traces of burrowing and small-scale cross-bedding; small patches of pyritic cement at several levels; becoming less clayey with depth but with widely spaced thin bands (up to 1 cm thick) of black or dark grey carbonaceous clay; cross-bedding and burrows picked out by concentrations of medium-grained sand; fining-upward graded-bedding units present at several levels; carbonaceous plant	

debris (some pyritized) common throughout; weakly glauconitic throughout but with burrowfill and cross-bedding concentrations of glauconite at several levels; planar base 17.58m

Clay, dark green, very sandy and glauconitic; resting on uneven surface of 0.02m

Sandstone, hard cream coloured, ferrugino-phosphatically cemented fine-grained sand (10 cm) passing down into greyish white soft sand (as above) with cross-bedding, glauconite and wisps of glauconitic green clay; small-scale rhythms with green clay bands (up to 1 cm thick) passing up into clean white sands 1.66m

Core loss 0.12m

Mintlyn Beds, dark green glauconitic clay

At outcrop above the water-table, the sands are extensively leached and are predominantly composed of fine-grained, angular, sub-angular and sub-rounded grains of clear quartz. Secondary iron-staining and cementation, ranging from pale yellow staining to a dense limonitic cement, is patchily present at all localities and stratigraphical levels above the water-table. In boreholes, and at outcrop where the water-table has been artificially lowered, the sands are glauconitic and contain pyritized bands and concretions, and wisps and drapes of grey carbonaceous clay and green glauconitic clay. Leaching does not greatly affect the appearance of sedimentary structures such as cross-bedding and burrowing, even though they are commonly picked out by glauconite grains and concentrations of clay minerals in unweathered sections, other than to make them less obvious.

Bioturbation in the form of indeterminate mottling is common at all levels in the Leziate Beds in the boreholes. Vertical or sub-vertical tubes cf. Skolithos, commonly cemented by pyrite or limonite, are very common; poorly preserved Rhizocorallium is also present, but rare. Possible burrows or casts of bits of rotted wood, lined with a carbonaceous film, are common at several levels, especially in the lower part of the formation. Tiny, hollow, pyritized tubes penetrate many of the clay bands; these are presumed to be burrows rather than the traces of rootlets. Plant stems and bits of wood, much of it cemented into pyritized masses (Plate 21), are common in the lower part of the formation where they appear to have formed waterlogged mats on the sea bed. Parallel lamination and cross-lamination, picked out by sand or glauconite grains in thin clay beds or by clay laminae within the sands, are common in the lower part of the formation in the boreholes. Many of the thin clay seams at this level occur as the bases of thin, 10 to 15 cm thick, rhythms identical to those in the Mintlyn Beds.

Although cross-bedding and other sedimentary features are present in even the smallest exposures of Leziate Beds, the sections are so widely spaced that they can only be qualitatively assessed. Lithological variations are also present whose significance, whether regional or local, are impossible to assess. For example, the upper part of the formation at Snettisham Common contains up to 10% of grains of soft white rotted limestone that were not recorded, except as a rarity, at any other locality. The same exposure contains a probable broad channel, another feature not seen elsewhere, and the lithology and this sedimentary structure may be related. Despite these limitations, the following generalisations can be made:

(i) the sands are predominantly fine-grained throughout the district but bands of medium-grained sand are more common in more northerly exposures and a few thin bands of coarse-grained sand, including tiny pebbles of ironstone and mud-stone, are present in the Hunstanton Borehole

(ii) they are finely micaceous at several levels at Hunstanton, and possibly at Snettisham, but become glauconitic south of Snettisham with the overall glauconite content, both as grains and as wisps and thin seams of glauconitic clay, increasing southwards. In the southern part of the district, at Blackborough, some thin bands of sand contain more than 40% glauconite

(iii) thin seams, wisps and clay drapes of grey carbonaceous clay occur throughout the outcrop, but glauconitic clay is restricted to its southern part (e.g. Plate 22)

(iv) the commonest sedimentary feature is slightly curved planar cross-bedding. This occurs at all but the highest stratigraphical levels, mostly in units 0.15m to 0.45m thick whose boundaries are parallel over larger distances than those visible in the exposures. Current reversals ('herringbone bedding') are common in many of these units. Even-parallel bedded units of similar thickness are also common. Planar cross-bedded units up to 1.5m thick were recorded at Leziate Sand Pit, and a probable broad channel at Snettisham Common. Small channel-fill structures occur in several of the boreholes (Plate 22)

(v) single lines of ripples are present, but rare, at several stratigraphical levels at most localities and are present, usually accompanied by clay drapes, in the highest 0.5m of the Leziate

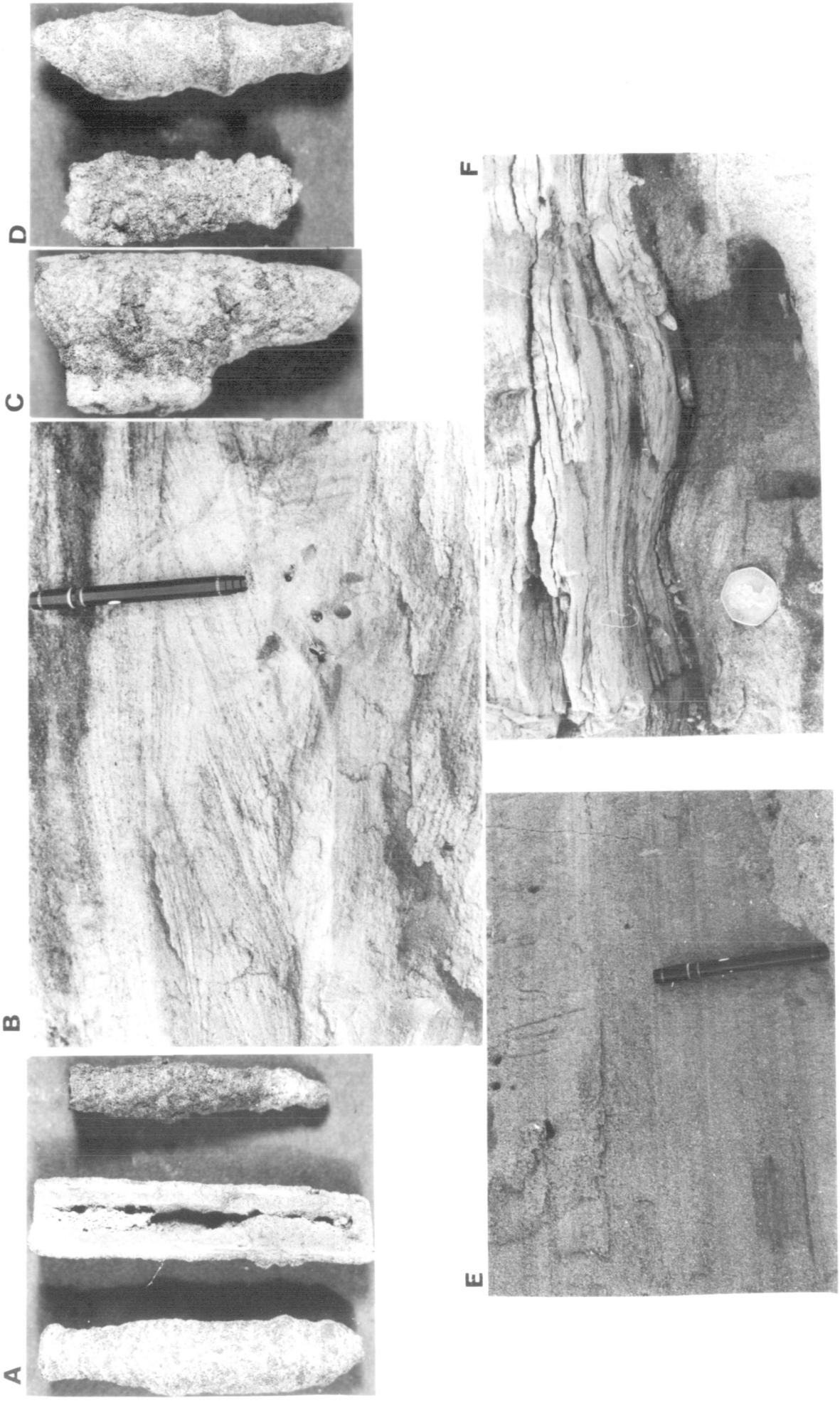
Plate 22. Sedimentary structures in the Leziate Beds.

A, C, D. Cylindrical ferruginous geodes. Hollow spheres or cylinders of ferruginous sandstone infilled with clean white sand are common at many localities on the Leziate Beds outcrop. Many of these are vertical or near vertical burrows that were originally preserved in pyrite and which have subsequently been oxidized; the oxidation products have diffused into the sediment and in some cases (e.g. D.) have picked out bedding features due to differences in permeability. Ling Common Sandpits, North Wootton. Natural size.

B. Cross-bedded fine and medium-grained clean quartzose sand showing small-scale cross-bedding with opposing dips (herringbone structure) in the lower part overlain by intersecting, small-scale trough cross-bedding, probably the erosional bases of large oscillation ripples. High Leziate Beds, Dersingham Common Sandpit.

E. Horizontal parallel bedding and lamination in fine-grained sands. Dersingham Common Sandpit.

F. Large wave ripples of medium- and coarse-grained sand showing form-discordant internal structure and characteristic curved bases; overlain by thin clay drape and fine-grained wavy-laminated sands. Highest part of Leziate Beds, Dersingham Common Sandpit.


A
B
C
D
E
F

Beds at most of the localities where the formation is overlain by the Dersingham Beds.

Schwarzacher (1953) made a comparative study of grain size and cross-bedding in the Sandringham Sands of Norfolk and the Woburn Sands of Cambridgeshire. No precise localities are given but the measurements in the Leziate Beds appear from his site map (1953, Fig. 2) to have been made in sandpits at Snettisham Common [6710 3362], Dersingham [6814 2937], Wolferton (widened railway cutting) [6622 2870], Castle Rising [653 243], Leziate [666 190 to 688 195] and Blackborough End [676 146]. One other locality, near Wallington Hall, South Runcton could not be traced in the present survey, but is also presumed to have been in the Leziate Beds. He measured the dips of a total of 56 cross-bedding units at Snettisham Common, Dersingham, Wolferton and North Wootton, and a total of 72 units at Leziate (3 separate localities), Blackborough End and South Runcton. Both areas showed a preponderance of easterly dips and led Schwartzacher to conclude, on the basis of the meagre published literature on natural and experimental cross-bedding available at that time, that the sands had been derived from a north-south coastline that had lain between Lincolnshire and Norfolk. 'Herringbone' bedding was noted to be a minor feature at most localities, but accounted for more than 5% of the cross-bedding at Snettisham Common, North Wootton, Leziate (one locality), Blackborough End and South Runcton.

Rastall (1919, pp. 214 - 5), in a study of the heavy minerals of the Lower Cretaceous of eastern England, described assemblages from Leziate Beds samples from Ling Common, Castle Rising [653 243]. A slide of the heavy minerals from this locality was figured by Hatch and Rastall (1913, Fig. 5). The principal heavy minerals found were kyanite, tourmaline, staurolite, rutile, pyroxene, muscovite, ilmenite and garnet with

small amounts of zircon, green biotite, hornblende and apatite, and possible rare anatase, barytes and sillimanite. The significance of the cross-bedding and heavy mineral data are discussed in Section 4.7.

Studies of the surface textures of quartz sand grains with the scanning electron microscope (SEM) have been made by a large number of authors in recent years in order to enable comment to be made on the depositional environments of sands. The technique and results of many of these studies have been summarized by Krinsley and Doornkamp (1973) and by Le Ribault (1975). Most of the earlier work was carried out on the assumption that the morphology of the grains was diagnostic of their environmental history and that specific surface features could be related to specific sedimentary environments. As more data was collected it became apparent that the interpretation of the surface features could be complex; in recent years it has been shown that the crystallography of the quartz governs the shape of many of these features (e.g. Wellendorf and Krinsley, 1980).

Many sand grains have experienced more than one depositional cycle and have, in addition, been subjected to weathering and/or diagenesis. Grains within a particular sediment can therefore show a great variety of surface features and, even where large numbers of grains can be studied, it is often difficult to make any comment on the depositional environment of the sediment on the basis of SEM studies alone. Despite these difficulties it has been stated that more than one depositional cycle can commonly be recognized in a single grain. An extreme example is the claim by Legigan and Le Ribault (1974) that individual sand grains from the Landes of western France show successive episodes of modification corresponding to seven environments: glacial, torrential riverine, high energy aolian, moderate energy fluviatile, pedological, aolian and finally pedological.

The reviews by Krinsley and Doornkamp (1973) and Le Ribault (1975) state that the sand-grain surface features characteristic of the more common depositional environments in which sands are deposited are those shown in Table 16. A few samples of typical Leziate Beds sands from outcrop and boreholes, together with quartzitic concretions from the outcrop, were examined with an SEM. The results were interesting, but not diagnostic of any specific environment.

Samples from shallow depths at outcrop at Snettisham and Castle Rising show a complex mixture of precipitation and dissolution features (Plate 23). The larger grains are commonly irregularly coated with several very thin platy layers of quartz beneath which the rounded edges of crystal faces and solution pits can be discerned. Many of the small- and medium-sized grains are euhedral crystals that have formed by the syntaxial overgrowth of quartz on the original grains. These also carry a variety of precipitation and solution features (Plate 23).

Secondary solution/precipitation features are absent from the sand samples from boreholes and from those from greater depths (< c 5m) at outcrop. Some of the larger, well rounded grains show features thought to be characteristic of aeolian environments; the majority of the grains show features indicative of marine or fluviatile environments, or a combination of the two.

An unusual feature of the Leziate Beds outcrop in the Castle Rising area, noted originally by Rose (1835), is the common occurrence of blocks of hard, pure quartzite up to 1m across. Whitaker and Jukes-Browne (1899, p. 7) implied that this sandstone was visible in situ in the Leziate Beds at Ling Common, but it was only recorded as loose debris in the drift in the present survey. SEM examination of chips and dis-

Plate 23. Electron micrographs of solution features affecting Leziate Beds sand grains at outcrop. All specimens gold-coated.

A. Fine and medium-grained poorly sorted, subangular to rounded grains, coated with limonite, from within 1 metre of ground surface. Photo. no. SEM 17789, Snettisham Common railway cutting. Magnification 30x.

B. Angular and subangular grains from about 2 metres below ground level in the same section as A. Angularity is due to overgrowths of quartz. Photo. no. SEM 17817, Snettisham Common railway cutting. Magnification 30x.

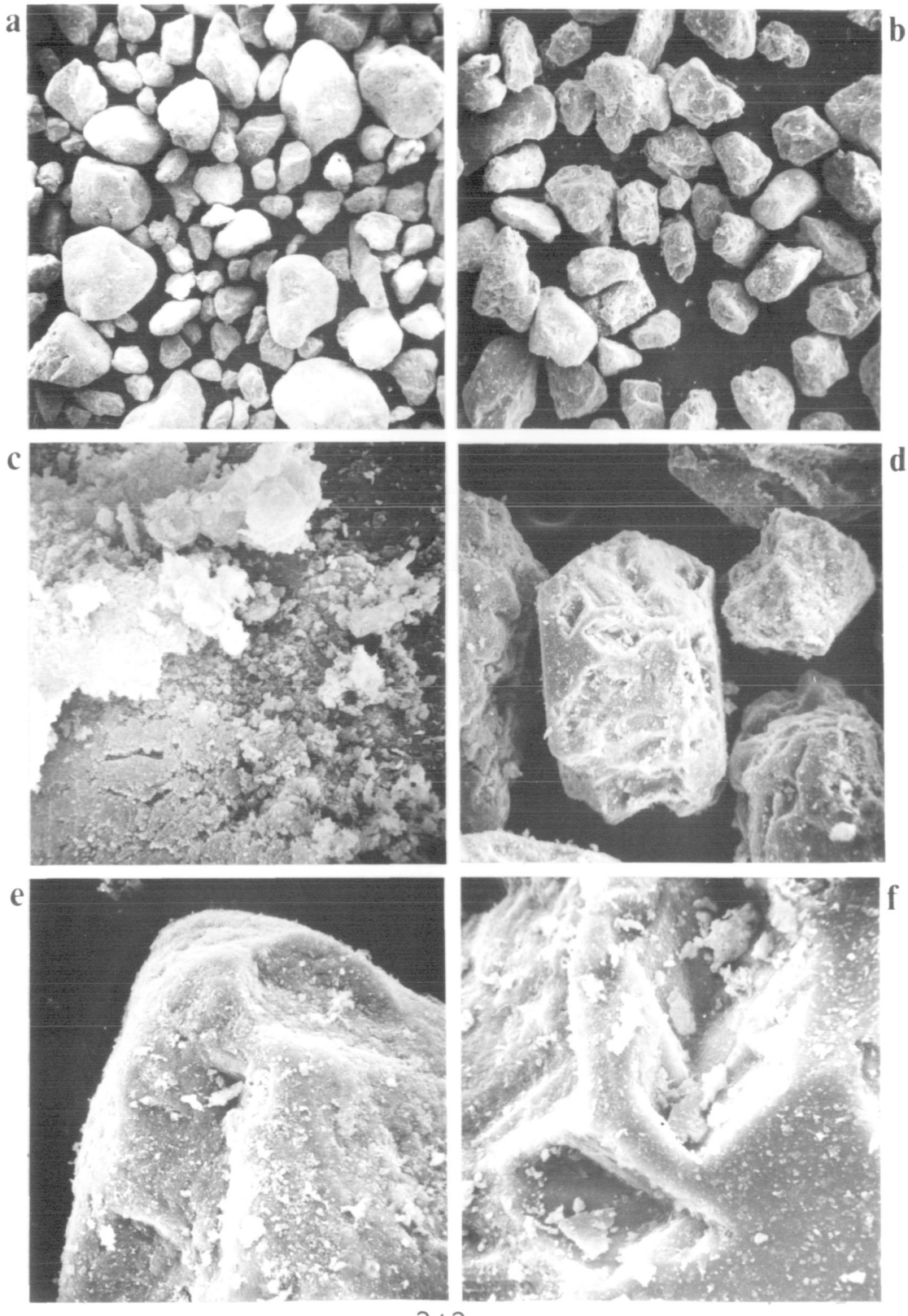
C. Detail of flaky quartz occurring as secondary precipitation on grains in B. Photo. no. SEM 17821. Magnification 1,100x.

D. Individual grain from the central part of the field of view in B. Solution pits and secondary quartz precipitation on a euhedral grain formed by the syntaxial growth of quartz on a sand grain. Photo. no. SEM 17790. Magnification 110x.

E. Detail of large quartz grain from A. showing surface etching, reprecipitation of quartz, and scaling obscuring old fracture surfaces. Photo. no. SEM 17795. Magnification 220x.

F. Detail of solution pitting and secondary small-scale quartz precipitation seen in top left of grain shown in D. Photo. no. SEM 17791. Magnification 550x.

Plate 23



Depositional environment	Surface features on sand grains
Pedological:	(a) where silica is being dissolved. Absence of transport features; presence of solution pits and hollows; surface scaling. (b) where silica is being deposited. Absence of transport features; presence of neomorphic crystal faces, silica globules and/or flowers.
Aolian:	well rounded grains with sharp edged fracture-impact pits devoid of polishing.
Hot deserts:	sinuous and rounded mechanical fractures coated with a scaly film of more soluble silica.
Glacial:	extremely angular grains with sharp edges and sharp-edged concoidal fractures; glacial striae.
Fluviatile:	(a) high energy. Common V-shaped fracture pits with polished (abraded) and smooth (dissolution) edges. (b) moderate energy. As (a) but fracture pits mostly cup-shaped and with less polishing and dissolution; silica globules in protected positions in some pits. (c) low energy. Low density of cup-shaped fracture pits; silica globules and flowers common in protected positions.
Marine:	nature and density of impact pits and degree of dissolution or precipitation varies considerably with energy of environment: many features similar to fluviatile environments but solution features more common due to undersaturation of sea-water with respect to quartz.

Environments intermediate between those described above (e.g. lagoons, delta), those from specific climates (e.g. tropical soils) and diagenetic modifications of the above have all been described.

Table 16. Relationship of sand-grain surface-features to depositional environments.

aggregated grains of the sandstone show it to be a form of sarsen or 'locked sand' (of Dusseault and Morgenstern, 1979) in which there is no cement and in which the hardness is due to a tightly interlocking network of quartz crystals that have formed as overgrowths on the sand grains (Plate 24). Elsewhere in Europe similar rocks have been described in large numbers from the Tertiary where they have generally been assumed (see Summerfield and Goudie, 1980 for review) to have formed under a tropical or sub-tropical environment in the Eocene to Pliocene. The field relationships of the Leziate Beds sarsens and the characters observed in the sands at outcrop, indicate that they are a relatively modern, probably Pleistocene, feature. Wilson (1979) has demonstrated experimentally that solution features can be produced in quartz sands, similar to those of Plate 23, by boiling the grains in a peat-water mixture for as little as 4 hours.

Pyritic concretions are common at many levels in the Leziate Beds, but because of their susceptibility to oxidation this is not immediately apparent at outcrop. Rose (1835, p. 178) noted that weathered sections in the Leziate Beds sands yield many hollow spheres and cylinders of sandy ironstone, referred to by him as 'ferruginous geodes', that are infilled with clean white sand. Many of these geodes have been incorporated in the Pleistocene deposits in west Norfolk and their abundance led Fowler (1970) to suggest that they were derived from the "Greensand" [Sandringham Sands and Dersingham Beds] or the Tertiary/Quaternary Crags, and that they had been formed by some, as yet, undescribed process. At Ling Common sand pits [652 238], Castle Rising, pyrite nodules, pyritized sand, geodes and irregular masses of limonite-cemented sand, and intermediate (part pyritic-part limonitic) forms all occur in situ. Many of the geodes are in the form of tapering, tube-

Plate 24. Electron micrographs illustrating the siliceous concretions formed within the Leziate Beds. All specimens gold-coated.

A. Loose boulder of fine-grained quartzite, typical of those commonly ploughed up from the Leziate Beds outcrop in the Castle Rising area. Scale 5 cm across; roadside verge, Lynn Road, Castle Rising.

B. Angular grains with quartz overgrowths, plucked from the concretionary block shown in A. by scratching with the thumb nail. Photo. no. SEM 17782. Magnification 55x.

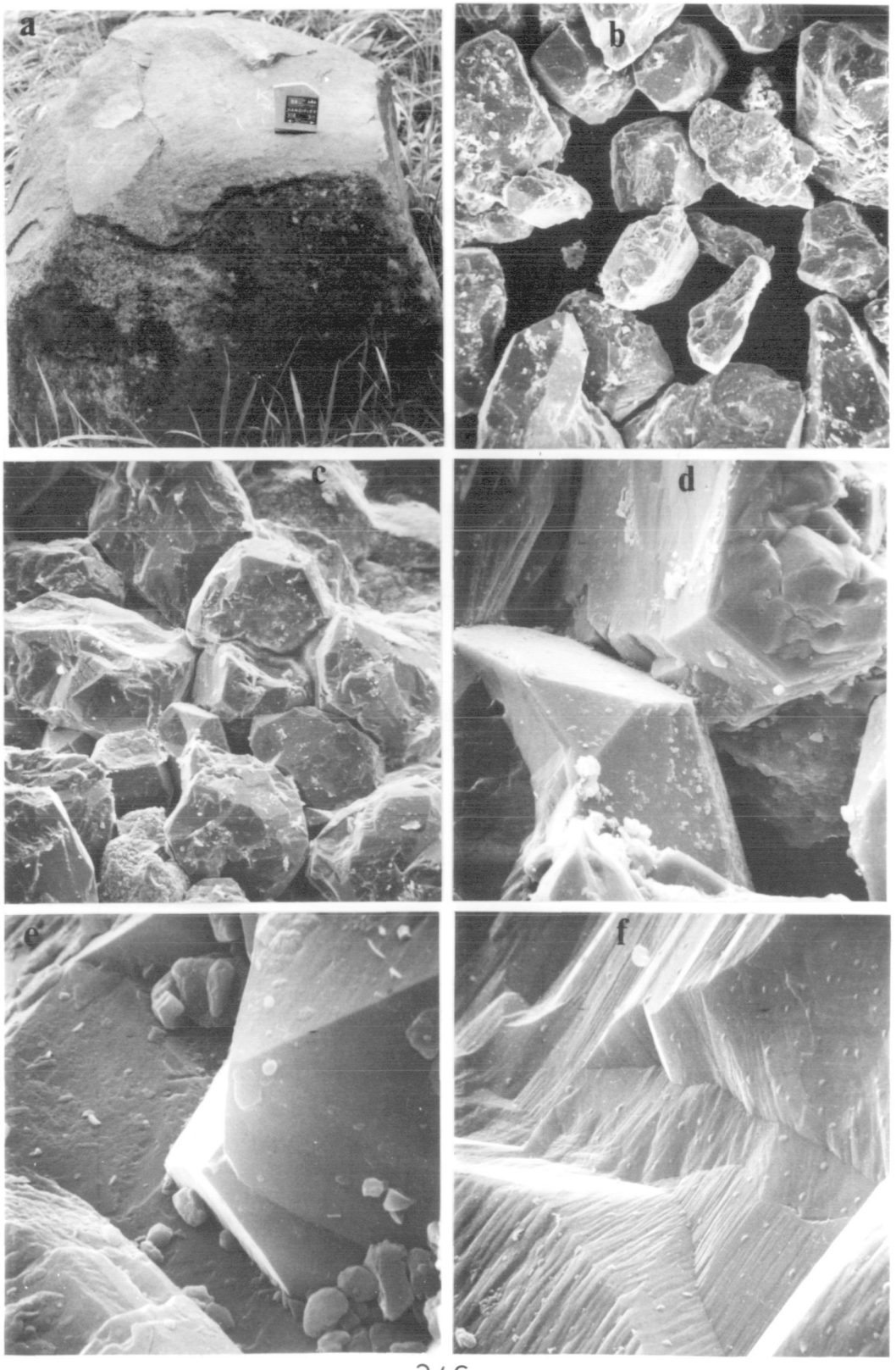
C. Fracture surface of quartzite block from Lyng Common Sandpits, North Wootton. The interlocking nature of the quartz grains and the absence of intergranular cement is clearly seen. Photo. no. SEM 17811. Magnification 60x.

D. Detail of grain contacts in central part of field shown in C.; well-developed euhedral cyrstals have formed by syntaxial overgrowth on the original sand grains. Photo. no. SEM 17810. Magnification 300x.

E. Free faces of quartz growing into a pore space, and with tiny (presumed late stage), quartz crystals forming on the faces. Locality as C. Photo. no. SEM 17801. Magnification 300x.

F. Detail of cleavage trace and tiny quartz flowers within an individual quartz grain. Locality as C. Photo. no. SEM 17806. Magnification 1,250x.

Plate 24



shaped burrows (Plate 22). Elsewhere at outcrop, pyrite nodules are ubiquitous where the Leziate Beds are below the water-table, and geodes are everywhere present where they are above it, irrespective of stratigraphical horizon. It seems clear therefore that the geodes are formed from pyritic concretions that have been oxidised and their ferruginous products reprecipitated in the adjacent sand. Many of the burrow-shaped geodes, which were presumably originally pyritic rods or tubes, now have irregular shapes that reflect variations in the permeability of the adjacent sand and they commonly preserve traces of sedimentary features such as cross-bedding.

Although well exposed in comparison with the other Lower Cretaceous formations in Norfolk, the Leziate Beds are palaeontologically the least rewarding part of the sequence. No body fossil has yet been recorded *in situ* in the sands but, in unweathered sections, pyritic concretions have yielded bits of coalified wood (Plate 21) and, more rarely, poorly preserved bivalves and rare unidentifiable ammonite ghosts. None of the determinable fossils is stratigraphically diagnostic. The pebbly head overlying an old sand pit in the Leziate Beds at Roydon Common [678 220] yielded an ammonite body chamber preserved as a hollow cast made of sandy ironstone. This was identified by Casey (*in* Casey and Gallois, 1973) as a ?*Polyptychites* and supports the presumed Valanginian age of the formation. This type of ironstone concretion is not known from the Mintlyn Beds but occurs in large numbers in the Leziate Beds and, less commonly, in the Dersingham Beds. However, the basal beds of the latter formation contain a Hauterivian fauna (Section 4.3) and could not have yielded a polyptychitid. The Roydon Common specimen is therefore believed to be the only fossil found to date that is indicative of the age of the Leziate Beds.

4.3 Dersingham Beds

The Dersingham Beds comprise a laterally variable, rhythmic sequence of thinly interbedded, fine-grained sands, ferruginous sandstones, silts and clays. The formation has an almost continuous, largely drift-free outcrop, between Heacham and the Babingley River. Southwards from there it crops out, mostly as a narrow strip from beneath extensive drift deposits, as outliers at Rising Lodge, Brow of the Hill and East Winch with the main outcrop on low ground between Roydon and Ashwicken. The Dersingham Beds are cut out by the southerly overstep of the Carstone in the vicinity of East Winch. The extent of their subcrop is poorly known. The formation was proved in the Gayton and Hunstanton boreholes and might be expected to occur beneath much of north-west Norfolk. It is probably included in beds classified by Kent (1947) as 'Snettisham Clay' in the North Creake Borehole.

At outcrop, the formation undergoes a broad lithological change, in addition to minor local variations, from predominantly arenaceous in the south to a mixture of arenaceous and argillaceous in the north. Between the most northerly outcrop (at Heacham) and the Hunstanton Borehole, the formation undergoes a rapid change to become predominantly argillaceous. The Dersingham Beds pass into the Tealby Beds beneath the Norfolk side of The Wash.

Throughout the Dersingham Beds outcrop the highest bed of the formation is a thin, 1.5m in the south thickening to 6m in the north, but laterally persistent bed of clay that Whitaker and Jukes-Browne (1899, pp. 6 and 9) termed the Snettisham Beds [Clay]. The stratigraphical relationship of this bed to the remainder of the Dersingham Beds is still not entirely clear; the reasons for considering it to be part of the Dersingham Beds instead of a separate formation are discussed below.

The formation takes its name from the Dersingham area where the harder bands within it give rise to a series of drift-free terrace-like features that, despite the paucity of exposure, enable the broad lithological sequence to be demonstrated. There is no single section that exposes the full sequence, and the more argillaceous parts of it are known only as deeply weathered spoil from ditches. Spoil from a shallow ditch dug across the outcrop at Dersingham Common [686 293] suggested that the following general sequence is present:

Carstone; soft ferruginous sand, spring-line at base .. .. 5m seen

Dersingham Beds

Snettisham Clay; grey clay and silty clay with lenses of fine-grained sand; clay ironstone concretions close to base; pebble bed at base or close above base with small well-rounded pebbles of quartz, quartzite, rotted chert, rotted limestone and phosphate .. .. .. c. 3m

Soft brown and white, fine-grained sands with possible thin clay seams .. .. c. 3m

Highly ferruginous fine and medium-grained sandstone and sandy ironstone, pebbly in part and with poorly preserved bivalves and plant debris .. .. .. c. 1.0m

Soft brown and white, fine-grained sands with possible thin clay seams 3m

Ferruginous fine- and medium-grained highly porous sandstone with casts of plant fragments and other possible fossils; locally flaggy and densely limonite-cemented and with sandy ironstone concretions .. .. c. 1.0m

Soft brown and white, fine-grained sands .. .. .. c. 4m

Ferruginous flaggy fine-grained sandstone .. .. .. c. 1m

Leziate Beds; soft white fine-grained sands .. .. 6m seen

In the Hunstanton Borehole the lateral equivalents of these strata are about 11.6m of clays and silts that form a complex rhythmic sequence. Many of the rhythms have erosional bases that bound beds of sparsely fossiliferous strata, and no detailed correlation can be made with the succession at outcrop. The Dersingham Beds are not exposed between the borehole and Heacham, and are poorly exposed between the latter locality and the type area. The lower part of the clayey sequence in the borehole appears to pass southwards in the Heacham-Snettisham area into a complex sequence of thinly interbedded sands, silts and clays in which the fossiliferous ferruginous sandstones of Lamplugh form a laterally persistent base. The Snettisham Clay of the outcrop is presumed to pass into the highest of a number of lithologically similar clays at the top of the borehole sequence. Farther south at outcrop, in the King's Lynn area, the lower and middle parts of the formation are wholly arenaceous.

The base of the Dersingham Beds, both at outcrop and in the Hunstanton Borehole, rests with sharp lithological contrast on the loose clean white sands of the Leziate Beds (Plate 25). At outcrop, the basal bed is a few centimetres of clay overlain by fine-grained ferruginous clayey sandstone; in the borehole it consists of soft mudstone. The contrast in permeability and hardness between the Leziate Beds and the Dersingham Beds gives rise to a weak spring line and one of the most prominent features in Norfolk (Plate 19), and the junction of the two formations is easy to survey.

At the top of the Dersingham Beds the Snettisham Clay can be traced at outcrop between Heacham and Ashwicken as a relatively thick clay that has been worked for brickmaking at several localities. It rests with

minor unconformity on the underlying beds throughout the outcrop. In the Leziate, Ashwicken and East Winch areas, close to the southern limit of its outcrop and its overstep by the Carstone, it appears to cut out the lower and middle parts of the Dersingham Beds and rests on the Leziate Beds. The critical sections, up to 2m of soft mudstone at Leziate Sand Pits and in the Gayton Borehole, are sparsely fossiliferous and yielded insufficient faunal evidence for their ages to be determined. They probably belong with the Snettisham Clay, but they could alternatively be a locally expanded equivalent of the persistent thin clay that marks the base of the Dersingham Beds.

At Hunstanton, the Snettisham Clay is conformably overlain by the Roach. Everywhere south of there it is unconformably overlain by the Carstone, and is overstepped by that formation near East Winch. At outcrop between Snettisham and Leziate, the Snettisham Clay and Carstone appear to have a concordant relationship in which their basal unconformities are almost parallel to one another. Correlation of the more important Dersingham Beds sequences in the district with one another is shown in Figure 66.

The Dersingham Beds fall naturally into three parts, the lower and middle part of the formation at outcrop, the Snettisham Clay at outcrop, and the Hunstanton sequence. They are described in that order here.

The lower and middle parts of the formation crop out as a series of small features capped by the Snettisham Clay and Carstone on the slopes of Lodge Hill, Snettisham, and between Snettisham and Dersingham. Most of the outcrop is obscured by downwashed sands and there are few exposures. Between Dersingham and the Babingley River the basal beds,

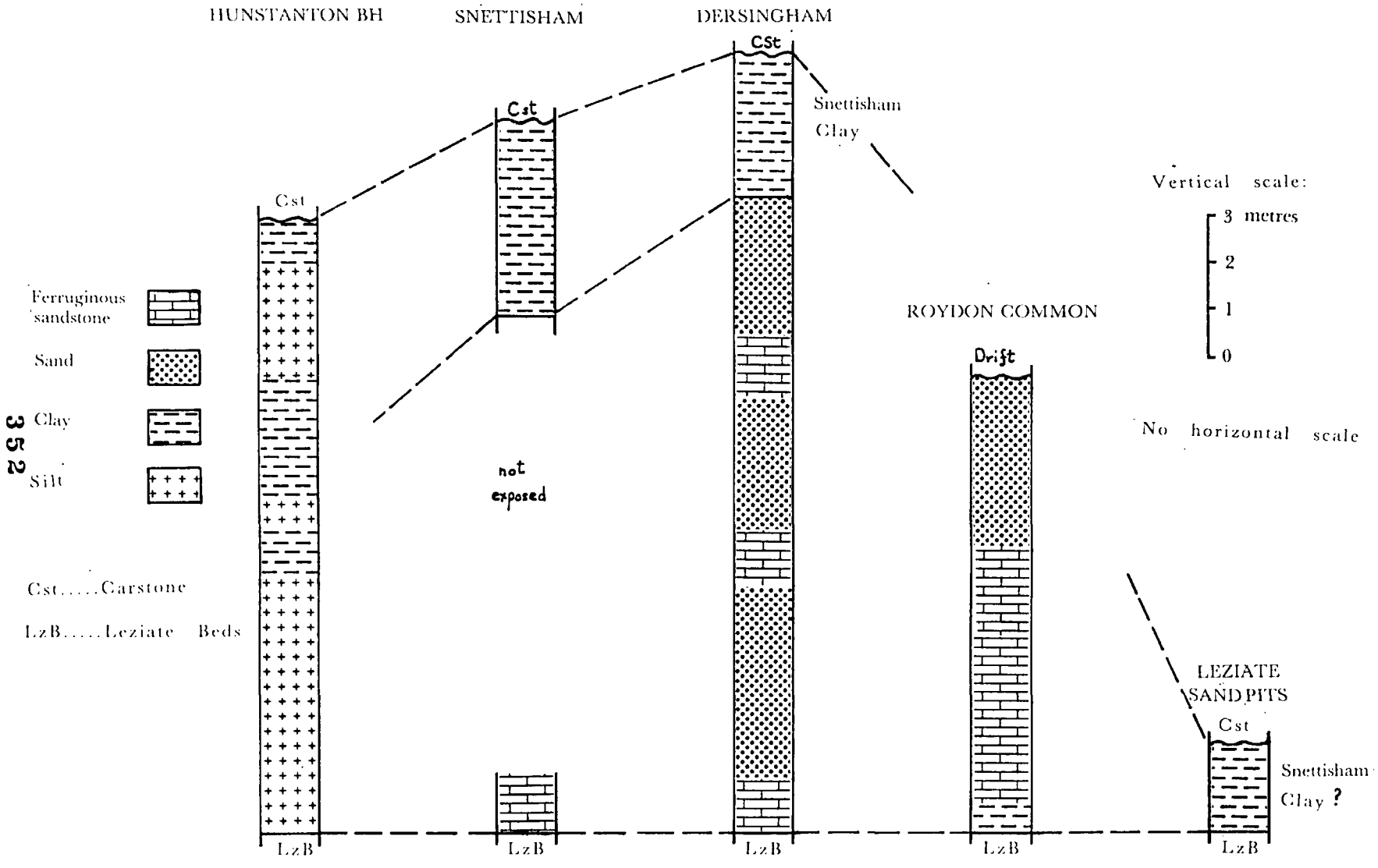


Figure 66. Correlations between the more complete Dersingham Beds sequences in Norfolk.

the ferruginous sandstones, form an extensive plateau on which they have been worked for building stone (known locally as 'Small Car' to distinguish it from the true Carstone) (Plate 25). The same beds cap a large outlier between Castle Rising, Grimston Warren and Roydon, but this is largely overlain by glacial deposits. A small outlier occurs at Pott Row.

The most complete section through this part of the Dersingham Beds is exposed in an old stone pit [672 222] at Grimston Warren that has been extensively expanded to provide hardcore. The following composite section was measured in the south-east face [6737 2215] of the modern pit:

Glacial deposits, chalky till and flint gravel 1.5m

Dersingham Beds

Sand, very fine-grained; pale grey with tiny ribs and kernels of brown ferruginous sand; traces of rotted pyritic concretions; even-flat bedded when fresh but becoming bleached to white running sand; becoming more grey in lowest part; line of limonitized clay ironstone nodules at base 3.5m

Clay, pale grey, softened .. .. 12 mm

Sandstone, soft, weakly ferruginously cemented, fine-grained, honey brown; friable and rubbly in upper part, becoming flaggy and thickly bedded in lower part 3.7m

Clay, pale grey, lenticular bed .. .. up to 25 mm

Sandstone, weakly ferruginously cemented, massive pale brown 0.41m

Plate 25. Sandringham Sands and Dersingham Beds; lithologies and features.

A. Junction of the Leziate Beds and Dersingham Beds, Wolferton Station railway cutting. The junction between the soft white quartzose sands of the Leziate Beds and the overlying ferruginous brown silty and clayey sands of the basal Dersingham Beds is picked out by the sand-martin burrows, iron staining and a line of small seepages. The top of the section and the talus slopes carry a heathland vegetation typical of this part of the Sandringham Sands and Dersingham Beds outcrop. Photo. no. A 10855.

B. Fine-grained, ferruginously cemented, flaggy-bedded sandstone used as building stone, Sandringham Church. This stone, known locally as "small car", was reputedly dug from pits in the basal beds of the Dersingham Beds at Sandringham Warren. Photo. no. A 10864.

C. Snettisham Clay scenery, Ingol valley, Ingoldisthorpe. The junction of the Snettisham Clay and the overlying Carstone is commonly marked by a spring or seepage line (foreground). In this part of the Ingol valley the clay occupies the lower slopes, and the outcrop is consequently marked by numerous small landslips. Photo. no. A 10871.

D. Snettisham Clay outcrop, Millionaires Row, Ashwicken. Here, close to the southern limit of its outcrop and its overstep by the Carstone, the Snettisham Clay is less than 2 m. thick and has little topographic effect. It crops out just below the crest of this Carstone-capped ridge; the bulk of the feature is made up of poorly consolidated Leziate Beds, and the feature as a whole is indistinguishable from similar features in south-west Norfolk in which only the Carstone and Leziate Beds are present. Photo no. A 11815.

E. Entrance to former adit worked for glass-sand in the Leziate Beds. In addition to the more usual method of working, by means of open quarries, the Leziate Beds were also worked at Dersingham by adits and shafts. In this adit, now largely collapsed, the flaggy ferruginous sandstones at the base of the Dersingham Beds were used to provide a stable roof. Photo. no. A 10854.

Plate 25

a

b

c

d

e

Clay, pale grey, softened	25 to 50 mm
Sandstone, soft, fine-grained, weakly cemented as above; passing down into more strongly ferruginously cemented sandstone with wisps and lenses of pale grey clay	0.32m
Clay, pale grey, lenticular bed	up to 12 mm
Sandstone, weakly cemented, massive, fine-grained, honey brown as above but with poorly preserved casts of bivalves and, more rarely, ammonites ..	0.46m
Sand, fine-grained with partings of grey clay ..	8 cm
Sandstone, hard, dark brown with dense ferruginous cement; very fine-grained, thickly bedded; line of limonitized clay ironstone concretions at base ..	0.48m
Interlaminated fine-grained sand and grey clay ..	0.13m
Clay, dark grey, plant-rich, with rare sand partings	0.15m
Clay, interbedded pale and dark grey, plant-rich in part, with partings of clean white fine-grained sand	0.13m
Sandstone, densely ferruginously cemented, fine-grained	3 mm
Clay, pale and dark grey with wisps and partings of white sand up to 12 mm thick	8 cm
Leziate Beds; sands, loose, fine-grained grey and white (up to 18m reputedly proved in boreholes)	

The lowest 3 to 5m of this sequence have been well exposed in the past in quarries at Dersingham (Rose, 1862, p. 31), Sandringham Warren and Wolferton (Lamplugh in Whitaker and Jukes-Browne, 1899,

p. 17), and the junction with the Leziate Beds has been exposed in sand pits at Roydon Common, Dersingham and Snettisham (Plate 25). The middle part of the formation has never been well exposed. The features in drift-free areas such as Sandringham Park and Lodge Hill suggest that it includes several relatively thick clay seams; small, degraded brickpits are present in both areas.

The Snettisham Clay can be traced almost continuously at outcrop from Heacham to Ashwicken, although the outcrop south of the Babingley River is largely drift-covered. The most southerly outcrop, close to its overstep by the Carstone, is near East Winch. At most localities the clay rests with marked lithological contrast on sands, the precise junction being a ferruginously stained surface that is commonly overlain by a thin, patchy pebble bed.

The Snettisham Clay was well exposed in Victorian times when it was dug for brickmaking at Heacham, Snettisham, Ingoldisthorpe and Dersingham. Heacham Brickworks [678 364] probably penetrated the full thickness of the Snettisham Clay and about 3m of the underlying sands. The section is now degraded and shows about 6m of deeply weathered brown and grey clays with a few concretionary ironstone fragments, overlying about 2m of fine- and medium-grained sands. Teall (1875, p. 17) recorded the following section (metricated here) in the lower beds:

Clay, passing up into sandy and then very sandy clay ..	2.4m to 3m
Clay, stiff dark blue with ironstone nodules containing ammonites	0.6m to 0.9m
Layer of indurated sandstone overlying sands of unknown thickness	

Lamplugh (in Whitaker and Jukes-Browne 1899, p. 12) measured what appears to be the full thickness of the Snettisham Clay, partly in the brickpit and partly in an excavation. The section can be summarized as follows:-

Head, brown loam with flints etc.	1.5m
Dark blue pyritic clay with decomposed pyritic layer at base	0.5m
Pale bluish brown clay with pale brown pyritic concretions containing crioceratid ammonites	0.9m
Dark brown and blue clay passing down into	1.8m
Dark pyritic silt	0.6m
Clay with pebbly clay ironstone nodules at base, some bored and serpulid encrusted	2.3m
Pale yellow sand	0.6m

Jackson (1911, p. 63) recorded the full thickness of the Snettisham Clay in the pit as 30 ft (9m) of greyish brown clay with a line of fossiliferous clay ironstones with pyritic cores about 10 ft (3m) from the top, and with ironstone concretions scattered throughout. Loose spoil in the modern pit suggests that the junction of the clays and the sands was marked by a band of ferruginously cemented medium- and coarse-grained sandstone, presumably Teall's "indurated layer" and Lamplugh's "pebbly clay ironstone", with small quartz and other pebbles including angular clay clasts. Jackson (1911, p. 63) recorded a bed of "iron-grit" with many shells and wood fragments at about this level. The colour differences between the Teall and Lamplugh sections are due to to weathering. The higher level of concretions have become justifiably famous because of their rich ammonite fauna, usually preserved as casts in brick-red or purplish red oolitic ironstone, and fine specimens are

included in many museum collections.

Snettisham Brickworks |6875 3380| was disused and overgrown at the time of the Old Series survey and no accurate measurement was possible. The bulk of the pit was in grey sandy clay, weathering brown, buff and red, with a bed of very shelly brown ironstone forming the floor. A band of purplish red fossiliferous clay ironstone nodules occurred in the middle part of the section. Museum specimens of the basal ironstone, deeply weathered to a rusty brown porous mass but presumed originally to have been a clayey limonite oolite, contain a rich bivalve fauna; the purplish red ironstones contain a more restricted fauna. A temporary section in the pit, recorded in the present survey, showed 4.6m of mottled red, brown and grey clays with three bands of ironstone; the lowest of these may be the basal ironstone of the earlier descriptions. Their lithological and faunal similarities suggest that the basal ironstone at Snettisham probably correlates with the "pebbly clay ironstone" at Heacham and with a fossiliferous ironstone recorded by Teall (1875, p. 18) in a pit [6677 3391] at Lodge Hill. The purplish red ironstones correlate with the similar fossiliferous nodules at Heacham. Fossiliferous ironstones were also exposed in a brickpit at 'Mount Amelia', Ingoldisthorpe (Fitton, 1836), probably that near The Hall [6873 3263].

The former Bawsey Brickworks at Brow of the Hill worked Snettisham Clay and Boulder Clay (Whitaker et al., 1893, pp. 18, 64) but does not appear to have yielded any fauna. The whole site has been removed by the modern sand workings; the following section was recorded in the overburden face of the modern workings [6844 1935], close to site of one of the original brickpits (Plate 21):

Carstone; soft brownish green sand .. .. .. 0.6m seen

Snettisham Clay

Clay, medium and dark grey, smooth textured but with many partings, wisps and burrow infillings of orange-brown stained very fine- and fine-grained sand; line of lenticular reddish brown clay ironstone concretions, up to 50 mm thick, in middle part of bed; irregular base with sandy limonitic clay resting on deeply iron-stained surface of the underlying sands 2.0m

Leziate Beds; fine-grained white sands .. .. >15m

This last section is similar to that proved in the Gayton Borehole, about 5 km east of Brow of the Hill; the borehole sequence summarized below is the only unweathered section yet recorded in the Snettisham Clay:

Carstone; pebbly yellowish green sand

Snettisham Clay

Clay, pale grey and brownish grey; Skolithos burrows infilled with Carstone sand extend down for 0.5m; lenses and burrow infillings of fine-grained micaceous silt occur throughout; small silt-filled washout at one level 0.60m

Sandstone, fine-grained, dark brown, densely ferruginously cemented; traces of oolitic grain coatings .. .. 25 mm

Ironstone, dense, medium brown clay ironstone .. 38 mm

Core loss; presumed clay with sand wisps and partings 0.29m

Clay, pale grey and brownish grey with partings, thin lenses, burrow and trail infillings and small washouts of fine- and very fine-grained white sand and micaceous silt; horizontal lamination where undisturbed by burrowing; burrows include many tiny horizontal and vertical tubes; parting of cream-coloured phosphatized clay at base with pseudoalgal structure 0.86m

Core loss; cavings of grey clay with small rounded pebbles of quartz and rotted chert suggest pebble bed at base similar to that at outcrop c.0.3m

Leziate Beds; white fine-grained sand

Sedimentary features, other than lamination picked out by partings of sand, are rare in the Snettisham Clay at outcrop. In the Gayton Borehole, bioturbation in the form of tracks, trails, vertical and sub-horizontal tube-shaped burrows and large poorly defined burrows, are common at several levels. A small silt-filled channel and syneresis cracks infilled with Carstone are also present. Fossils are rare except in the ironstones and in a few of the rare pyrite concretions.

The Hunstanton sequence of the Dersingham Beds is predominantly argillaceous and passes beneath The Wash into the even more argillaceous Tealby Beds. Both sequences are made up of fining-upward rhythms (Fig. 67). The Snettisham Clay appears to be the correlative of one or possibly two rhythms in the upper part of the Hunstanton sequence; each of the lithologies in the generalized Hunstanton rhythm is present in Snettisham Clay spoil in the Heacham to Snettisham area, but the exposures are now too poor for their sequence to be determined. Even with good exposure, it would be difficult to make correlations in this

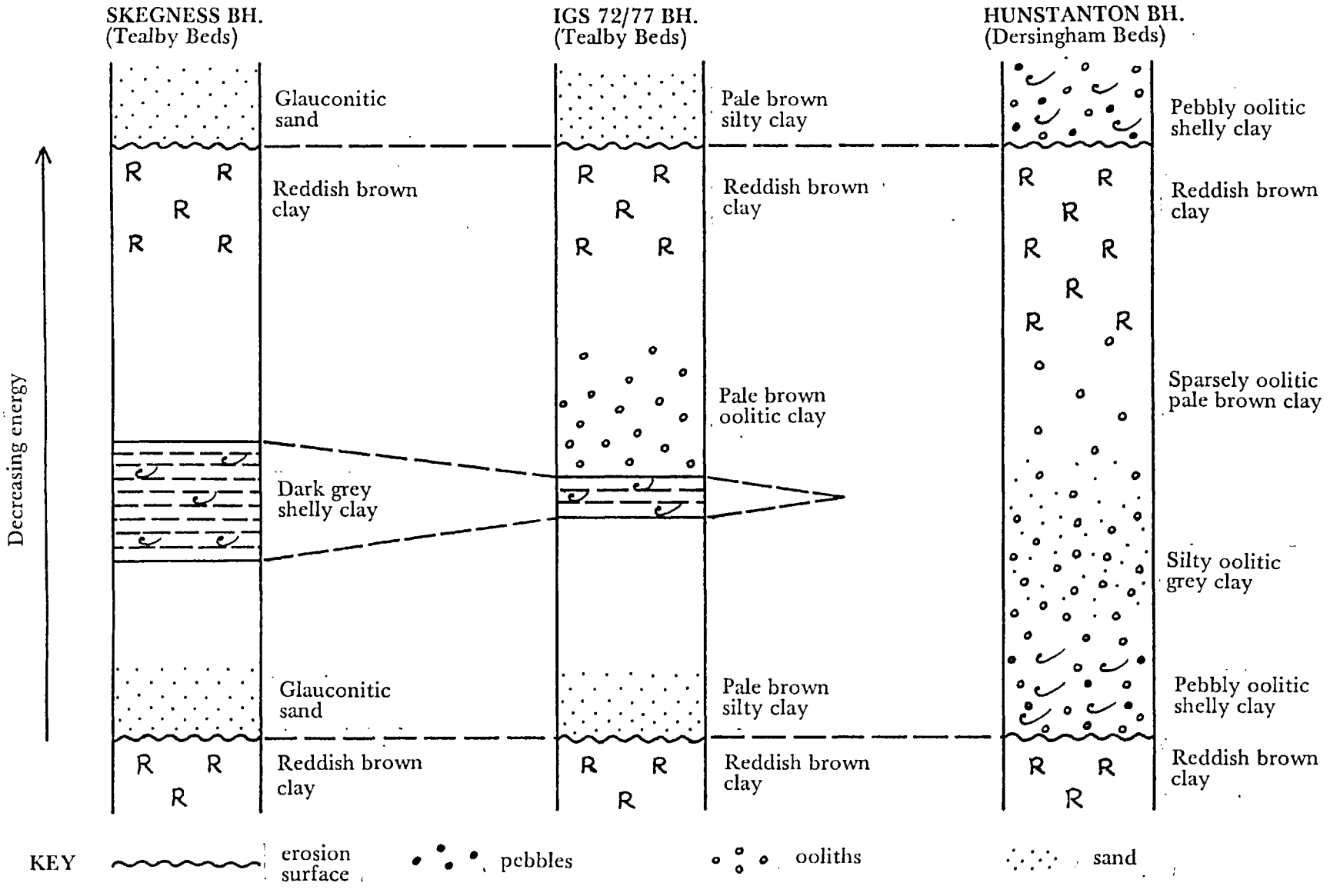


Figure 67. Correlation of generalized rhythms in the early Barremian sediments of the Wash area (not to scale).

type of sparsely fossiliferous sequence that contains numerous erosion surfaces. An example of the variability of the sequence is provided by the Tealby Beds sections at this stratigraphical level in IGS Boreholes 72/77 and 72/78, sited only 2.2 km apart (Fig. 68).

The following succession was proved in the Hunstanton Borehole:

Roach; pebbly clays

Dersingham Beds

Clay, khaki, brown and red, oolitic (limonite) in part, silty in part; intensely burrow-mottled throughout; pebbly in part with small-scale rhythms of pebbly clay passing up into silty clay and smooth-textured clay; shelly and calcareously cemented at one level; passing down into 0.99m

Silt, clayey, sparsely oolitic, brown and grey burrow-mottled; rare small pebbles; ooliths concentrated in burrows; rhythmic with small-scale rhythms with erosive bases of pebbly silt resting on burrowed surfaces with Arenicolites and Skolithos at several levels, sparse fauna includes bivalves and rare pyritized ammonite fragments; erosion surface at base 2.45m

Clay, very silty and silty, pale and medium grey; shelly with numerous tiny bivalves; becoming oolitic and pebbly with depth; passing down with burrowing into 0.38m

Clay, pale and medium grey, very oolitic, pebbly, intensely burrow-mottled; poorly preserved bivalves and lignite fragments; burrowed surface in middle part of bed resting on sparsely oolitic silty clay

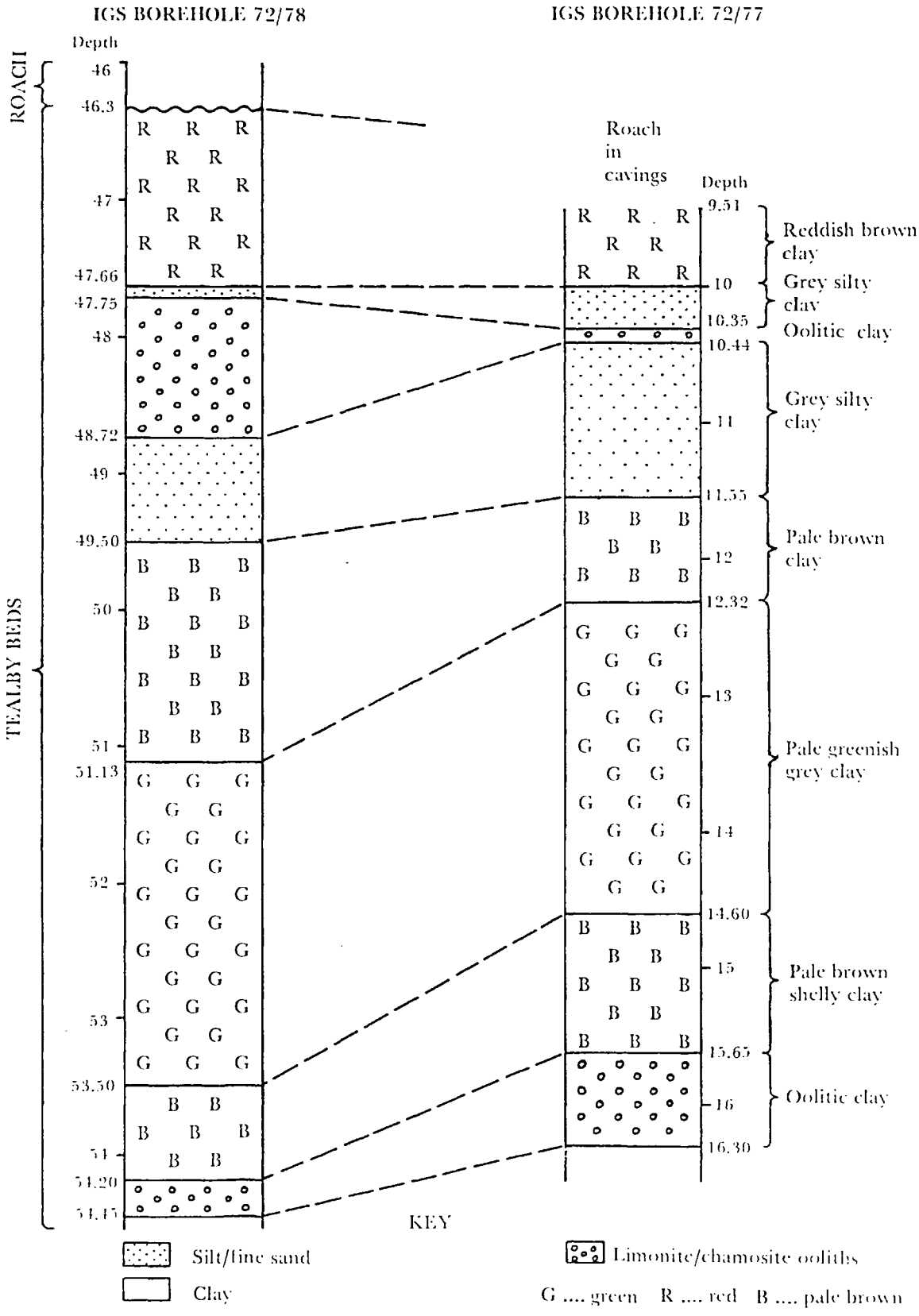


Figure 68. Correlation between the Tealby Beds sequences in IGS Boreholes 72/77 and 72/78.

with wisps and burrowfills of coarse silt; 1 to 3 cm-thick lenticular bed of pale brown clay ironstone at one level; bed of course sand grains and tiny pebbles at base resting on burrowed surface 2.07m

Silt, fine- and coarse-grained, pale grey and brown, burrow-mottled, finely micaceous in coarser silts; burrows include Ophiomorpha; some burrows partially pyritized, others clay-lined; pebble bed at base with well rounded pebbles of vein quartz, grey clay and soft chalky limestone set in plant-rich glauconitic silt; interburrowed junction with 0.78m

Clay, medium grey, smooth-textured with burrowfills of pale brown silt, sharp base 0.10m

Silt, pale grey and pale brown, fine- and coarse-grained, burrow-mottled; micaceous in part; becoming clayey in lower part; faintly glauconitic in part; burrowfills of fine-grained quartz sand at several levels; burrows include Chondrites and Ophiomorpha; small bivalves and coalified wood fragments common at several levels; becoming increasingly sandy with depth and with tiny vein quartz pebbles; very clayey in lowest 0.2m; interburrowed junction with 5.16m

Leziate Beds; medium- and coarse-grained sands

Many of the Dersingham Beds lithologies are sparsely fossiliferous, largely because of their unsuitability for preservation. The two notable exceptions are the ferruginous sandstones at the base of the formation and clay ironstone nodules in the Snettisham Clay, both of which have given rise to extensive museum collections. The

three exposures in the basal sandstones, at Wolferton [662 287], Sandringham Warren [669 276] and Roydon Common [675 222], that were listed by Whitaker and Jukes-Browne (1899, p. 27) as fossiliferous, are still open and they, together with a small number of additional exposures in the same area, have yielded a relatively rich fauna. This is dominated by bivalves (24 species), but includes common plant fragments, trace fossils, serpulids and gastropods and rare ammonites and echinoids. The ammonites include species of Endemoceras that indicate a Hauterivian age. Casey (1967, p. 91) recorded the late Hauterivian early Barremian ammonite Craspedodiscus as a derived fossil in the basal bed of the Carstone at West Dereham, in south-west Norfolk, and he presumed it to have been derived from an outcrop of Dersingham Beds or their lateral equivalent that lay some distance beyond the southern limit of the present-day outcrop. The non-ammonite fauna of the Dersingham Beds is long ranging and not stratigraphically diagnostic. Casey (1973) has noted, however, that the occurrence of large numbers of the Boreal bivalve Buchia in the basal part of the Dersingham Beds can be correlated with a similar influx of Buchia in the Hauterivian part of the Speeton Clay of Yorkshire.

The former brickworks in the Snettisham Clay at Heacham, Snettisham and Ingoldisthorpe yielded a rich bivalve fauna, common gastropods, ammonites, plant fragments and serpulids, and rare brachiopods, belemnites, crinoids and fish debris. Many of the ammonites are well preserved as uncrushed brown, ironstone casts and they were much sought after when the pits were in work. Many of the finer specimens are now in museum collections. They all belong to the crioceratid genera Acrioceras, Crioceratites (Hoplocrioceras) and C. (Paracrioceras) and were shown by Spath (1924) to be indicative of an early Barremian age.

The sections are all now degraded and the published descriptions of several of them are either incomplete or in disagreement with one another. The provenance of much of the fauna can no longer be demonstrated but re-examination of museum collections by Mr Morter strongly suggests that the bulk of it belongs to one or other of two assemblages of differing ages. Contemporary descriptions of the brickpits suggest that these assemblages came from two separate horizons, one close to the base of the Snettisham Clay and one in its upper part. The older fauna is by far the more varied and includes plants, annelids, brachiopods (2 species), bivalves (22 species), gastropods (7 species), crioceratid ammonites including Acrioceras sp., species of the belemnites Aulacoteuthis and Praeoxyteuthis and fish vertebrae, all preserved as nests in large rusty brown clay ironstone concretions or in ferruginous oolitic clays. The ammonites and belemnites suggest correlation with the early Barremian zone of Crioceratites (Hoplocrioceras) fissicostatum. At Heacham and Snettisham brickworks this type of fossiliferous ironstone appears to have been present at the base of the Snettisham Clay and possibly at one or more levels in the lowest 2m of it. The younger fauna is more limited and consists of species of Crioceratites (Hoplocrioceras) and C. (Paracrioceras) and a few bivalves and gastropods, beautifully preserved in buff, red or purplish red clay ironstone. The ammonites are indicative of the mid-Barremian zone of Crioceratites (Paracrioceras) elegans.

At Dersingham [6935 2997], Lamplugh (in Whitaker and Jukes-Browne, 1899, p. 10) collected a fossiliferous phosphatic nodule from the pebble bed at the base of the Snettisham Clay. The fauna can be matched with part of that of the basal ironstone at Heacham and Snettisham. Its presence in a derived preservation at Dersingham

suggests that the base of the Snettisham Clay is diachronous, and that it youngs southwards.

4.4 Roach

The presence of clay beneath the Carstone outcrop on Hunstanton beach appears to have been first recorded by Rose (1835) who presumed it to be the Kimmeridge Clay. He subsequently (1862, p. 235) described the junction of the two formations as a "non-brecciated bed of Carstone" resting on the clay. Wiltshire (1869, p. 189) described the base of the Carstone as marked by a pebble bed that contained small phosphatic pebbles enclosing numerous ammonites, and large rounded masses of fossiliferous ironstone. Keeping (1883, pp. 33 and 57) reviewed the faunas collected from these pebbles and described those from the phosphatic pebbles as mostly water-worn casts of Lower Aptian ammonites. He described the ironstones as boulders of iron-cemented, fossiliferous fine-grained sandstone "as big as large cannonballs" with casts of small bivalves and fragments of an uncoiled ammonite, "Hamites or Ancyloceras", which he clearly considered to be pre-Aptian in age. Lamplugh (in Whitaker and Jukes-Browne, 1899) described the basal bed of the Carstone on the foreshore as a pebble bed set in a green clayey sand. The contact with the underlying clay was not at that time exposed, but he noted that "hard grey clay", presumed to be Snettisham Clay, had previously been seen in the spoil from the pier foundations.

Keeping's conclusions concerning the age and origin of the pebbles in the basal bed of the Carstone were confirmed and elaborated upon by Casey (1961, p. 571). The fauna of the phosphatic pebbles was shown to be derived from two zones of the Lower Aptian, and Keeping's hamitid

from the ironstones was redetermined as a Barremian Paracrioceras.

The present survey of the Hunstanton area provided little additional data on the clay underlying the Carstone other than the fact that it appeared, from augering at and below low-water mark on the beach, to pass locally into sand and very sandy clay. The continuous cores of the Hunstanton Borehole further complicated the issue because there the Carstone appeared to pass down, without any obvious erosion surface or phosphatic pebble bed, from pebbly oolitic (limonitic) clayey sand into a complex sequence of sandy clays and clayey sands that were themselves locally pebbly and oolitic and lithologically unlike the Snettisham Clay. This unsatisfactory situation led to the digging of a number of deep trenches on Hunstanton beach to examine the base of the Carstone and the nature of the underlying beds.

The composite section proved in these trenches is shown graphically in Fig. 69. The ironstone nodules with Paracrioceras were present in situ in sands that are unconformably overlain by the Carstone and which are lithologically unlike the Snettisham Clay. They can, however, be matched with parts of the Roach of Lincolnshire. This correlation was confirmed by Morter (1975) who concluded that the non-ammonite fauna of the in situ ironstones was similar to that of parts of the Roach, and that it was probably Middle Barremian in age. The sequence in the trenches can be matched lithologically with that in the Hunstanton Borehole, with the execption that the borehole cores do not contain any macrofauna at this stratigraphical level nor are any derived phosphatic or ironstone nodules present. The trenches showed that the basal bed of the Carstone (Bed 2 of Fig. 69) is laterally variable in lithology over short distances and that the distribution of the phosphatic pebbles is patchy.

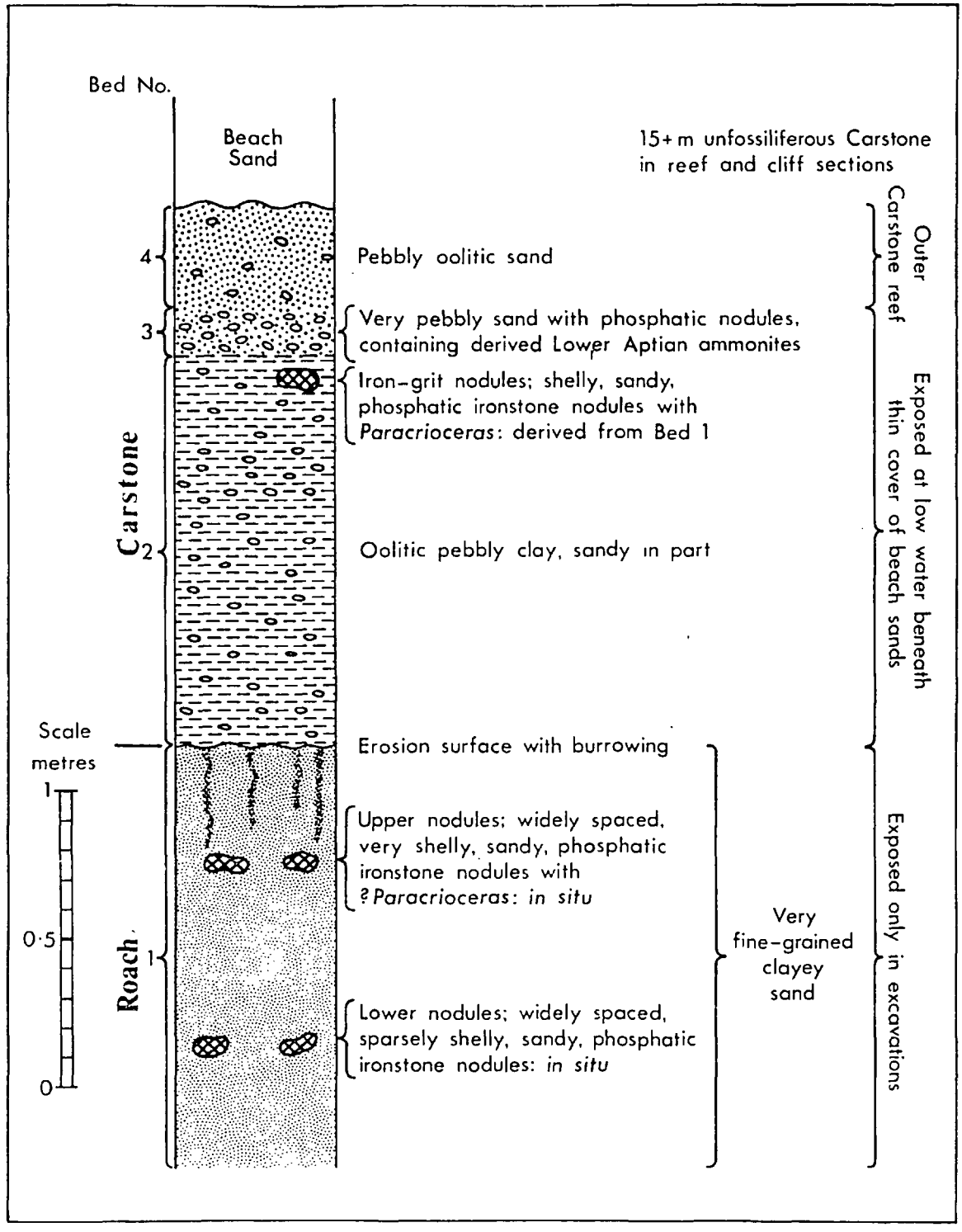


Figure 69. Graphic section showing the beds adjacent to the Roach-Carstone junction proved in trenches on Hunstanton beach.

A total of 11.6m of beds have been assigned to the Roach in the Hunstanton Borehole. The sequence is more complete beneath The Wash and in Lincolnshire, due to the south-easterly overstep of the Carstone, and both the Skegness and IGS 72/78 boreholes proved 21.7m of the formation.

The term 'Roach' was first used by Jukes-Browne (1887, p. 19) for a group of oolitic and pebbly sandy clays in the upper part of the Lincolnshire Lower Cretaceous sequence. Swinnerton (1935, p. 4) divided the formation, on the basis of a cored borehole at Alford, Lincolnshire, into a 'Lower' and an 'Upper' member separated by a calcareously cemented oolitic sandstone that he called the 'Roach Stone'. Swinnerton also introduced the name 'Fulletby Beds' to describe the three divisions (Table 14). Thurrell (in Owen and Thurrell 1968, p. 106) later used 'Roach Stone' in a description of the Lower Cretaceous sequence at outcrop, but he widened Swinnerton's definition to include any hard bed that gave rise to a feature at about the middle part of the Roach outcrop, irrespective of its lithology. In the absence of a recognisable Roach Stone, Swinnerton's 'Fulletby Beds' and Jukes-Browne's 'Roach' are synonyms. No Roach Stone was recognised in the Hunstanton Borehole and it was therefore decided to use the older formation name for the Norfolk deposits until such time that the Lower Cretaceous sequence in Lincolnshire has been re-described (Plate 26).

The beds assigned to the Roach in the Hunstanton, Skegness and IGS 72/78 boreholes consist of a complex rhythmic sequence of inter-burrowed and interbedded lithologies made up of varying amounts of clay, chamosite mud, chamosite ooliths (mostly limonitized), quartz

Plate 26. Roach and Carstone lithologies.

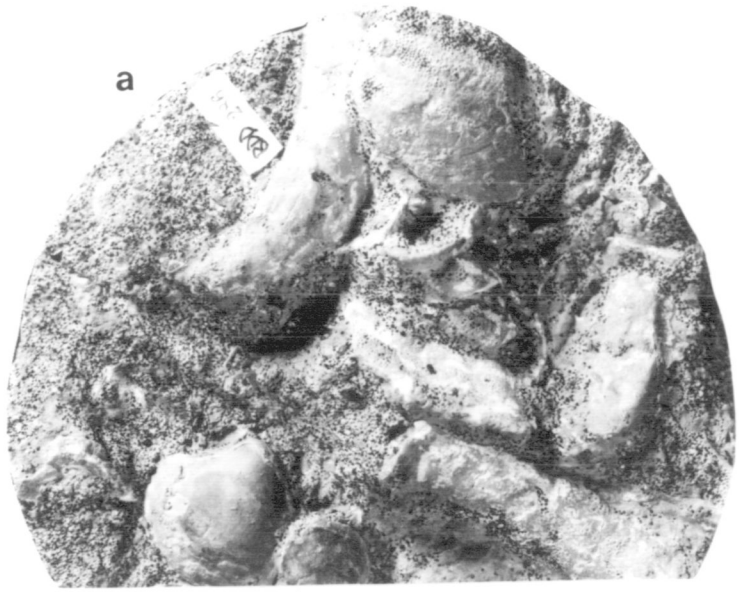
A. Bedding-plane view of typical 'Roach Stone' lithology, composed of a bioturbated mixture of limonitised ooids, clay, tiny pebbles, sand grains, and an abundant fauna of thick-shelled, poorly preserved bivalves (mostly oysters). Specimen no. BDD 2869, Hunstanton Borehole, 178 ft 2 in. Natural size.

B. Section of weakly calcite-cemented 'Roach Stone' cut normal to bedding, showing bioturbation and distribution of shells. Specimen no. BDD 2865, 177 ft 7 in. Natural size.

C. Carstone outcrop on Hunstanton foreshore showing the rectilinear pattern of joints referred to by Whittaker as reminiscent of a giant icthyosaur paddle. Photo. no. A 10850.

D. Typical pebbly Carstone showing pebbles of ironstone, quartz, rotted limestone, etc. set in a matrix of sand, limonitised ooids and ferruginous oxidation products. Hunstanton foreshore.

Plate 26









sand and small pebbles of quartz and ironstone. The position chosen for the lower boundary of the formation is somewhat arbitrary because the formation had not previously been recognised in Norfolk and it was necessary to make comparisons with a type section about 50 km distant in what are likely to be laterally variable beds. The base of the formation has been taken at a minor erosion surface which has been recognised in all three boreholes (Fig. 70). This surface separates the predominantly oolitic and pebbly clays of the Roach from the smoother-textured, more fossiliferous clays of the Tealby Beds at Skegness and beneath The Wash, and seems to be close to the Roach-Tealby Beds junction as originally defined by Swinnerton (1935, p. 6) in the Alford Borehole. At Hunstanton, this surface separates the Roach from the predominantly argillaceous, sparsely pebbly Dersingham Beds. In all three boreholes the basal Roach erosion surface lies a little above the highest well developed reddish brown, smooth-textured clay of the Tealby Beds and Dersingham Beds. Thin beds of grey and reddish brown clay occur in the Roach, but the presence of thick beds of this lithology appear to be a useful distinguishing characteristic of the Tealby and Dersingham beds.

The outcrop of the Roach is almost entirely covered by drift deposits in Norfolk. It underlies much of the lowest part of the beach to the north of Hunstanton pier, but has been everywhere overlain by beach sand and gravel in recent years. Southwards from Hunstanton the formation is covered by till except for a small area near the Firs, on the south side of Hunstanton. There, a deep trench [678 392] revealed pebbly sandy clay beneath a cover of sandy downwash. This is the most southerly known occurrence of the Roach and it is presumed that the formation is overstepped by

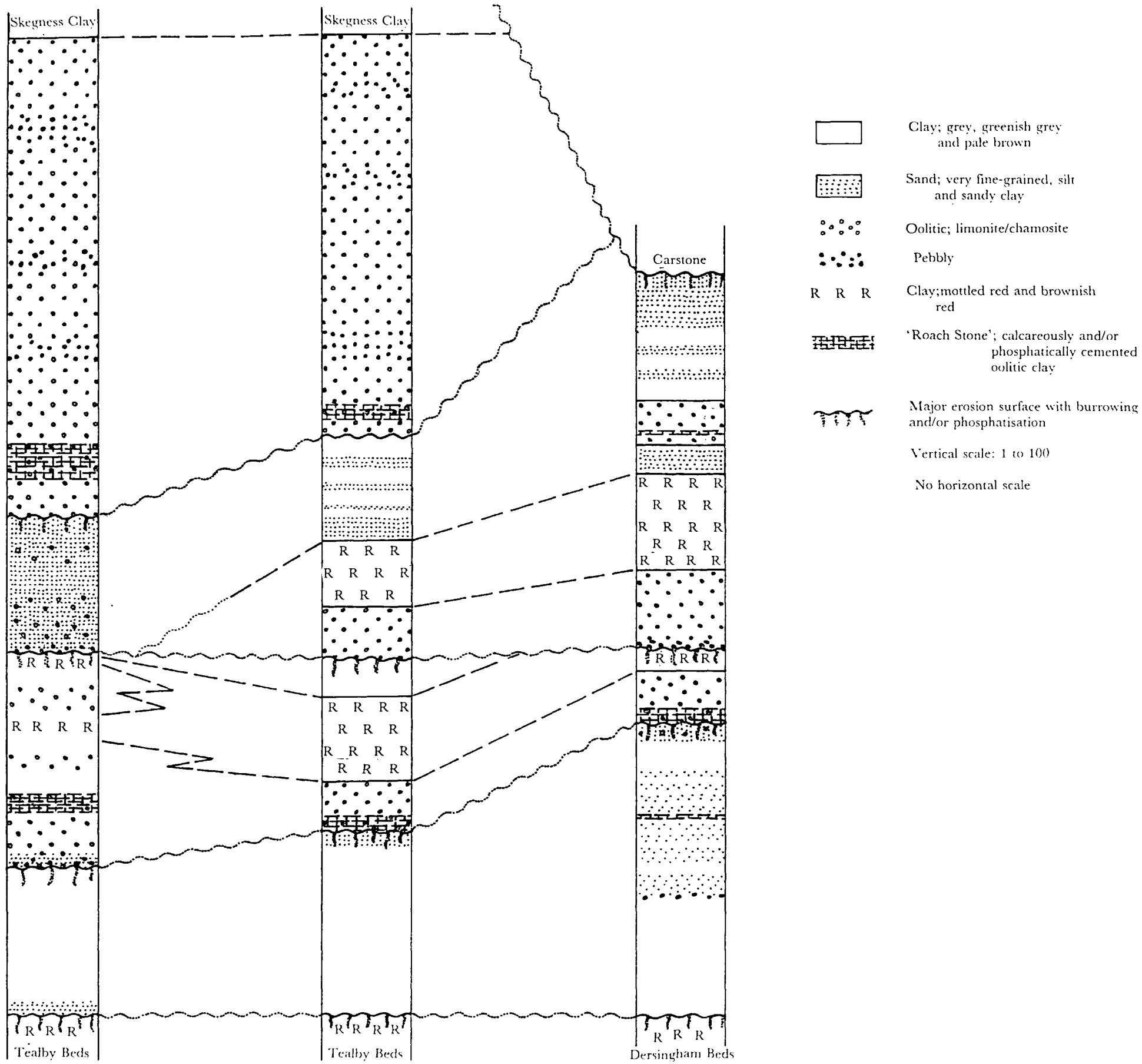


Figure 70. Correlations between the Roach sequences in the Wash area.

the Carstone in that area.

The only complete section through the Roach yet proved in Norfolk is that in the Hunstanton Borehole, where the following succession is present:

Carstone, very pebbly oolitic clay

Roach

Sand, very fine-grained, very clayey, burrow-mottled dark grey and greenish yellow brown oolitic (limonite) in part; barren except for plant fragments; passing down into 2.69m

Clay, very sandy, burrow-mottled, sparsely oolitic with ooliths concentrated in bands; rare ironstone pebbles and calcite-shelled bivalves in lowest 10 cm; passing down into 0.78m

Ironstone, densely calcite-cemented; muddy, oolitic and sparsely sandy; burrow mottled; shelly with thick-shelled bivalves; becoming softer in lowest part; interburrowed junction with 0.18m

Sand, very clayey, burrow-mottled, medium and dark grey; sharp base with burrowed surface.. .. .. 0.77m

Clay, smooth-textured, pale brown, khaki and reddish brown, burrow-mottled with Chondrites and other burrows; line of small, ?phosphatic concretions in top 5 cm; barren; small pyritized patches and pyritized trails present; wisps of pale grey silt at several levels; interburrowed junction with 2.15m

Clay, silty, oolitic and very oolitic, burrow-mottled pale grey and brownish grey; rare bivalves and plant fragments; passing locally into clayey oolite or clayey

silt as proportions of constituents vary; burrowfill wisps of glauconitic silt at one level; becoming pebbly in lowest 35 cm with small quartz and ironstone pebbles, small oysters and rolled belemite fragments; very pebbly in lowest 7 cm with large pebbles of quartz, ironstone, chert, phosphate and rotted limestone; resting on sharp, strikingly burrowed surface 1.81m

Clay, silty, reddish brown, smooth textured, rare bivalves; becoming more silty with depth and passing down into 0.33m

Clay, sandy and sparsely pebbly, burrow-mottled, medium grey with paler silt burrowfills; interbedded with oolitic burrow-mottled clays; sparsely pebbly in lower part; passing rapidly down into 1.14m

Mudstone, tough, calcite and phosphate-cemented, burrow-mottled; sparsely pebbly; scattered bivalves including oysters; sharp base with burrowed surface 0.15m

Clay, very silty, intensely burrow-mottled, finely micaceous, sparsely oolitic and pebbly in part; burrowfills and thin interbeds of reddish brown clay; sharp base 1.68m

Clay, pale slightly greenish grey, smooth textured; faintly burrow-mottled with burrows picked out in pale grey silt; sharp base 0.46m

Clay, silty, oolitic, intensely bioturbated; interbedded with clayey silts and sandy and oolitic clays in fining-upward, sharp-based rhythms; densely calcite-cemented in part; interburrowed junction with 4.42m

Dersingham Beds; red, brown and khaki clays

The Roach sequence at Hunstanton continues the fining-upward rhythmic succession of the Dersingham Beds (Fig. 67). In contrast to the Dersingham Bed rhythms those of the Roach are commonly thin (< 1m) and end in silt or silty clay with the overall result that the Roach is more silty, oolitic and pebbly than the Dersingham Beds. Most of the rhythm bases appear to be erosive and probably give rise to rapid lateral changes that make correlation of the Roach sequences across the mouth of The Wash difficult and uncertain (Fig. 70). Bioturbation is present throughout, but is rarely sufficiently well defined to be identifiable. Traces of cross-bedding are present in the sand at the top of the formation, both in the borehole and in the beach sections, but this too is disturbed by burrows.

Although the ironstones obtained from the beach excavations at Hunstanton yielded a rich fauna, both in numbers and variety, the Roach in the boreholes is barren at many levels. It is probable that the fauna is concentrated, probably through selective preservation, in the more cemented lithologies and in the smoother textured clays. The fauna of the beach concretions is dominated by small bivalves (18 species) but also contains fragments of ammonites (Hoplocrioceras and ?Paracrioceras), gastropods (2 species and several small indeterminate forms), brachiopods (2 species), scaphopods and common wood fragments (Morter 1975, pp. 29 - 30). The faunas from the Roach in the Hunstanton, Skegness and IGS 72/78 boreholes are similarly dominated by small bivalves. The full faunal list is given in Appendix D. Despite the length of this list the bulk of the Roach has a low diversity fauna and flora in which only the bivalves Corbula isocardiaeformis Harbort, Entolium germanicus (Wollemann), Paranomia

laevigata (J. de C. Sowerby) and Parmicorbula striatula (J. de C. Sowerby) and plant fragments are common.

Most of the fauna and flora is long-ranging and none of the plants, scaphopods, echinoderms, bivalves or gastropods is diagnostic of a single stage. Many of the bivalves are characteristic 'Neocomian' forms and range from the Ryazanian to the Barremian. A few have Aptian affinities and suggest a Barremian or Aptian rather than an earlier age. Hoplocrioceras and ?Paracrioceras range from the Upper Hauterivian to the Middle Barremian and their record here adds little to the stratigraphical information already available for the age of the Roach. The brachiopod Rhynchonella parkhillensis Davison has only previously been recorded from the Roach Stone of the Lincolnshire outcrop (Owen and Thurrell, 1968, p. 119). The presence of Middle Barremian ammonites in the Snettisham Clay (on which the Roach rests with only minor unconformity), and an apparently conformable junction with the Aptian Skegness Clay (Section 4.5) beneath The Wash and Lincolnshire where the full thickness of the Roach is preserved, suggests that the Roach preserved in Norfolk is late Middle to early Upper Barremian in age.

4.5 Skegness Clay, Sutterby Marl and Woburn Sands

In the offshore area to the north-west of Hunstanton, the Roach is overlain by two argillaceous formations, the Skegness Clay and the Sutterby Marl, that are known only from boreholes in The Wash and at Skegness, and from a limited outcrop in Lincolnshire. These formations were deposited during the time interval represented by the unconformity between the Roach and the Carstone at Hunstanton. Both formations were probably formerly widespread in the district, but were removed by erosion and are now represented in the land area only by derived faunas in the

basal pebble bed of the Carstone. In the south-west of the district, the most northerly outcrop of the Woburn Sands, glauconitic sands that are probably in part contemporaneous with the Sutterby Marl, occurs as a low island in the Suffolk fenland; its subcrop probably extends to the county boundary.

Swinnerton (1935), in his description of the Lower Cretaceous rocks of Lincolnshire noted that the Roach and the Carstone were separated throughout much of their outcrop by a thin bed of pale grey calcareous clay. No exposure of the clay was available for study partly because of its susceptibility to weathering and partly its occurrence at the foot of the Lower Chalk escarpment where its outcrop is covered by a downwashed mixture of Carstone Red Chalk and Chalk. Swinnerton therefore chose a relatively drift-free area near the village of Sutterby and examined the clay in a trench section which he described (1935, pp. 18 - 19) as the type section of a new formation, the Sutterby Marl. The base of the Sutterby Marl was not rigidly defined by Swinnerton but appears to have been taken a little below a phosphatic nodule bed which yielded a rich ammonite fauna. Swinnerton (1935, pp. 24 - 25) believed this fauna to be indigenous and, because it included the ammonite Prodeshayesites, to indicate an early Aptian age.

The lithological change from the sandy, pebbly and oolitic clays of the almost barren upper Roach to the smooth-textured calcareous fossiliferous clays of the Sutterby Marl was therefore thought to be coincident with the Barremian-Aptian boundary. Casey (1961b, pp. 570 - 571) subsequently showed that the fauna referred by Swinnerton to the early Aptian was not indigenous but was made up of elements derived from three Lower Aptian zones, those of Prodeshayesites fissicostatus,

Deshayesites deshayesi and Tropaeum bowerbanki. Casey further suggested on the basis of a specimen of Columbiceras in the Swinnerton collection from Sutterby, that the Sutterby Marl was Upper Aptian in age.

The sequence proved between the Roach and the Carstone in the Skegness Borehole and in IGS Borehole 72/78 in The Wash, is more complex than that described from Sutterby in that two clays are present, separated by an erosion surface. The upper clay can be matched in faunal and lithological detail with the Sutterby Marl of the Sutterby trench section. The lower clay is predominantly dark grey and contains indigenous crushed iridescent aragonite-shelled Prodeshayesites indicative of a basal Aptian age. Because of the differences in the lithologies of the lower and upper clays, their disparate ages and their unconformable contact, the name Skegness Clay was proposed for the lower clay (Gallois, 1975).

The Skegness Clay has not been positively identified outside these two boreholes; it is absent in Norfolk but probably underlies much of the Norfolk side of the Wash. The offshore seismic evidence (Wingfield et al., 1979) suggests that it may approach within 2 km of Hunstanton beach. It seems likely that it is also preserved to the north and west of Skegness and probably crops out in the southern part of the Lincolnshire Wolds. Swinnerton seems to have been unlucky in choosing a site for the Sutterby Marl excavation at a place where the basal unconformity of the Sutterby Marl has cut out the Skegness Clay (Fig. 71). Elsewhere in east Lincolnshire he recorded borehole sections, mostly drillers' logs, which can be more closely matched with the Skegness Borehole sequence than with that of the Sutterby excavation. In the Alford Borehole (Swinnerton, 1935, p. 5)

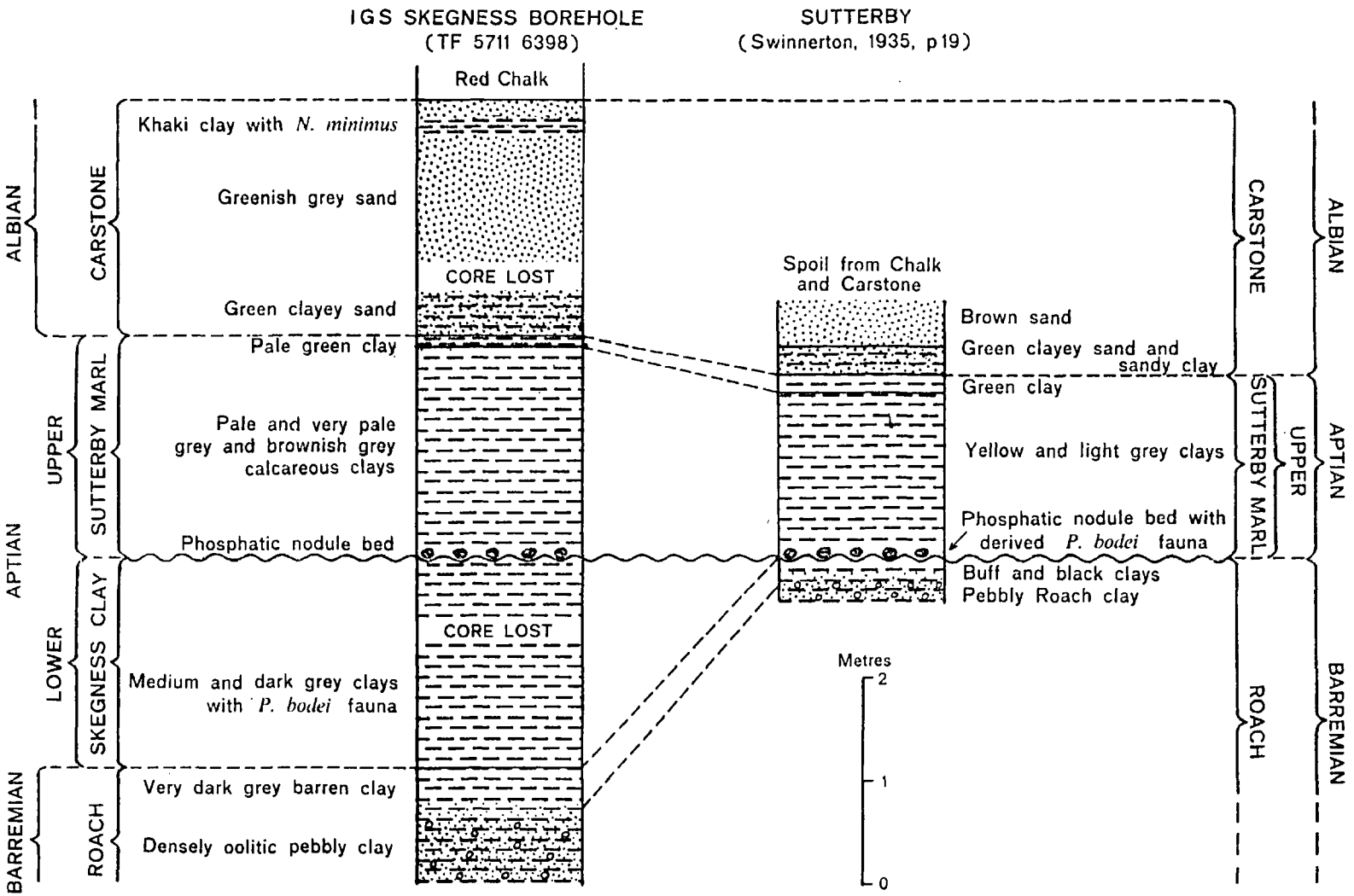


Figure 71. Correlation of the Barremian to Albian sequence in the Skegness Borehole with that proved at Sutterby, Lincolnshire.

the Carstone was underlain by 6 ft (1.83m) of 'light grey marl' and 5 ft (1.52m) of 'dark grey and black clay', all classified as Sutterby Marl. A similar section was recorded in the Maltby Borehole (1935, p. 13), consisting of $3\frac{1}{2}$ ft (1.07m) of 'light grey marl' passing down into 6 ft (1.83m) of 'black marl'. The sections would be comparable to that of the Skegness Borehole if the lower clays were reinterpreted as Skegness Clay.

The relationship of the Skegness Clay to the Roach, Sutterby Marl and Carstone in The Wash area, including the positions of the indigenous and derived Aptian faunas, are summarized in Fig. 72.

The Skegness Clay in IGS Borehole 72/78 consists of 1.26m of medium and dark grey and brownish grey smooth textured clays with some bioturbation, pyritized trails and a sparse fauna of small bivalves, common crushed iridescent ammonites and rare gastropods and corals. The junction with the underlying pebbly oolitic clays of the Roach is bioturbated, but sharp and apparently conformable. The ammonites have been identified by Dr Casey as Aconeceras nisoides (Sarasin), Prodeshayesites germanicus Casey, P. lestrangei Casey and P. cf. lestrangei. These last three species are especially common as derived phosphatized specimens in the basal pebble bed of the Carstone at Hunstanton beach. In addition to the above the Skegness Borehole, the type section, yielded Prodeshayesites cf. bodei (von Koenen), P. fissicostatus (Phillips) and Toxaceratoides royerianus auctt. non d'Orbigny. The assemblage is indicative of the P. bodei Subzone of the P. fissicostatus Zone. The base of the Aptian Stage in Britain has been taken by Casey (1961b, p. 496) to be marked by the entry of the ammonite family Deshayesitidae. The faunas from the boreholes include the earliest

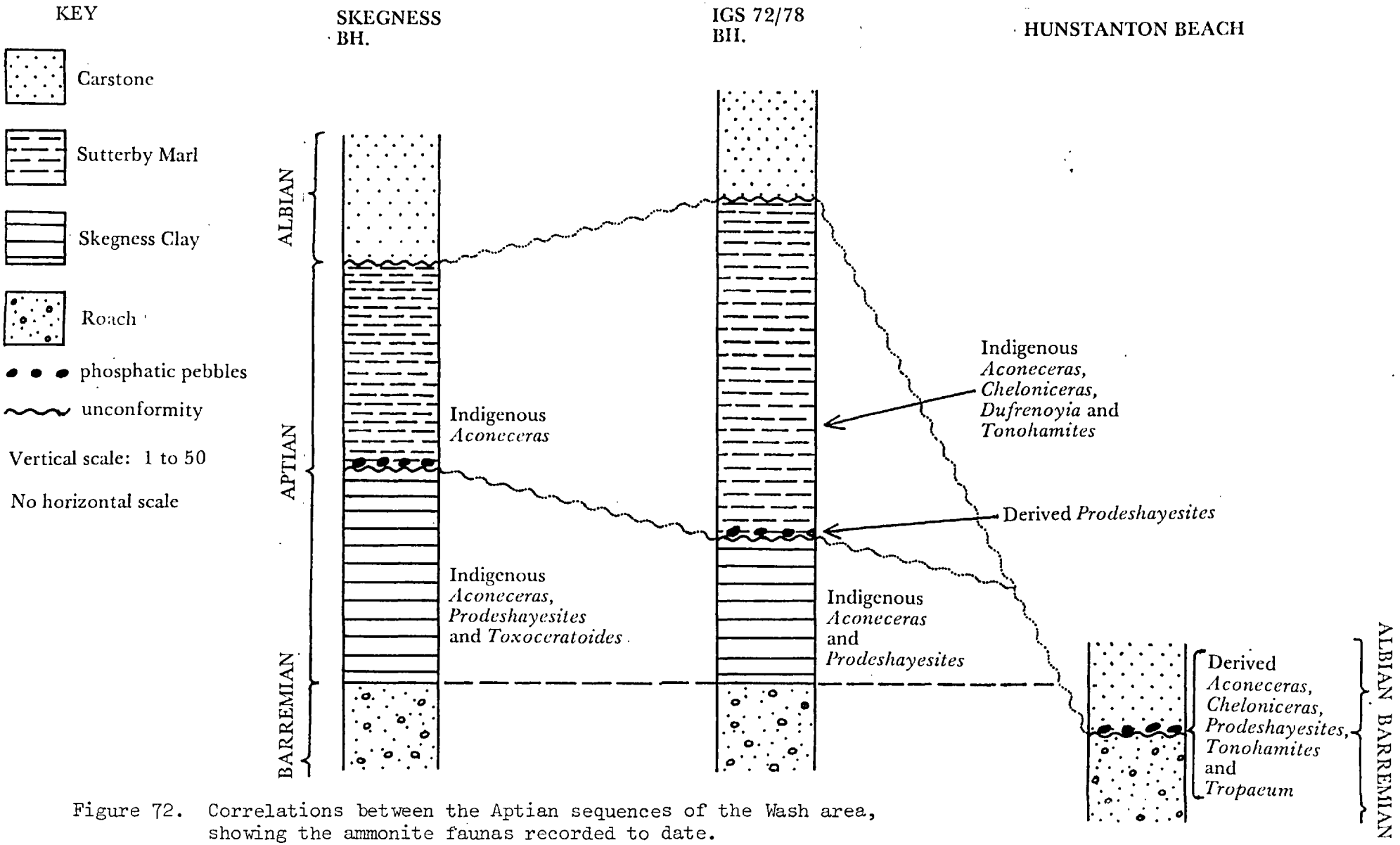


Figure 72. Correlations between the Aptian sequences of the Wash area, showing the ammonite faunas recorded to date.

deshayesitids recorded to date, and the junction of the Roach and the Skegness Clay has therefore been taken to mark the Barremian-Aptian boundary.

The non-ammonite fauna of the Skegness Clay has been identified by Mr Morter. It consists largely of small bivalves, most of which are long-ranging forms of Camptonectes, Corbula, Grammatodon, Paranomia and Vnigriella, that have also been recorded from the Barremian Tealby Beds and Roach. A small ahermaphytic coral, 'Trochocyathus' and a small ?fusinid gastropod were recorded in IGS Borehole 72/78, together with the belemnite Hibolites cf. minutus Swinnerton, a species that occurs in the highest B Beds of the Speeton Clay.

The Sutterby Marl consists of very pale grey and pale yellowish grey, bioturbated, highly calcareous clays with a rich and diverse marine fauna of ammonites, belemnites, bivalves and brachiopods with rarer echinoids and corals. Chondrites is the only recognisable trace fossil. Much of the calcareous content is made up of coccolith debris (Black, 1972- 75). The formation rests with minor unconformity on the Skegness Clay and has at its base a pebble bed composed largely of phosphatized body chambers of ammonites derived from the Skegness Clay and water-worn belemnite fragments, set in a matrix of silt and comminuted shell debris. The highest part of the formation consists of pale green calcareous silty clay that is separated from the underlying beds by a minor erosion surface. Another, apparently minor, erosion surface separates this bed from typical Carstone lithologies and it is unclear, in the absence of faunal evidence, which erosion surface represents the major stratigraphical break that marks the base of the Carstone.

The Sutterby Marl is at least 3.14m thick in IGS Borehole 72/78 where the junction with the Carstone was lost during coring. Only 1.98m of Sutterby Marl is present at Skegness and Swinnerton (1935) recorded only 1m to 2m of the formation in boreholes and at outcrop in Lincolnshire. The contact with the Carstone is therefore probably irregular on a regional scale and variations in the depositional thickness of the Sutterby Marl can no longer be determined. Between IGS Borehole 72/78 and the Norfolk coast, a distance of 8 km, the Carstone cuts out about 10m of Roach, 1.3m of Skegness Clay and 3.1m of Sutterby Marl. It seems likely therefore that the Sutterby Marl is overstepped by the Carstone about 5 km north west of Hunstanton. The Skegness Clay and the Sutterby Marl could not be differentiated in offshore seismic traverses (Wingfield et al., 1979), but it is assumed here that the older formation extends farther south than the younger.

The Sutterby Marl fauna in IGS Borehole 72/78 (Morter in Gallois and Morter, 1979) includes elements, such as common thin-shelled terebratulid and terebratellid brachiopods and finely-tapered Neohibolites, which appear to have been destroyed by weathering at outcrop at Sutterby. The borehole yielded the echinoid ?Toxaster, the brachiopods Platythyris sp., 'Terebratula' moutoniana auctt. and cf. Tamarella tamarindus (J. de C. Sowerby), the bivalves Astarte, ?Ctenoides rapa (d'Orbigny), Inoceramus cf. ewaldi Schleuter, Nanonavis carinata (J. Sowerby), indeterminate ostreids and Plicatula, the ammonites Aconeceras nisoides (Sarasin), Cheloniceras sp., Dufrenoyia sp. and Tonohamites?, the belemnites Neohibolites ewaldi (von Strombeck), and indeterminate aporrhaid and cerithiid gastropods. The pebble bed at the base of the formation contains fragments of water-worn and bored

phosphatized Prodeshayesites bodei (Koenen), P. fissicostatus (Phillips), P. cf. fissicostatus and P. spp. that are presumably derived from the Skegness Clay.

The belemnites from the Sutterby Marl at outcrop in Lincolnshire have been described by Swinnerton (1935, 1936 - 55) and the ammonites, both indigenous and derived, have been discussed by Casey (1961b, pp. 570 - 571). These authors assigned the formation to the Upper Aptian on the basis of the presence of Neohibolites ewaldi (von Strombeck) and Colombiceras respectively. The presence of indigenous Cheloniceras and Dufrenoyia in the lowest part of the Sutterby Marl in the borehole suggests that the beds at this level are late Lower Aptian or early Upper Aptian in age (Casey: pers. comm.). The bivalve fauna is distinctly Aptian, in contrast to the strongly Barremian affinities of the Skegness Clay bivalves. The Sutterby Marl contains numerous small oysters including forms of Aucellina and Inoceramus characteristic of the Lower Greensand of southern England and the Ewaldi Marls of North Germany (Morter: pers. comm.). Considering the fauna as a whole it seems likely that the bulk of the Sutterby Marl is Upper Aptian in age.

The upper limit of the formation in the type section at Sutterby was taken by Swinnerton (1935) at an erosion surface at the base of the Carstone. In the Skegness and IGS 72/78 boreholes the basal beds of the Carstone consist of greyish green sandy clays and green silty clays. Two closely spaced erosion surfaces occur at the approximate level of the Sutterby Marl-Carstone junction in each borehole. In the Skegness Borehole these erosion surfaces are separated by only 8 cm of burrow-mottled green silty clay and it is impossible to determine which surface correlates with the widespread unconformity at the base of the Carstone. A specimen of Neohibolites strombecki Miller (indicative of the Leymeriella tardefurcata Zone of the Lower Albian) was recorded

in this silty clay and suggests that these beds may be a remnant of a hitherto unrecorded formation intermediate in age between the Sutterby Marl and the Carstone. The comparable beds in the IGS 72/78 Borehole were mostly lost during coring. Burrow-mottled pale and dark green silty clays (5 cm), lithologically similar to the green silty clay at Skegness, occur immediately above the core loss. The total-gamma-ray log of the interval of core loss suggests that it was in loose sands with their base (presumably the lower of the two erosion surfaces) about 2.6m below the green silty clay. It is therefore unclear whether the beds between the erosion surfaces (c. 2.65m) should be grouped with the Sutterby Marl or with the Carstone.

In Norfolk and Suffolk, William Smith's 'Sand beneath the Golt', which became the 'Lower Greensand' of later surveys (Whitaker et al., 1891 and 1893) is made up of three distinct arenaceous deposits of different ages (Table 17). The oldest of these, the basal beds of the Sandringham Sands, has already been discussed. The middle deposit, that shown on the published geological surveys of the Cambridge, Huntingdon and Biggleswade districts as the 'Lower Greensand', is referred to here as the Woburn Sands following the suggestion of Cameron (1892) and endorsed by Hancock (1972). The youngest deposit, the Carstone, is described in Section 4.6.

The Woburn Sands can be traced as an almost continuous outcrop from Buckinghamshire north eastwards to their most northerly known exposure close to the Norfolk-Suffolk boundary at Little Ouse. The Carstone can be traced as a continuous bed from Hunstanton to Southery, where it passes beneath Recent deposits, and the two formations appear to occupy mutually exclusive areas. Attempts have been made to explain

Wm Smith 1819	Whitaker et al., 1891 and 1893	Present account		Zone	Stage
CHALK	LOWER CHALK	LOWER CHALK		Acanthoceras rhotomagense Mantelliceras mantelli	CENOMANIAN (pars)
GOLT BRICK EARTH	GAULT	GAULT		Stoliczkaia dispar Mortoniceras inflatum Euhoplites lautus Euhoplites loricatus Hoplites dentatus ?Douvilleiceras mammillatum ?Leymeriella tardefurcata	ALBIAN
SAND BENEATH THE GOLT	LOWER GREENSAND	LOWER GREENSAND	CARSTONE		
			WOBURN SANDS	?Parahoplites nutfieldiensis	APTIAN (pars)
		SANDRINGHAM SANDS (pars)		Paracraspedites oppressus	VOLGIAN (pars)
OAKTREE CLAY	KIMMERIDGE CLAY	KIMMERIDGE CLAY		Pictonia baylei to Pectinatites hudlestoni	KIMMERIDGIAN

? Denotes identification of zone uncertain. ~~~ unconformity

Table 17. The nomenclature and zonal scheme for the late Jurassic and early Cretaceous rocks of south-west Norfolk and north-west Suffolk.

this as due to a lateral passage of the Woburn Sands into the Carstone (e.g. Chatwin, 1948) or to tectonic structure (e.g. the 'Southery Hinge' of Kelly, unpublished Ph.D., London, 1977). However, recent work in the Ely district suggests that the present distribution owes much to the depositional distribution of the two formations. Furthermore, the Carstone is younger than the Woburn Sands and probably rests on them unconformably (Fig. 73). The area of overlap of the two formations is much larger than that indicated on the published maps because, in Suffolk and Cambridgeshire, a thin development of Carstone has been included with the 'Lower Greensand'.

The Woburn Sands are composed of medium and coarse-grained glauconitic greenish grey sands and pebbly sands that weather to grey, greenish yellow and rusty yellowish brown. They are locally in part calcareously or siliceously cemented; where unweathered they are commonly cross-bedded. In north-west Suffolk, the formation rests unconformably on either the Kimmeridge Clay or the Roxham Beds, the junction being marked by a pebble bed containing phosphatized fossils derived from late Jurassic and early Cretaceous strata. In the Little Ouse area they are themselves cut out by the Carstone (Fig. 73).

The basal pebble bed of the Woburn Sands contains a great variety of fossils (see Casey in Worssam and Taylor, 1969, pp. 26-7 for list), including ammonites, bivalves, brachiopods, bryozoans, and gastropods, derived from the Oxford, Ampthill and Kimmeridge clays, and possibly the Sandringham Sands and Dersingham Beds. Phosphatized ammonites representative of the Prodeshayesites fissicostatus, Deshayesites forbesi, D. deshayesi and Tropaeum bowerbanki zones of the Lower Aptian are also present (Casey in Worssam and Taylor, 1969). Only three indigenous ammonites have been recorded to date, Colombiceras sp. nov. cf. tobleri

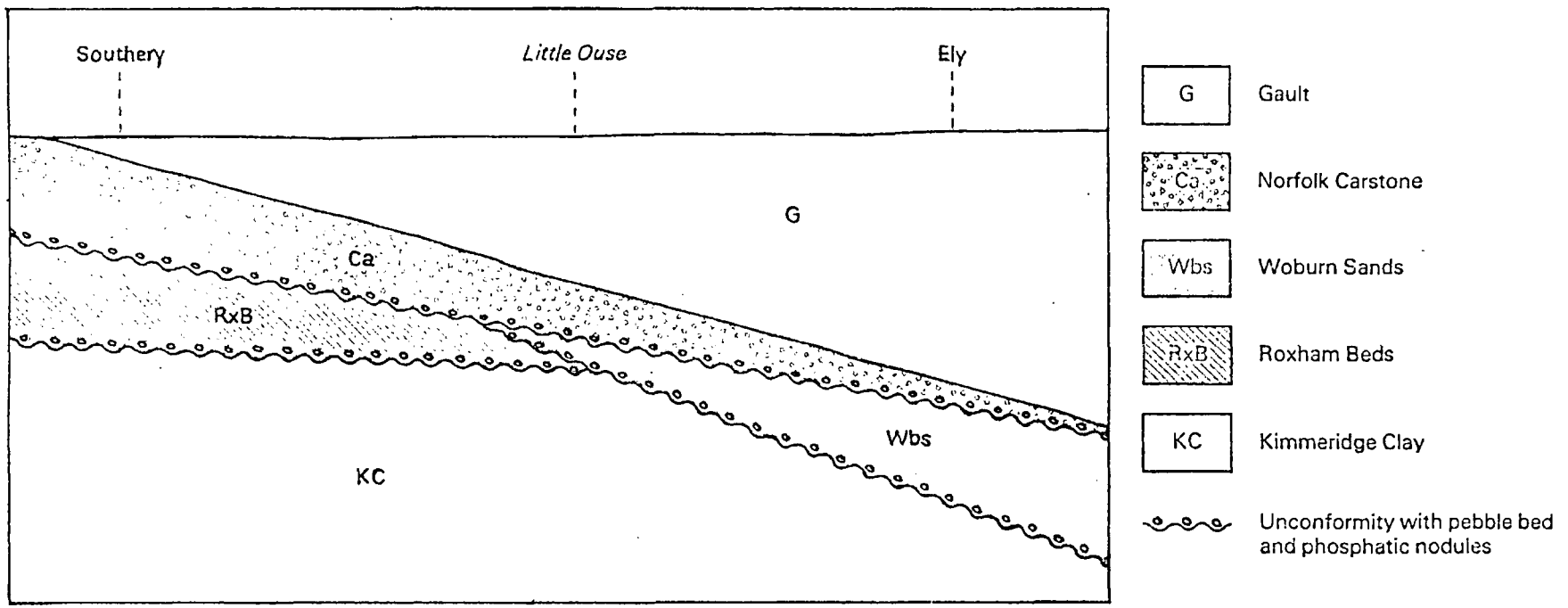


Figure 73. Relationship of late Jurassic and early Cretaceous unconformities in south-west Norfolk and north-west Suffolk.

(Jacob) and Tropaeum keepingi Casey (Casey, 1961b, p. 569), and Dufrenoyia (Dr C.L. Forbes, pers. comm.). The only other indigenous fossils of stratigraphical significance from the Woburn Sands at outcrop appear to be specimens of the Aptian belemnite Neohibolites ewaldi, a species that is common in the Sutterby Marl where it occurs with Colombiceras and Dufrenoyia.

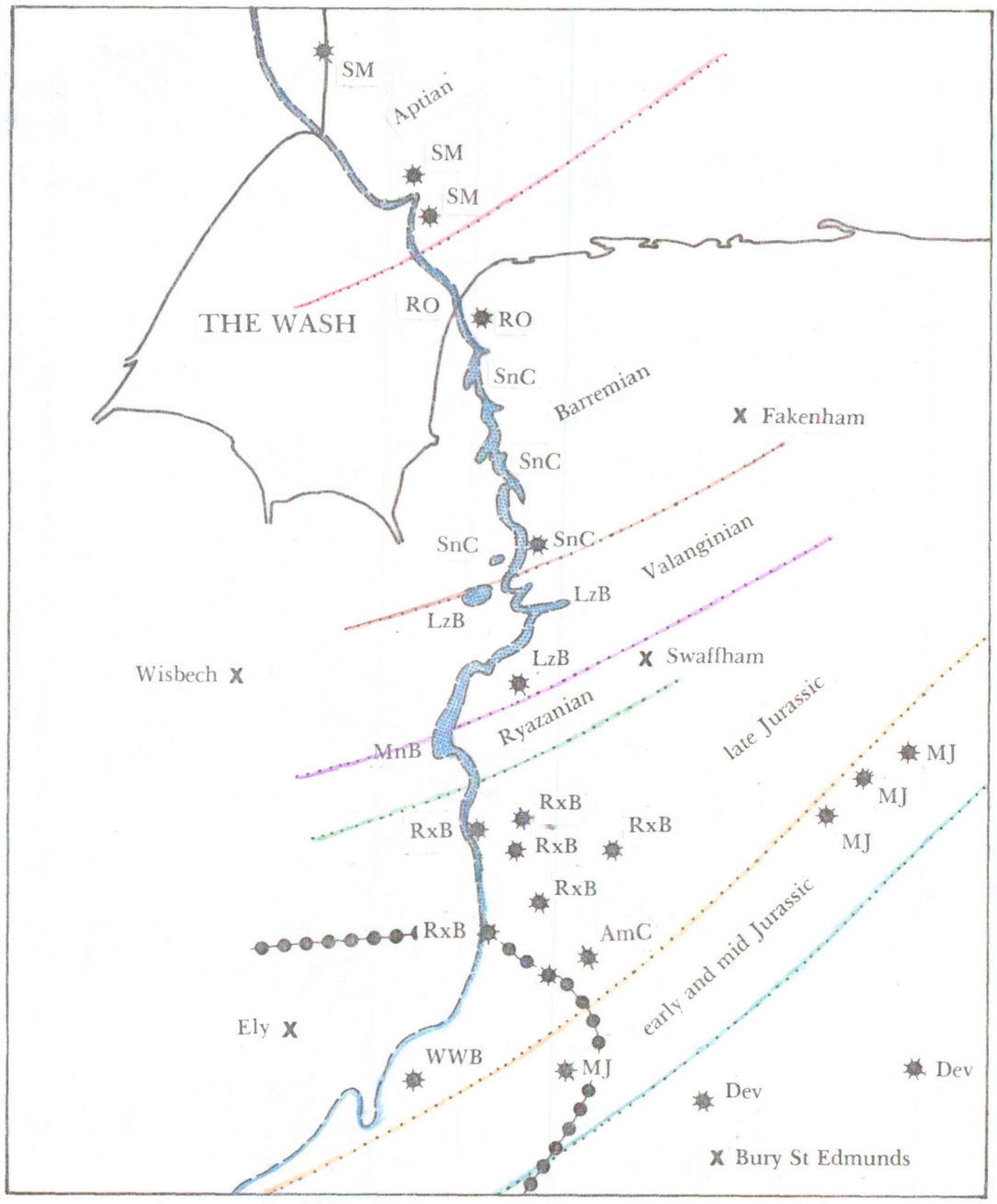
4.6 Carstone, Red Chalk and Gault

4.6.1 Introduction and History of Research

The later phases of the 'Kimmerian' earth-movements caused widespread effects around the edges of the mid Cretaceous depositional basins. In north-west Norfolk and beneath The Wash, the erosion surfaces at the bases of the Sutterby Marl and Carstone represent small breaks in sedimentation that can be correlated with much larger breaks close to the London Platform. In south-west Norfolk and north-west Suffolk the probable correlative of the Sutterby Marl (the Woburn Sands) rests on Jurassic rocks (Fig. 73), and the Carstone rests on Jurassic rocks (in Norfolk) or Woburn Sands (in Suffolk). In the intervening area any evidence of earlier Cretaceous unconformities has been removed by erosion at the base of the Carstone.

The age of the strata on which the Carstone rests increases southwards in Norfolk (Fig. 74), but the rate of erosion in terms of thickness of strata removed per kilometre of overstep varies markedly (Table 18). The Carstone appears to have been especially erosive in the Hunstanton area, less erosive in the southern part of Norfolk, and barely erosive beneath much of The Wash and west Norfolk. In north-west Suffolk the Carstone and/or the Woburn Sands base is again highly erosive, but this is related to folding in the Jurassic strata close to the edge of the London Platform (Fig. 52).

The Albian Stage is represented in Norfolk by three inter-related



Borehole, see Fig. 00 for names

Dev	Devonian
MJ	Middle Jurassic
WWB	West Walton Beds
AmC	Ampthill Clay
RxB	Roxham Beds
MnB	Mintlyn Beds
LzB	Leziate Beds
SnC	Snettisham Clay
Ro	Roach
SM	Sutterby Marl

Postulated northern limit of Woburn Sands; probably patchy

Carstone outcrop

Figure 74. Sketch map showing the age of the strata on which the Carstone rests.

From	To	Distance km	Rate of overstep m/km	Strata eroded
Skegness	IGS 72/78	20	-0.1	upper Sutterby Marl
IGS 72/78	Hunstanton	9	1.6	Sutterby Marl Skegness Clay Roach
Hunstanton	Heacham	2	5.8	Roach
Heacham	East Winch	21	0.2	Snettisham Clay*
East Winch	Ryston	17	1.2	Leziate Beds
Ryston	Hockwold	18	0.5	Mintlyn Beds upper Roxham Beds

* possible southerly thinning of the Snettisham Clay could account for almost all the estimated loss.

Table 18. Estimated rates of southerly overstep of the Carstone beneath The Wash and in Norfolk assuming regular regional variations in the depositional thicknesses of the underlying formations.

formations of markedly different lithology, the Carstone, Red Chalk and Gault. In the northern part of their outcrop and in their subcrop beneath The Wash, the Albian sediments consist of up to 19m of rusty brown and green, pebbly, limonite and chamosite oolith-rich sandstone (Carstone) overlain by 1m to 5m of thinly interbedded pink limestone and brick red marl (Red Chalk). When traced southwards along its outcrop from Hunstanton cliffs,

the Red Chalk thickens from about 1.1m of pink and red limestones to about 2m of interbedded creamy white limestone and pink marl at Dersingham.

Between Dersingham and the Babingley River, the Red Chalk undergoes a rapid lithological change at outcrop and passes southwards into grey clay and pale grey calcareous clay with bands of soft chalky white limestone (Gault). This progressive change to a more argillaceous lithology continues southwards until, in the Gayton area, the Gault consists almost entirely of clay and calcareous clay. The Carstone thins southwards from Hunstanton to Dersingham in almost direct proportion to the thickening of the Red Chalk in the same direction, and from Dersingham southwards in proportion to the thickening of the Gault. At the county boundary near Weeting, the Gault is over 17m thick and the Carstone consists of only 2m of oolitic, clayey sand.

When Rose (1862) and Teall (1875) subdivided the beds between the Kimmeridge Clay and the Gault in Norfolk they adopted the local name Carstone (also known as Car Stone = Fen Stone) for the highest of their divisions as typified by the ferruginous sandstones in the cliffs at Hunstanton. In the absence of other suitable material in west Norfolk, 'Carstone' was formerly used extensively as a building

stone. It should be noted, however, that the local term refers to any rusty brown sandstone that has been used for building and it includes fissile, ferruginous sandstones (known as 'small Car') from what are here referred to as the Dersingham Beds, the thickly bedded and massive ferruginous sandstone of the Carstone proper ('big Car'), and modern secondary iron-pan or 'chevick' that forms on low-lying parts of the Mintlyn Beds outcrop.

The outcrop of the Carstone was traced southwards from Hunstanton by Whitaker et al. (Old Series Sheet 69, 1886) as far as Ashwicken by means of a feature and spring line formed at the junction of the Carstone and the Snettisham Clay. Southwards from Ashwicken, in the area where the Snettisham Clay is overstepped and the Carstone rests on either Dersingham Beds or the Sandringham Sands, all the beds between the Kimmeridge Clay and the Gault, on the southern part of Old Series Sheet 69 and on Sheet 65 (1886), were mapped as 'Lower Greensand'. It was found in the present work that the Carstone is lithologically sufficiently distinctive from the Dersingham Beds and the Sandringham Sands for its outcrop to be mapped out in that area.

The striking colour contrast formed in Hunstanton Cliffs by the rusty brown Carstone, the Red Chalk and the White Chalk, together with the richly fossiliferous nature of the Red Chalk, has attracted the attention of large numbers of geologists, both amateur and professional. In addition, the complex sedimentology of the Red Chalk and the difficulties of demonstrating its stratigraphical relationships to the Carstone and the Gault have generated a wealth of geological literature. William Smith appears to have been the first geologist to have recorded the Red Chalk at Hunstanton, in his table of strata (1816) and geological map of Norfolk (1819). Early descriptions of the cliff sections include

those of Taylor (1823), Woodward (1833), Rose (1835) and Fitton (1836). More detailed descriptions of the Red Chalk were provided by Wiltshire (1859, 1869), Seeley (1861, 1864a, 1864b, 1866), Whitaker (1883), Jukes-Browne and Hill (1887) and Whitaker and Jukes-Browne (1899). These authors, together with Barrois (1876), Jukes-Browne (1900), Kitchin and Pringle (1922, 1932) and Rastall (1930, 1936) discussed its stratigraphical relationships with the Carstone, Gault and Chalk. The sedimentology of the Red Chalk of Lincolnshire and at Hunstanton has been described by Jeans (1973, 1980), and Clarke (1964) has examined belemnite orientations within it at Hunstanton. Casey (in Larwood, 1961, pp. 290-291) has re-examined the bivalve, gastropod and cephalopod faunas from Hunstanton and Owen (1979, p. 580) has recently reviewed the significance of the ammonites in relation to the modern zonal and subzonal scheme for the Albian.

The upper limit of the Carstone, its relationship to the overlying Red Chalk and the age of the two formations was for some time a matter of controversy. All the early workers noted that the Carstone passed up, by the rapid addition of calcareous content and diminution of sand and oolith content, into the Red Chalk in the cliffs at Hunstanton and that the two formations appeared to be conformably bedded throughout the 1.2 km of continuous cliff exposure. Rastall (1930, p. 445) agreed with the field evidence of the conformable junction and, in addition, showed that the insoluble sandy residue of the Red Chalk was identical in lithology and heavy-mineral assemblage to that of the Carstone. Difficulties arose, however, when Spath (1930) assigned the Carstone to the early Aptian on the basis of phosphatized ammonites that occur in its basal bed at Hunstanton. This fauna, as already noted above,

is now known to have been derived from the Skegness Clay and Sutterby Marl but, at that time, Spath was merely agreeing with the opinion of Wiltshire (1869) and Lamplugh (in Whitaker and Jukes-Browne, 1899) that it was indigenous and disagreeing with that of Keeping (1883). As a result of Spath's observations, Kitchin and Pringle (1932) attacked Rastall's methodology and conclusions and re-iterated their own earlier (1922) conclusion that the Red Chalk rested unconformably on the Carstone, and that a time break (late Aptian to mid Albian) was present at the junction between the two formations (1932, p. 34). They threw doubt upon, but admitted they could not disprove, the apparent parallellism of the bedding in the Carstone and the Red Chalk of Hunstanton cliffs, and explained Rastall's petrological results by suggesting that the heavy minerals in the Red Chalk were derived from Carstone.

No field evidence has yet been reported to support the presence of an unconformity between the Carstone and the Red Chalk at Hunstanton. With the confirmation that the fauna from the basal nodule bed of the Carstone is derived (Casey, 1961, p. 571), no unconformity is required. Kitchen and Pringle (1932) were in effect looking at the wrong part of the Carstone; if they had confined their efforts to a study of the fauna of the nodule bed at its base, they would not have needed to postulate the presence of an unconformity at its top. In recent years, palaeontological evidence has been accumulated to suggest that the Carstone is early to mid Albian in age.

Despite the early recognition by Sedgwick (1846) that the Red Chalk at Hunstanton was the lateral equivalent of the Gault of Cambridgeshire, there was much subsequent discussion as to its precise age. Whitaker (1883) summarized the possibilities as being

that the Red Chalk was the equivalent of (i) the Gault, (ii) the Upper Greensand, (iii) a combination of (i) and (ii), (iv) the Chalk Marl or (v) a combination of (i) and (iv). Later work has shown that the Upper Greensand of southern England passes laterally into the Gault, and its stratigraphical position is therefore superfluous to the discussion of the age of the Red Chalk. Whitaker (1883) expressed a preference, on the basis of a diverse fauna that had been collected from the Red Chalk, for alternative (iv), with (v) as a possibility. On the basis of field studies on Old Series Sheet 65, Jukes-Browne and Hill (1887) claimed to be able to demonstrate that the Chalk Marl thinned northwards at outcrop in Norfolk and that its basal bed passed laterally into the basal bed of the Chalk at Hunstanton, thus making the Red Chalk the equivalent of all or part of the Gault. Whitaker's main objection to the correlation of the Red Chalk with the Gault was the occurrence in the Red Chalk of certain non-ammonite species that were at that time known only from the Lower Chalk. Most of these are now also known from the Gault; others are known to be facies-dependent and associated with chalky limestones. Over 30 species of ammonite are known from the Red Chalk (Casey in Larwood, 1961, p. 15), and these have been shown by Spath (1923-43) and Owen (1959) to be indicative of the same mid to late Albian time span in which the Gault was deposited.

The Gault was first shown as a discrete formation in East Anglia by William Smith, where it was referred to as the "Golt Brick Earth" on his geological map of England and Wales (1815) and subsequently, in more detail, on his geological maps of the counties (e.g. that of Norfolk, 1819). The formation was extensively worked for brickmaking in the 19th century and, additionally in Cambridgeshire and Norfolk,

for agricultural phosphate. The Gault is richly fossiliferous at many stratigraphical levels and extensive collections, especially of ammonites and bivalves, were made from the exposures available to collectors at that time. These collections are commonly stratigraphically poorly documented because the exposures were separated from one another by long stretches of outcrop where the Gault is deeply weathered and rarely, if ever, exposed.

It is not surprising, therefore, that most recent stratigraphical studies of the Gault have been concentrated on working brickpits in the Weald and on the cliff and foreshore exposures of the type section at and adjacent to Folkestone, Kent. At the last locality the whole of the formation has been available for study at some time or another, albeit in separated sections. De Rance (1868, 1875), Price (1874, 1876), Jukes-Browne (1900), Spath (1923-43), Casey (1961b) and Owen (1971, 1976) have all contributed to the understanding of the stratigraphy of the Gault and, as a result, the succession of ammonite assemblages on which the formation is zoned is now known in considerable detail.

Attempts have been made from time to time to correlate the Gault in East Anglia with the Folkestone sequence, but because of the scattered nature of the exposures these attempts have mostly been limited to correlations of individual, usually small, sections with the type section and have added little to our knowledge of the Gault stratigraphy of East Anglia as a whole. Little has been published about the Gault at outcrop in Norfolk since Jukes-Browne's review in the Cretaceous Rocks of Britain (Vol. 1, 1900) in which the local details are based largely on those given in the memoirs

for Geological Sheets 65 and 69. A number of critical sections in Norfolk, where the succession was poorly exposed but was believed to be relatively complete, were described by Jukes-Browne and Hill (1887) and Kitchin and Pringle (1922). Brighton (1938) reviewed the data from boreholes and temporary sections in East Anglia. He noted that large parts of the Folkestone sequence had not been recorded in the region and suggested that this was probably because of lack of suitable exposures rather than due to non-sequences within the Gault. Black (1972-75) has described the coccolith floras of the Gault, mostly from boreholes in East Anglia (including one in Norfolk) and adjacent areas, and compared the sequence of coccolith assemblages there with that at Folkestone.

4.6.2 Carstone

The Carstone has an almost continuous outcrop in Norfolk from Hunstanton to West Dereham, that is broken only by the wide drift-filled valleys of the rivers Babingley and Nar and by patches of glacial deposits. Between Hunstanton and the Babingley River, this outcrop is largely free from drift deposits; southwards from the river the outcrop becomes increasingly obscured by drift until, between the River Nar and West Dereham, large parts of it are wholly obscured. The Carstone forms small outliers that cap broad ridges at Brow of the Hill and Middleton, but these too are largely obscured by drift.

Between Hunstanton and Sandringham, the Carstone mostly crops out on a steep feature that is capped by Red Chalk and Chalk; it has its most extensive outcrops at Lodge Hill, Snettisham and at Sandringham, where it forms small plateaus. The Carstone becomes thinner and more argillaceous southwards from Sandringham

and the outcrop, in consequence, mostly occupies low ground. The formation is poorly exposed except for its type section in Hunstanton cliffs and a small number of quarries dug for building stone and hard-core between there and the River Nar. In drift-free areas north of the River Nar it gives rise to a well drained, rusty brown sandy soil with common fragments of ferruginous sandstone, and its outcrop can be readily mapped out. The formation is more argillaceous and less massive south of the River Nar, and has not been worked. It locally caps a weak feature, in which it is underlain by the soft sands of the Leziate Beds, that is separated from the Chalk escarpment by the low ground of the Gault outcrop. Parts of the Carstone in this area weather to the rusty brown sandstone typical of more northerly areas but, where close to the water table, much of it consists of relatively unaltered green and grey clayey sands. These can be readily distinguished from both the green and white sands of the underlying Leziate Beds and the grey clays of the overlying Gault by augering.

The Carstone thins steadily southwards from West Dereham to the county boundary. Peat wastage has revealed a small deeply weathered outcrop at Stubb's Hill, Southery, but apart from this the formation is known only from boreholes in the most southern part of the county. In Suffolk and Cambridgeshire the Carstone is not a discrete mappable formation, but is probably present as a thin pebbly sand at the base of the Gault. No outcrop of Carstone has yet been recorded south of the River Little Ouse, but the presence of specimens of its characteristic lithology in the Soham Borehole, Cambridgeshire (Gallois, in press), and of sand with abundant limonite ooliths and iron-stained vein quartz pebbles (both typical of the Carstone) immediately

beneath the Gault in other boreholes in Cambridgeshire and more southerly counties, suggests that a thin (< 1m) development of Carstone is present at the base of the Gault beneath much of its East Anglian outcrop. Future work is likely to show that the Woburn Sands and Carstone, shown jointly as "Lower Greensand" on Geological Survey Sheets 187 (Huntingdon), 188 (Cambridge) and 204 (Biggleswade), are separable over much of their outcrop. Until this is done, however, the regional significance of the Carstone as an early Albian deposit cannot be assessed.

The maximum recorded thickness of the Carstone is 18.9m in the Hunstanton Borehole; a similar thickness is probably present in Hunstanton cliffs and foreshore. The formation thins north westwards beneath The Wash and is only 6.4m thick in I.G.S. Borehole 72/78. It thins southwards at outcrop and is 8.5m thick in the Gayton Borehole, 5.6m in the Marham Borehole and 2m at the county boundary.

The extent of the Norfolk subcrop is poorly known. About 17.7m of Carstone was proved in the North Creake Borehole (Kent, 1947), a similar amount in the South Creake Borehole, and about 6.8m in the Great Ellingham Borehole (Gallois in Cox et al., in press). The formation was not recorded in the rock-bitted deep hydrocarbon boreholes in the eastern part of the county at Saxthorpe, Somerton and East Ruston, but this could be due to the difficulty of distinguishing it from other Jurassic and Cretaceous sands in the rock cuttings and geophysical logs. The Carstone was represented by only a few small pebbles and sand grains in the I.G.S. Trunch Borehole (Gallois and Morter, 1976) in north-east Norfolk.

The best exposed development of Carstone in eastern England is that at Hunstanton. There, the full thickness, totalling about 18m, crops out on the foreshore and in the cliffs. The whole of the formation is exposed with the exception of the basal beds and a thin, presumed softer, bed in the middle part of the formation. Even the unexposed parts are overlain by only a thin covering of beach sand.

The basal beds and the junction with the Roach (Fig. 69) were exposed by trenching on the foreshore (Gallois 1973b, 1974). The following composite section is based on those proved in three trenches |6712 4152, 6705 4168 and 6715 4177| dug close to the outer Carstone reef:

Recent beach sand, gravelly in places .. .. .. 0.3 to 0.5m

Carstone

Fine-grained, orange-brown, pebbly, oxidised and rotted, ferruginous soft sandstone; ghosts of limonite ooliths throughout; very rare phosphatic nodules as below; passage at base into 0.3m

Sandstone, as above but very pebbly and including dark brown generally well rounded phosphatic nodules (up to 0.1m across but mostly 0.02 to 0.03m), some with worn specimens of Lower Aptian ammonites including species of Cheloniceras, Dufrenoyia, Prodeshayesites, and Tropaeum; larger unfossiliferous phosphatic nodules (up to 0.12m across) also occur, mostly of burrowfill shape; phosphatic nodules are extremely rare in some sections, in others they occur in clusters; locally less pebbly and indistinguishable from bed above; ferruginous seepage at base .. .. 0.15 to 0.20m

Dark grey and greenish grey oolitic (chamosite, largely oxidised to limonite) pebbly clay, sandy in part, intensely burrow-mottled and varying both laterally and vertically in composition with pebbles and ooliths concentrated in bands generally 0.15 to 0.20m thick; pebbles (mostly iron-stained quartz) lithologically identical to those of overlying bed; large well rounded nodules of very fossiliferous sandy phosphatic ironstone (the 'iron-grit' nodules of Keeping 1883, p. 33) were collected from near the top of this bed in the 1930s (e.g. British Museum (Natural History) specimen Nos. C35512 and C35238); thickness variable; very irregular sharp base with burrow-fills of fine and medium-grained greenish yellow sand (Carstone lithology) extending down 0.5m into Roach; irregularities of up to 0.15m observed in 2m length of junction .. .. 1.0 to 1.5m

Roach, fine-grained grey sand

Carstone forms two prominent reefs on the southern part of the beach, separated by a sand-covered slack that may conceal softer, possibly finer-grained or more clayey Carstone. A line of springs at the base of the higher reef adds weight to this suggestion. The outer reef runs north for about 700m from near the Esplanade Gardens [6714 4115] and consists of dark greyish green fine-grained sparsely pebbly oolitic sandstone weathering to the usual rusty brown. Its outer edge is close to the base of the formation and phosphatized fragments of ammonites derived from the basal beds

are common as beach pebbles. The inner reef occupies much of the higher part of the intertidal area northwards from the northern end of the Esplanade [6724 4131] and its width expands northwards as progressively more of the formation is brought down to the foreshore by the northerly component of the dip. Most of this reef is composed of sparsely pebbly and pebbly fine- and medium-grained dark greyish green Carstone that weathers to the typical rusty brown. Its most striking feature is the manner in which it has been eroded; at beach level it appears to form an irregular collection of rounded lumps of sandstone, but when viewed from the adjacent cliff-top these can be seen to be separated by a remarkably uniform rectilinear set of joints that give rise to an outcrop pattern that was aptly likened by Whitaker (in Whitaker and Jukes-Browne, 1899, p. 16) to an enormously magnified ichthyosaur paddle (Plate 26).

When traced northwards from the Esplanade the two reefs appear to merge north of the latitude of St Edmund's Chapel [6758 4195], but the outcrop may be complicated there by a small fault. At very low tides, a small reef composed of sparsely pebbly medium-grained Carstone is exposed offshore of the outer reef [6708 4152 to 6709 4180] and therefore appears, from the gentle north-easterly dip of the reefs, to be at a lower stratigraphical level than the basal pebble bed. A small fault, downthrown to the west, has been postulated to explain this apparent anomaly (Fig. 75). The possibility cannot be excluded that this bed has been downthrown by an ancient landslip that failed in the argillaceous Dersingham Beds and Roach at some time in the Pleistocene when the Carstone and Lower Chalk formed a single high cliff.

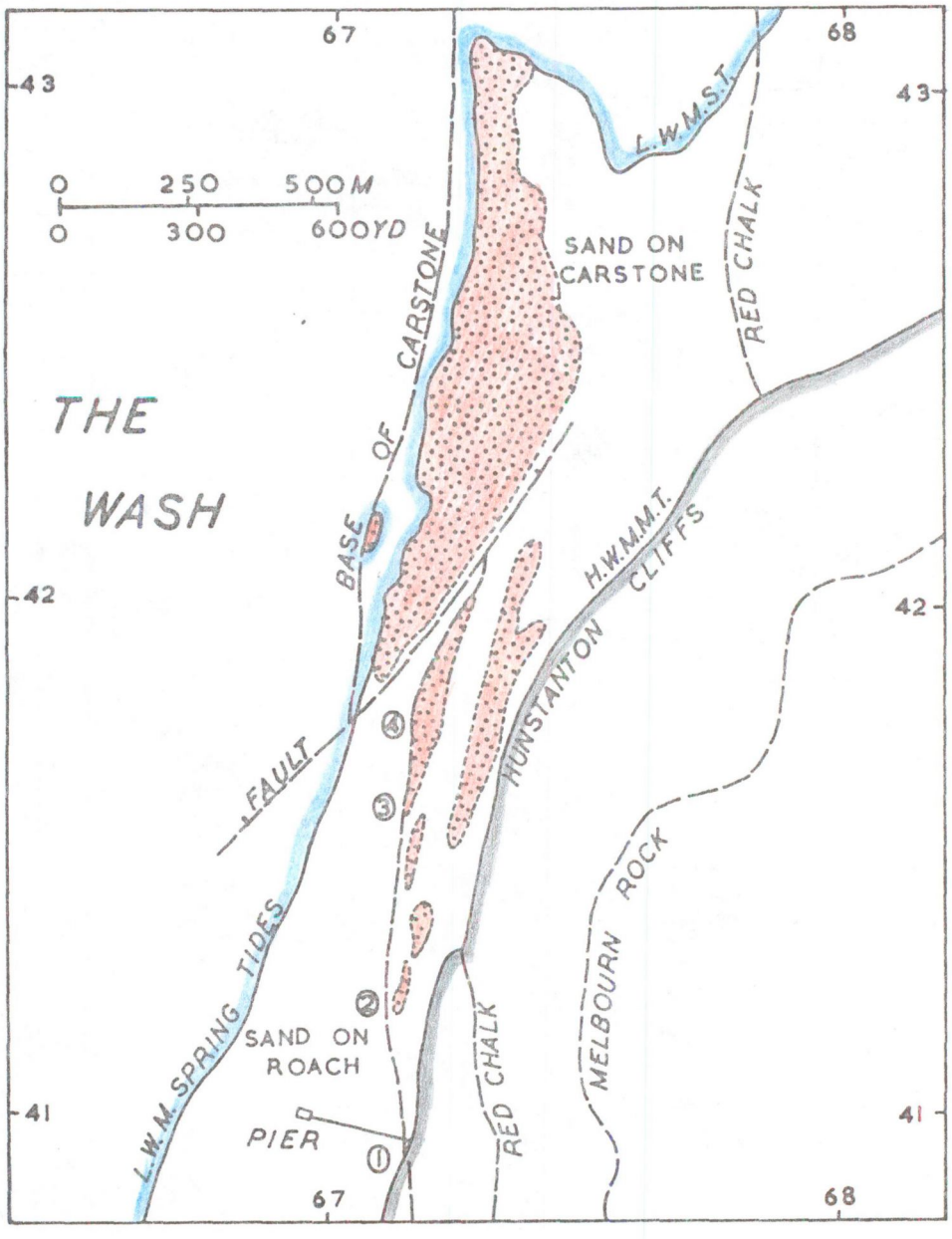


Figure 75. Geological sketch map of Hunstanton beach showing Carstone outcrops (based on 1972 air photographs) and sites of trenches.

The upper 10m of the Carstone, including the junction with the Red Chalk, are well exposed in the cliffs between the Esplanade [6723 4124] and St Edmund's Point [6786 4239]. The Carstone there is composed of fine-, medium- and coarse-grained sands and pebbly sands; some levels in the upper part of the sequence, notably a 4.5m-thick band 3m from the top of the formation, are sufficiently pebbly to be termed pebble beds (Plate 26). The section is a deeply weathered rusty brown with much secondary veining, cementation and Liesegang precipitation of limonite and other iron materials. Planar cross-bedding, in units 0.3 to 0.5m thick, is discernible at several levels, but other sedimentary features are usually obscured by the limonitic weathering. Fresh cliff falls show the rock to be a dark greyish green, oolitic (chamosite, limonite and limonitized chamosite), cross-bedded sandstone with large number of long, thin vertical burrows of the Arenicolites and Skolithos types. Such sections weather within a few months to produce the limonite-crust and boxstone weathering that it typical of the formation. No body fossil has been recorded from the Carstone at Hunstanton, probably partly because of their rarity at the time of deposition, and partly because of their susceptibility to weathering in such a porous medium.

Unweathered Carstone has only been seen in boreholes and even there limonitisation has occurred at a number of levels due to oxidation within the zone (and former zones) of water-table fluctuation. The best-preserved section recorded to date is that in the cores of the Hunstanton Borehole where the following sequence was proved:

Red Chalk, soft sandy limestone

Carstone

Sandstone, fine and medium-grained, orange-brown and khaki; earthy textured with limonitic weathering products in matrix; burrowfills of red and brown calcareous clay extend down through the top 0.3m; becoming tougher, greenish and yellowish brown with depth with many limonitized ooliths and patchy chamosite-mud cement; burrow-mottled in part; small pebbles common in lower part; passing down into 1.75m

Oolite, chamosite and limonitized-chamosite coatings of fine-grained quartz sand; very sandy in part; glistening blackish brown; burrow-mottled in part; pebbly in part with small quartz and ironstone pebbles; very pebbly in one 3m-thick band with ironstone pebbles up to 3 cm across; traces of cross-bedding; graded bedding in part with pebbly oolite passing up into sandy oolite; Arenicolites and Skolithos-type burrows common at several levels; pale greyish green and dark green chamosite-mud cement at some levels; passing down into 13.82m

Sandstone, fine and medium-grained; very oolitic as above; greyish green with patchy pale green chamositic cement; burrow-mottled in part; becoming uniformly coarser and pebbly in lowest 2m; pebbles up to 3 cm across consisting of milky and brown vein quartz, brown to brick red ironstones,

chert, soft white chalky limestone and soft green and brown clays; passing down with interburrowing into 2.26m

Clay, dull khaki and greenish yellow-brown, very sandy and pebbly; burrow-mottled; becoming predominantly sandy with depth with dark grey clay burrowfills; irregular contact with apparent channelling into bed below 1.07m

Roach, fine-grained clayey sand

The base of the Carstone is not marked by a major lithological change in the borehole, probably because much of the sediment in the basal bed has been derived from the underlying Roach. Comparison of the basal beds of the Carstone in the borehole with those in trenches on Hunstanton Beach has enabled the boundary to be accurately placed in the borehole (Fig. 76). The patchy distribution of the ammonite-rich phosphatic pebble bed close to the base of the Carstone has made identification of the precise junction with the underlying beds difficult at many localities. Elsewhere at outcrop in Norfolk, sections have been recorded in the present work in which the junction of the Carstone and the underlying beds is marked only by an erosion surface with burrowing; this would be extremely difficult to identify in boreholes.

When fresh, the bulk of the Carstone appears in hand specimen to be a relatively pure chamosite oolite with a partial cement of chamositic and/or sideritic mudstone. This is deceptive, however, and in thin section many of the ooliths can be seen to consist of chamosite overgrowths on quartz grains (Plate 27). In all but a few samples, the total quartz content of the rock is > 50% by

Plate 27. Carstone mineralogy and textures. All photographs in transmitted light.

A. Limonite peloid (centre), ooids and angular quartz grains with thin coating of chamosite, and intergranular pores infilled with siderite. Specimen no. E 40047, Hunstanton Borehole, 60 ft 6 in. Magnification 20x.

B. Well-formed limonite ooids and broken ooids, one with detrital quartz core, cemented by chamosite (pale grey) and siderite or ferroan calcite (white). Specimen no. E 40047, Hunstanton Borehole, 60 ft 6 in. Magnification 20x.

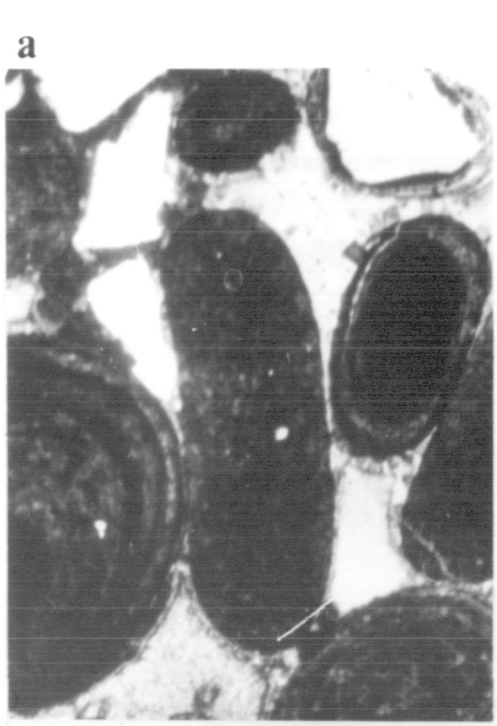
C. Ooid with quartzite core, and angular quartz grains set in chamosite cement. The angularity of the core in this and other specimens suggests modification of original detrital grain by overgrowths. Specimen no. E 40048, Hunstanton Borehole, 65 ft 6 in. Magnification 20x.

D. Limonite ooid partially crushed and exfoliated by compaction, with secondary dolomite cement filling cracks; small ironstone core. Specimen no. E 40048, Hunstanton Borehole, 65 ft 6 in. Magnification 30x.

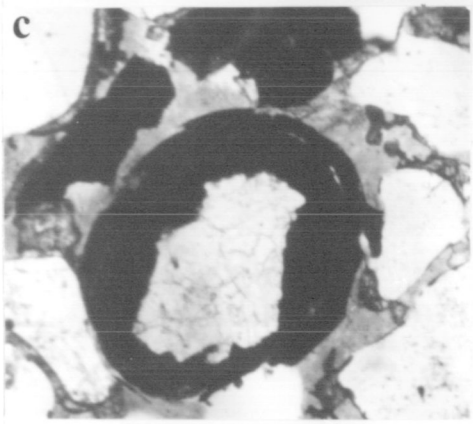
E. Angular quartz, rounded ironstone and sandy ironstone grains set in a granular cement of siderite rhombs. Specimen no. E 40058, Hunstanton Borehole, 115 ft 0 in. Magnification 20x.

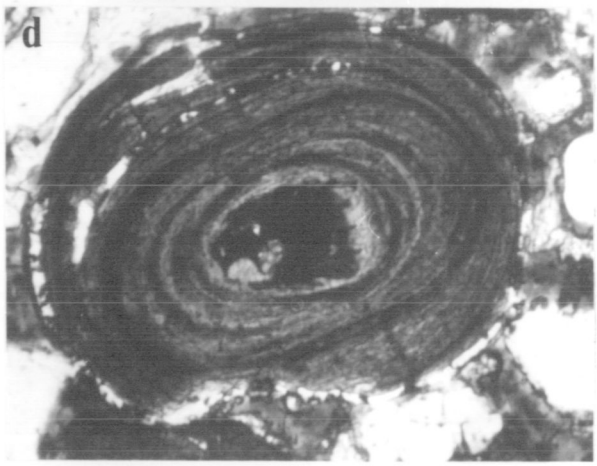
F. Quartz and ironstone grains, broken limonite ooids and small quartzite pebble (left) with chamosite cement; the angularity of some of the quartz grains (e.g. top left) suggests possible syntaxial overgrowth. Specimen no. E 40055, Hunstanton Borehole, 100 ft 0 in. Magnification 10x.

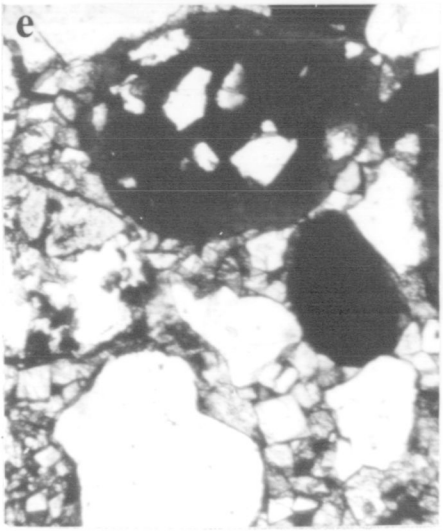
Plate 27

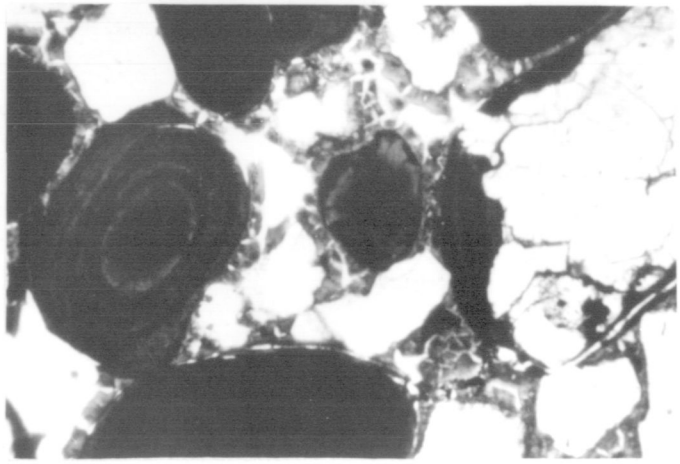












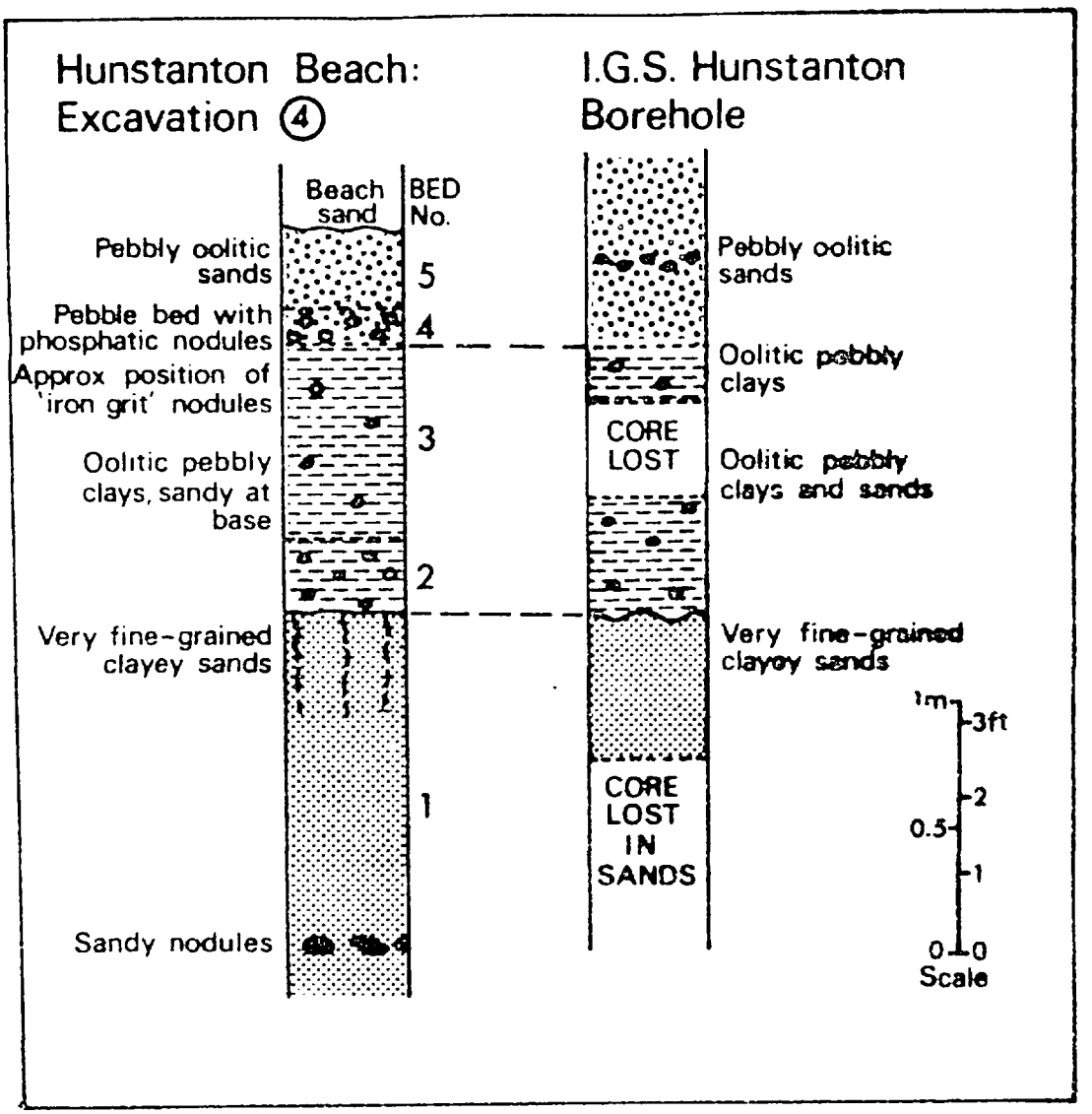


Figure 76. Lithological comparison of the basal beds of the Carstone at outcrop on Hunstanton beach with those in the Hunstanton Borehole.

volume. In the terminology developed by Taylor (1949) for the lithologically similar Northampton Sand ironstones they are 'chamosite oolite-sandstones'. Most of the ooliths are partly or wholly oxidized; so too are the pebbles of clay ironstone and oolitic ironstone that are abundant in the more pebbly parts of the rock. Typical ooliths from the Hunstanton Borehole were examined by X-ray diffraction by Mr R.J. Merriman (pers. comm.) and were shown to consist largely of goethite and quartz with minor amounts of siderite, chamosite and a montmorillonoid mineral (? nontronite). By contrast, the chamosite mud in the matrix is mostly fresh; in places a small part of it is replaced by siderite. This suggests either that some of the oxidation of the ooliths was penecontemporaneous or that they have been preferentially oxidised at some later date. None of the pebbles in the Carstone can be identified with confidence but most of ironstones and mudstones can be matched with lithologies in the Roach or Dersingham Beds of Norfolk, or the Claxby Beds, Tealby Beds or Roach of Lincolnshire. The chalky limestones may have been derived from the Tealby Beds. Clastic materials other than quartz and the pebbles noted above make up less than 2% by volume of the rock. Some unweathered Carstone samples from the borehole that were examined by Dr J.R. Hawkes (pers. comm.) contain small fragments of metaquartzite, quartz-schist, acid-igneous rock of possible volcanic origin and grains of plagioclase and perthite; these materials are presumed to have been derived from more distant sources.

The Carstone thins north-westwards beneath The Wash and southwards along its outcrop, the change being accompanied in both cases by a decrease in the proportion of ooliths. In the most southerly

part of its outcrop, south of Wimbotsham, the formation becomes progressively more argillaceous. Southwards from Hunstanton the Carstone forms a steep feature which reveals, when ploughed, a dark brown sandy soil with common soft sandstone fragments. A spring line at the junction with the Snettisham Clay and soil brash at the junction with the Red Chalk enables the outcrop to be readily traced to the Babingley River. The formation has been worked for building stone and hardcore in small quarries at Heacham, Snettisham, Ingoldisthorpe, Dersingham and Sandringham and continues to be worked in a large quarry [685 349] at Snettisham.

Between the Babingley and Nar rivers the main Carstone outcrop occupies low ground that is mostly drift covered. It forms outliers at Brow of the Hill and Middleton, but these are also mostly drift covered. It has been quarried at Brow of the Hill, Roydon, Middleton, East Winch and Blackborough and is worked intermittently for hardcore in very extensive quarries [673 143 to 683 146] at Blackborough End. The unconformable junction with the Leziate Beds is especially well exposed at this last locality (Plate 28).

The Carstone emerges from beneath the wide drift-filled valley of the River Nar as a small outlier capping a low rise at Shouldham Warren and as a continuous outcrop, mostly on drift-covered low ground, that runs from Shouldham to Shouldham Thorpe. The formation then disappears beneath a broad tract of till and reappears about 7 km to the south in the Denver and West Dereham areas. There, the outcrop is extensive and large parts of it are drift-free, but the formation is more argillaceous and less massive than in more northerly areas and has not been worked for building purposes. There are, in

Plate 28. Sedimentary structures in the Carstone.

A. Skolithos, Arenicolites and large irregular burrows extend down from the irregular basal surface of the Carstone (dark coloured ferruginous clayey sands) into the soft white sands of the Leziate Beds. Many of the larger burrows have a ferruginously cemented lining and have been picked out by weathering. Photo. no. A 11796. Blackborough End aggregate pit.

B. The basal bed of the Carstone in A. contains numerous well-rounded pebbles of white quartz siltstone, many of which are bored by cf. Trypanites. Natural size.

C. Planar cross bedding in deeply weathered Carstone; height of face about 3 m. Photo no. A 10844, southern end of Hunstanton cliffs.

D. 'Double-barrelled' burrows penetrating the top part of the Snettisham Clay and infilled with Carstone. These are identical in size and cross-section to the longer burrows in A. Specimen no. BDB 8728, Gayton Borehole, 100 ft 3 in, Natural size.

E. Planar cross bedding in partially weathered Carstone. Hunstanton cliffs, face behind fresh cliff fall.

F. Burrows, presumed escape structures, in Carstone. Photo. no. A 11800, Blackborough End aggregate pit.

Plate 28

consequence, very few exposures in the area.

The most southerly recorded outcrop of the Carstone is that described by Casey (in Casey and Gallois, 1973, pp. 10 - 11) in the excavations dug for the Cut Off Channel. The formation thins southwards from West Dereham and is probably absent as a discrete mappable formation, being only a thin pebbly sand at the base of the Gault, south of the Norfolk county boundary.

Burrows and cross-bedding are present at many levels in the Carstone, and may be ubiquitous, but their presence is almost always masked at outcrop by ferruginous weathering products. Where seen in less unweathered faces after fresh cliff falls at Hunstanton, in temporary excavations and in boreholes, the burrows are mostly long (commonly > 1m), thin, vertical tubes, either single (cf. Skolithos) or double (cf. Arenicolites). They are especially abundant at the base of the formation and large numbers commonly penetrate the subjacent formation irrespective of its lithology. Where the underlying formation is a soft sand, a variety of larger, more irregular burrows are present (Plate 28). Planar cross-bedding, in units 0.3m to 0.5m, is present in the Carstone at Hunstanton (Plate 28), in a few inland quarries and in the cores of the Hunstanton, Gayton and Marham boreholes, but was too rarely observed for any comment to be made on its orientation. Schwarzacher (1964, p. 322) did not record any cross-bedding in the Carstone. At Hunstanton, cross-bedding is present at three localities and dips northwards at each. The adjacent beds at each locality are even-parallel bedded in units up to 0.5m thick and are themselves within units that are even-parallel bedded and up to several metres thick. The thicker units are commonly bounded by surfaces that have large numbers of burrows associated with them.

The distribution of heavy minerals in the Carstone and Red Chalk has been described and discussed by Rastall (1919, 1930). Samples taken from several horizons in the Carstone at Hunstanton yielded kyanite, staurolite, rutile, zircon, tourmaline, garnet and ilmenite, and small quantities of hornblende, diopside and muscovite (1919, p. 213). Many grains of the commoner minerals are large and angular and Rastall thought they had not travelled far from their source.

The upper limit of the Carstone is well exposed in the cliffs at Hunstanton. The junction with the Red Chalk is gradational but rapid. In the present work it has been taken at a weakly developed bedding plane that separates a 23 cm-thick bed of tough red calcareously cemented clayey sandstone that becomes less calcareous, less clayey and paler red with depth (Red Chalk) from a 28 cm-thick bed of soft yellowish brown, fine-grained sandstone (Carstone) containing numerous burrow infillings of the overlying pink, calcareous sandstone, some including wisps of red clay. A band of widely spaced, pale brown phosphatized, sandstone burrowfills and nodules, mostly 5 cm to 10 cm in length, forms a useful marker band 28 to 60 cm below the top of the Carstone (Fig. 81).

Fossils, other than plant debris and burrows, are rare in the Carstone and its age was in doubt until relatively recently. At Hunstanton, Casey (1961b, p. 571) showed that the phosphatized ammonites from the basal beds were derived from two zones of the Lower Aptian. The first undoubtedly indigenous shelly fossils to be recorded from the formation in Norfolk were terebratulid brachiopods collected by Casey (1967*, p. 91) from the Cut-Off Channel near West Dereham [TL 662 996]. These were considered by him to be con-

* in IGS Ann. Rep. for 1966.

specific with forms from the Lower Albian Shenley Limestone of Bedfordshire; other brachiopods collected by Casey from the same locality include specimens of Burrihynchia leightonensis (Walker) (Owen et al., 1968, p. 518), a species known elsewhere only from the Shenley Limestone and the Carstone of Lincolnshire/Humberside.

Casey (in Casey and Gallois 1973, p. 11) also recorded the ammonites Beudanticeras newtoni Casey, Douvilleiceras mammillatum (Schlotheim) and Leymeriella sp., indicative of the Leymeriella tardefurcata and Douvilleiceras mammillatum zones of the Lower Albian, in phosphatic nodules in the top part of the Carstone in the Cut-Off Channel. Teall (1875) had recorded a similar fauna, but including Sonneratia kitchini Spath (indicative of the mammillatum Zone), from nodule beds at the same stratigraphical level in agricultural-phosphate workings in the West Dereham area. It is difficult to determine how closely these ammonites reflect the age of the deposit because although they are completely phosphatised, they appear to be little worn even though they are preserved in an abrasive, pebbly sand matrix. It seems reasonable to assume that this part of the Carstone is of mammillatum or post-mammillatum Zone age.

The Gault at West Dereham, and throughout its Norfolk outcrop at least as far north as Gayton, overlies the Carstone without any obvious major break in sedimentation. The presence of abundant Hoplites spp., including Hoplites (H.) dentatus Spath, in the lowest part of the Gault suggests a mammillatum or early Hoplites dentatus zone age for the Carstone there. At Hunstanton, the base of the Carstone can be dated as post-Lower Aptian on the basis of the youngest (bowerbanki Zone) derived ammonites in its basal bed.

There, too, the conformable contact with the overlying Red Chalk, which contains indigenous Middle Albian ammonites, suggests that the Carstone is late Lower or early Middle Albian in age. The recent discovery* of a loose Hoplites (H.) dentatus at Hunstanton, in the same preservation as the phosphatic nodules that occur at the top of the Carstone, may be direct evidence of a dentatus Zone age for the top of the formation. In situ evidence will be needed before this can be confirmed.

4.6.3 Red Chalk

The type section of the Red Chalk is the continuous cliff that runs from the northern end of Hunstanton Promenade [6725 4130] almost to old Hunstanton [6786 4238], a distance of about 1.2 km. The formation is readily accessible at the northern end of the section where it falls to beach level, by climbing cliff falls between there and the lighthouse, and in large fallen blocks.

Between Hunstanton and Snettisham the Red Chalk forms a thin but persistent marker band that is one of the most easily mapped in Britain. At times when the fields are ploughed its soil brash, together with that from the adjacent Carstone and Chalk, forms a colour and lithological

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* The specimen was delivered to the B.M. (N.H.) by the present author and was collected either by him or Mr H. le Strange of Hunstanton. Neither admits to doing so.

contrast that is only slightly less muted than that in Hunstanton cliffs. Between Snettisham and Dersingham the colour of the Red Chalk becomes paler in a southerly direction until it is predominantly pink and cream coloured; even there, an abundant soil-brash of nodular limestone fragments that enclose numerous belemnites, sand grains and small pebbles, makes the boundaries of the formation easy to map out. At Dersingham, within a distance of less than a kilometre between Hill House Farm [694 310] and Doddshill [696 301], the Red Chalk limestones pass laterally into red, pink and cream-coloured highly calcareous clays with nodules and thin bands of pink and cream limestone in their upper part. These beds provide little soil brash and their outcrop is largely covered by downwash. The lateral passage from the Red Chalk into the Gault is rapid and takes place in the vicinity of York Cottage [700 283], Sandringham. There, the pink and cream limestones and clays of the Red Chalk pass into the brown sandy clay and grey, cream and brown silty clays of the Gault. Between Sandringham and Flitcham the Gault thickens rapidly southwards and the Carstone thins by a corresponding amount (Fig. 77). Thin beds of pink and white nodular chalky limestone similar to those of the Red Chalk, continue to be present in the top of the Gault as far south as Gayton, but they form only a minor part of the Gault everywhere south of Sandringham.

The Red Chalk thickens north-westwards from Hunstanton (1.1m of limestone with marl wisps) into The Wash (3.2m of limestone with marl wisps in IGS Borehole 72/78, and Lincolnshire (5.5m of interbedded limestone and red clay in the Skegness Borehole) (Fig. 78). The sequence is weakly rhythmic in part at Skegness with small-scale rhythms, mostly < 0.5m thick, in which red calcareous muds pass up

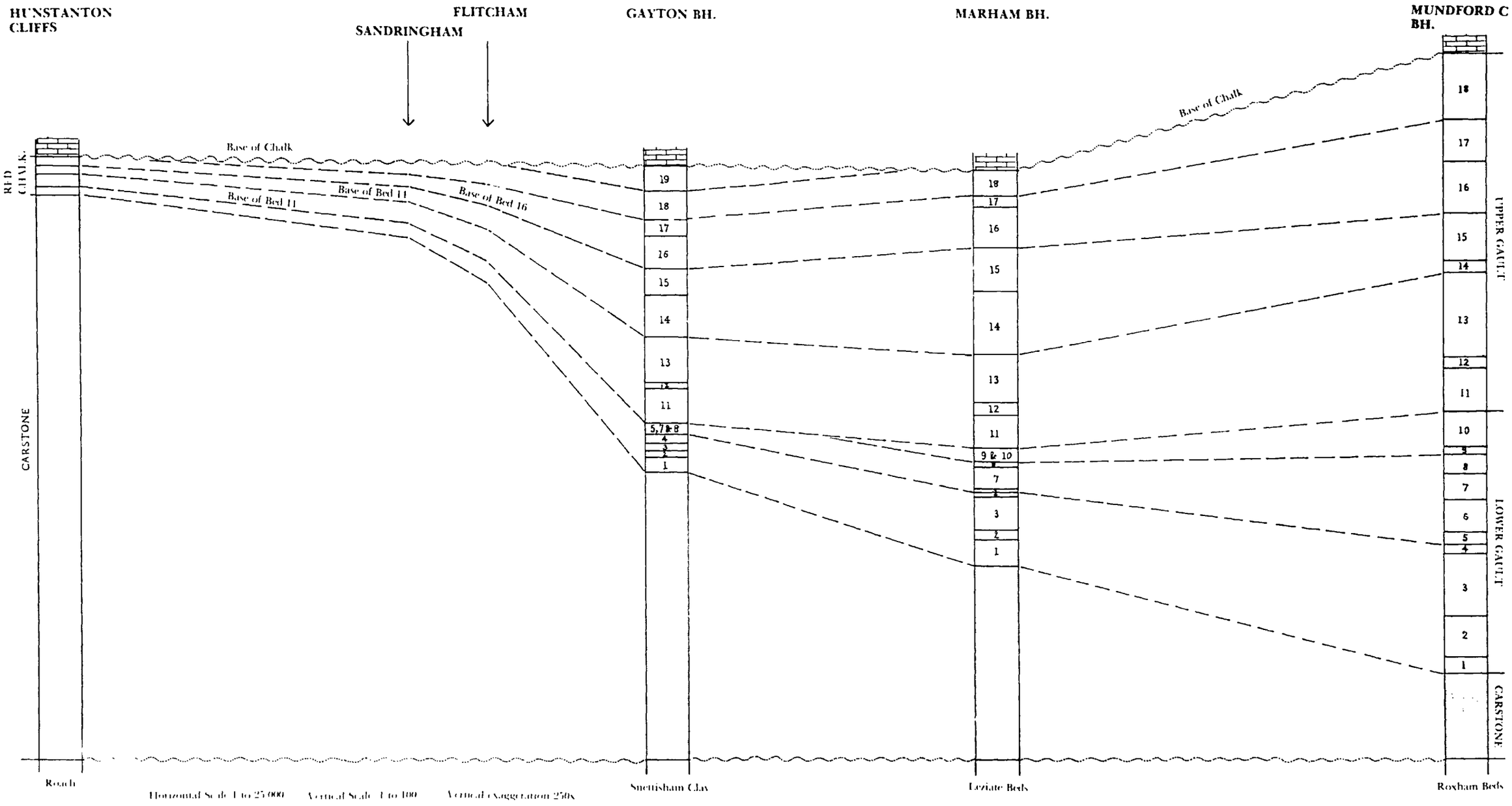


Figure 77. Correlation of selected Albian sequences between Hunstanton and Mundford, south-west Norfolk.

into hard nodular limestones (Fig. 79). The lower parts of these rhythms appear to be attenuated at Hunstanton where they are represented only by wisps of red calcareous mudstone. The Red Chalk can be traced, at outcrop and in boreholes, continuously from Skegness to the North Yorkshire coast at Speeton. Its thickness varies from 5.5m in the Lincolnshire Wolds to 12.8m on the Yorkshire coast (Kent, 1980) with an area of marked attenuation, where the formation is only 1m to 2m thick, over the Market Weighton Axis (Jeans, 1973).

The Red Chalk has an extensive subcrop in Norfolk. It was proved in the deep onshore hydrocarbon boreholes at North Creake, South Creake, Saxthorpe, East Ruston and Somerton in numerous offshore hydrocarbon boreholes (e.g. 78/22-2; Rhys, 1974) and in the IGS Trunch Borehole. It is presumed to underlie the whole of the county north of a line from Sandringham to Great Yarmouth (Fig. 80). The thickness of the Red Chalk is difficult to determine in rock-bitted boreholes because the distinctive red marls and tough limestone fragments are commonly conspicuous in the cuttings over a wider range than the true thickness. The formation is 0.56m thick in the cored borehole at Trunch.

Wiltshire (1859) and Seeley (1864a) divided the Red Chalk at Hunstanton into three beds of limestone separated by two prominent seams of red sandy marl. There are numerous minor local variations in the sequence, but this general five-fold division can be recognised throughout the cliff exposure. The following composite sequence is based on sections in the vicinity of the lighthouse [675 420]. Its correlation with the sequence proved in the Hunstanton Borehole is shown graphically in Fig. 81.

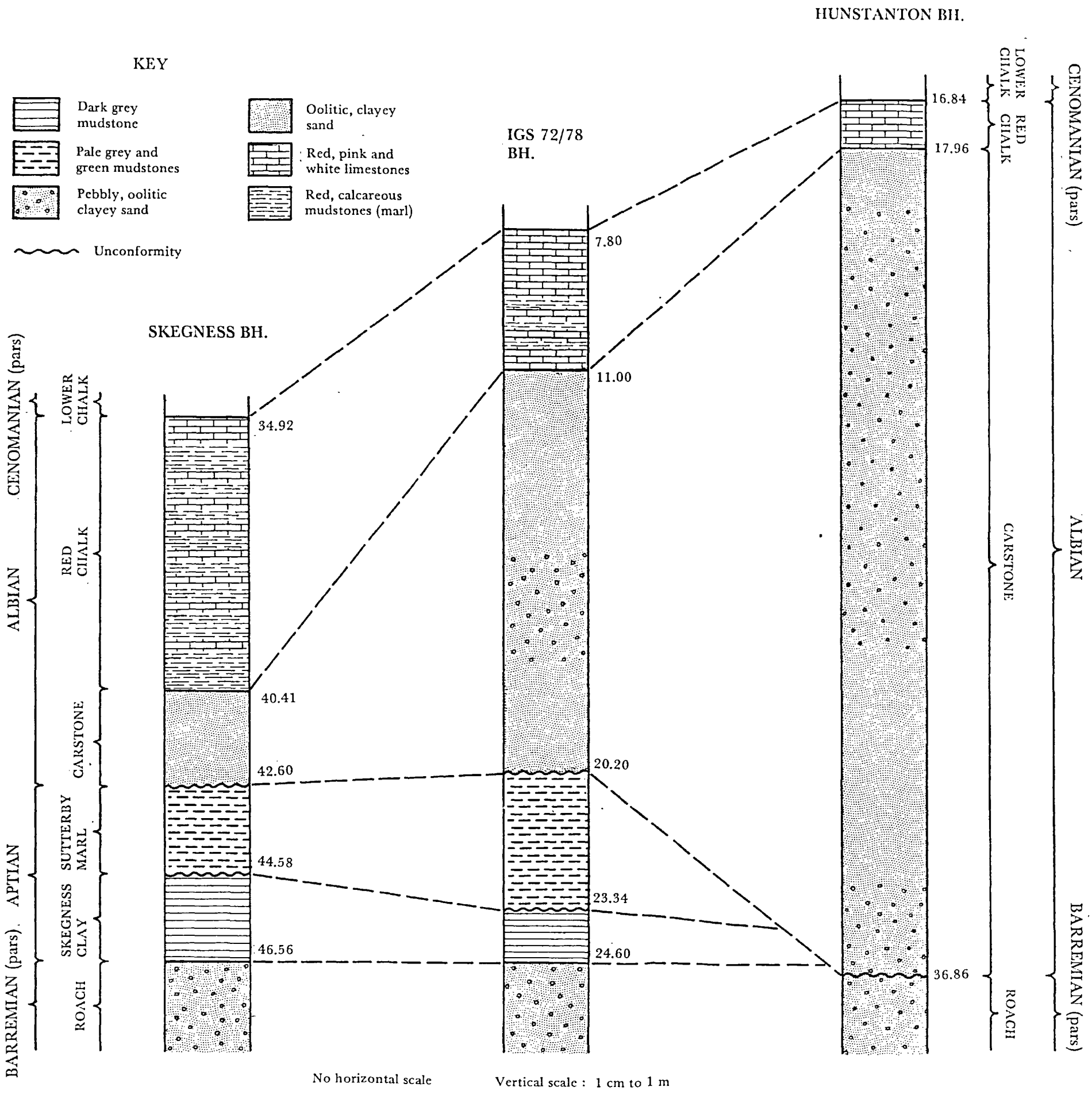


Figure 78. Lithological comparison of Aptian and Albian sequences in the Wash area.

Lower Chalk, Paradoxica Bed

Red Chalk

Bed 5: limestone, hard, fine-grained and chalk-like; mottled pink to deep brick red; intensely biotubrated with burrows mostly picked out by paler infillings and darker coloured linings; nodular-texture when weathered, persistent purplish red-stained irregular surface 75 mm to 130 mm below within top of bed; scattered sand grains and tiny angular pebbles common below this surface and increasing with depth; a few belemnites; irregular base .. 0.38 to 0.43m

Bed 4: mudstone, dark red and brownish red, highly calcareous, earthy textured and with numerous sand grains and tiny angular pebbles, mostly of brown stained quartz and ironstone; abundant belemnites; irregular base with local shearing and loss of bed .. .. .. up to 30 mm

Bed 3: limestone, firm, fine-grained, chalk-like but with common sand grains, small angular pebbles and belemnites; pink and red burrow-mottled; burrow-linings, infillings and pressure-solution wisps of deep red sandy calcareous clay occur throughout; weathering to nodular and rubbly texture; irregular base .. .. 0.41 to 0.43m

Bed 2: clay, dark red, sandy, highly calcareous; localled sheared out and replaced by irregular purplish red to brown ferruginously stained surface .. .. up to 20 mm

Bed 1: limestone, soft, fine-grained, very sandy; passing down irregularly with much bioturbation

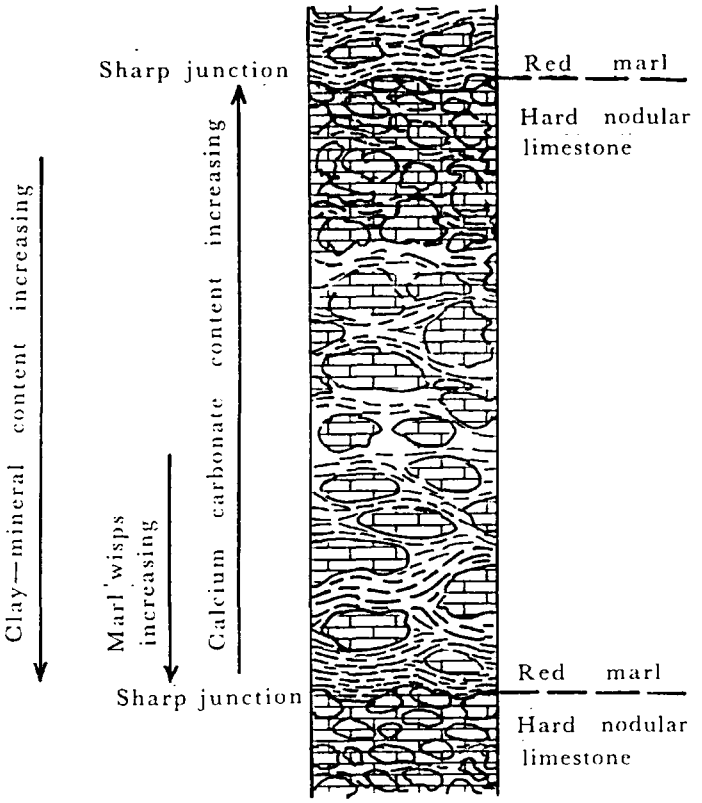


Figure 79. Generalized rhythm for the Red Chalk in the Skegness Borehole.

into pink and brown highly calcareous sand; sharp lithological break at base at almost planar, but burrowed, surface .. .. 0.23 to 0.28m

Carstone; yellowish brown fine- and medium-grained sand

The limestones contain a variety of primary sedimentary structures, such as burrows, borings and probable stromatolithic laminations, but many of these have been considerably modified by secondary lithification, cementation and mineral migration. Some idea of the degree of the complexity involved can be gained from the descriptions of these processes given by Jeans (1980), and the selected examples of structures are shown by him.

The Red Chalk at Hunstanton has yielded a remarkably rich and diverse fauna, much of it from fallen blocks. However, the great variety of echinoderms, polyzoans, brachiopods, bivalves and ammonites, many beautifully preserved specimens of which can be seen in museum collections, reflect more than 150 years of patient collecting, rather than an obvious abundance in the rock. Le Strange (1974, p. 47-48), basing his observation on more than 50 years collecting at Hunstanton, notes that the commonest fossils in the Red Chalk are Inoceramus, Neohibolites and the brachiopod Moutonithyris dutempleana (d'Orbigny). Cidarids and stems of Torynocrinus are relatively common, but other echinoderms are rare; well preserved ammonites and nautiloids are rare; corals, except for the solitary Podoseris, and gastropods are very rare.

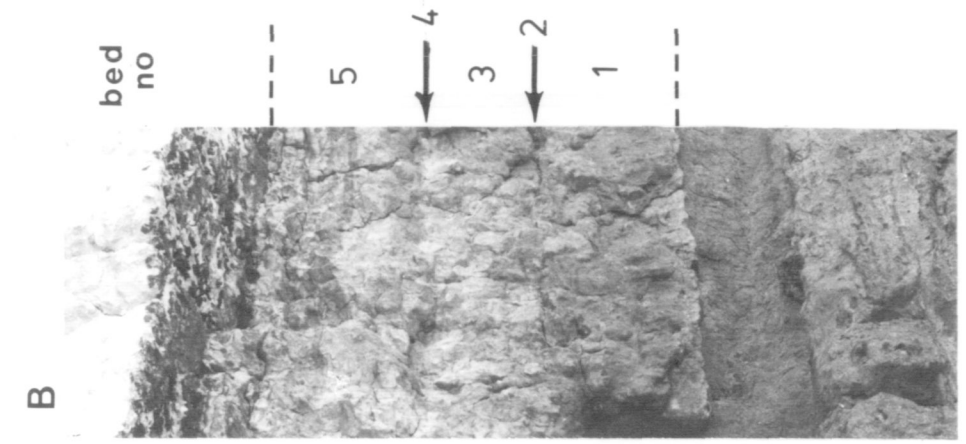
Most of the fauna preserved in museum collections probably came from loose blocks and is not stratigraphically identified, except as

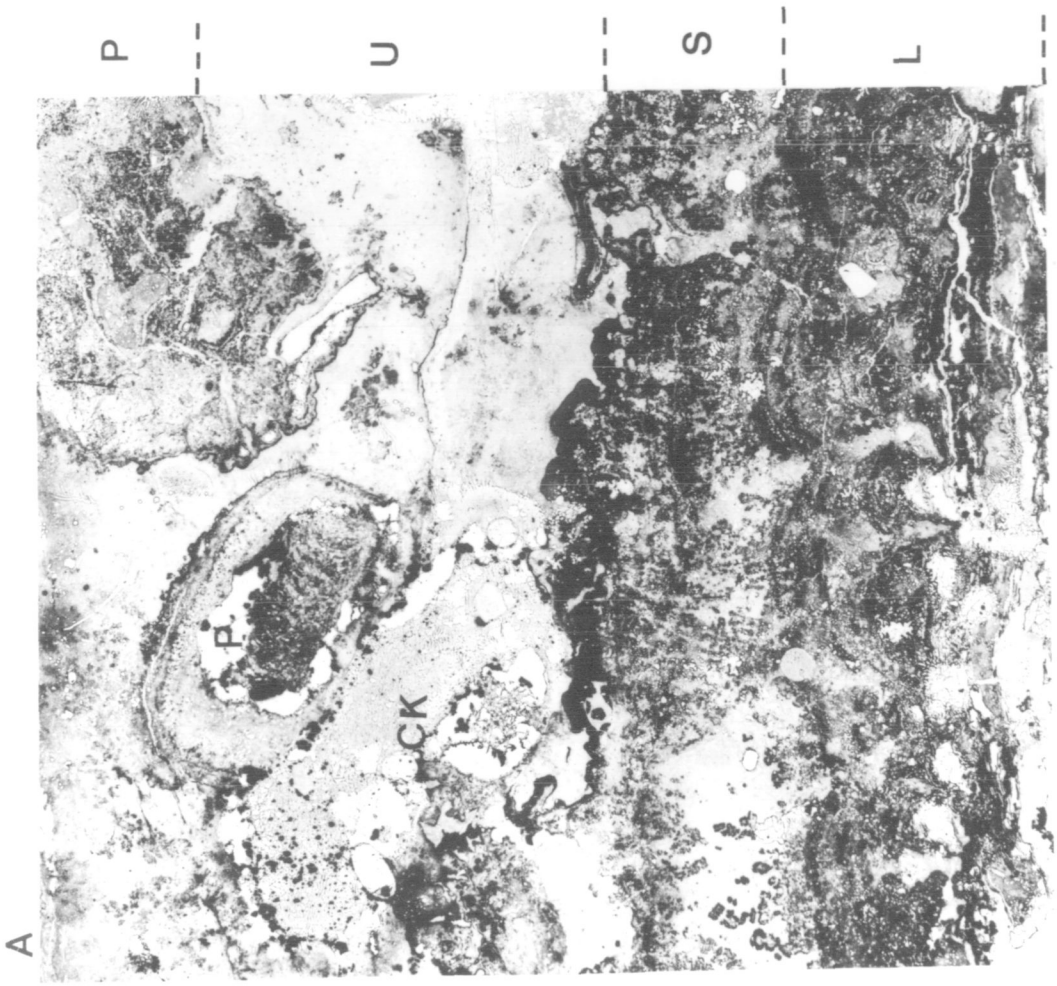
Plate 29. Red Chalk sequences in the Trunch Borehole and at Hunstanton.

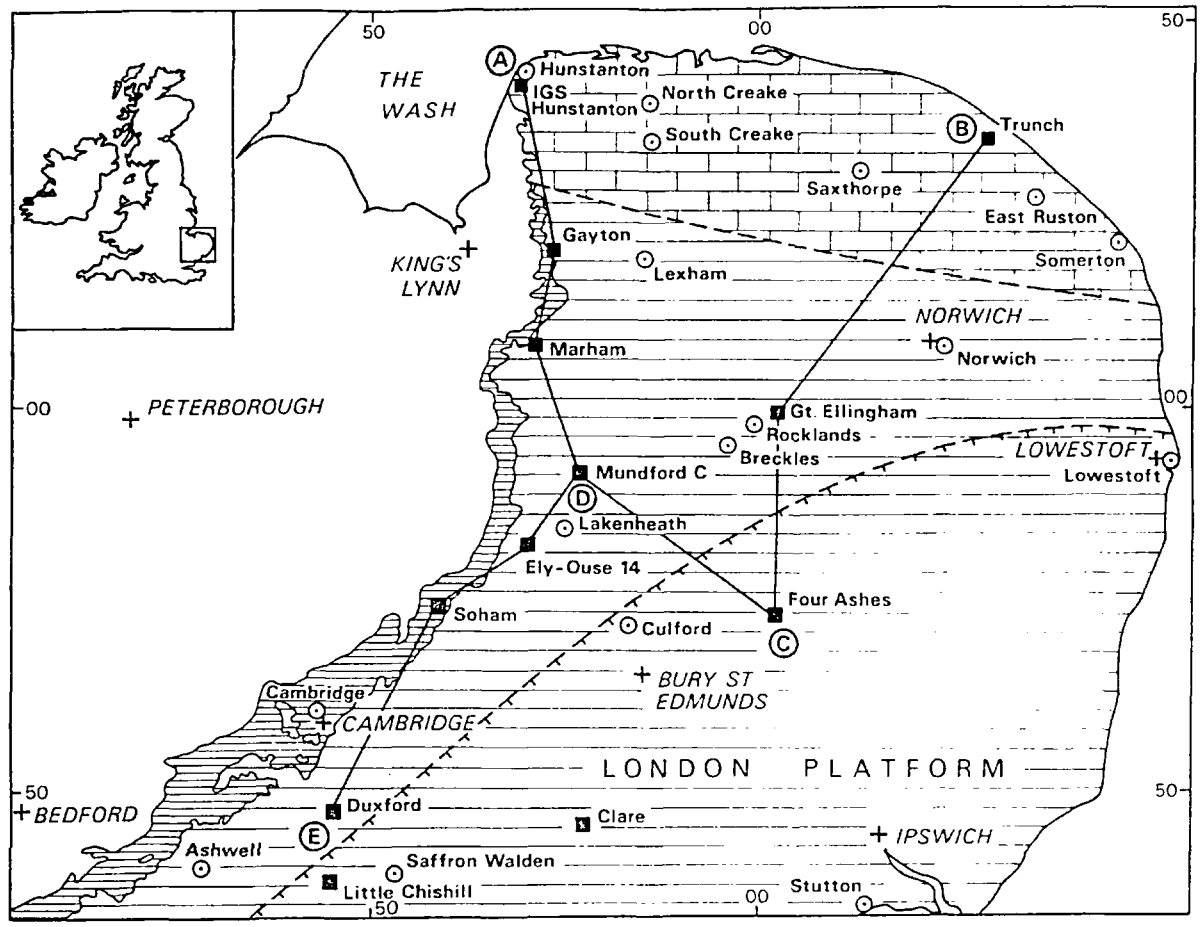
A. True-scale photograph of lacquer peel of weakly acid-etched core cut normal to bedding, Trunch Borehole, showing almost the full thickness of the Red Chalk. The basal bed of the Red Chalk consists of laminated (L) fine-grained chalky limestone with numerous limonite-coated sand grains and scattered small pebbles; it rests on pebbly Carstone sand at the bottom of the photograph. The laminated sandy limestone passes up into uniform chalky limestone rich in foraminifera and calcispheres (U) via stained chalky limestone (S) with traces of lamination. The highest bed contains large burrows infilled with soft white Chalk (CK) and large rounded pebbles of Red Chalk limestone (P) with laminated skins and some with included burrow structures. The junction with the Chalk is an irregular surface 1 to 5 cm above the top of the sample seen here.

B. Red Chalk sequence at Hunstanton; cliffs near the lighthouse close to the measured section described on pp. 424-426. The total thickness of the Red Chalk seen here is about 1.1m.

Plate 29







KEY

Gault outcrop

Gault subcrop beneath Chalk

Red Chalk outcrop and subcrop

older strata

Approximate edge of London Platform : Aptian or Albian sediments rest on Palaeozoic

Borehole cored or partially cored in Gault or Red Chalk

Borehole rock-bitted or unsampled (including samples lost) in Gault or Red Chalk

Scale

0 10 20 30 40 50 km

Figure 80. Distribution of the Gault and Red Chalk in East Anglia.

Red Chalk. Other material is identified in terms of the three limestone divisions of Seeley or Wiltshire, but with varying degrees of reliability. Owen (1979, p. 580) has summarized the ammonite evidence and has shown that Wiltshire's limestones (labelled from the top downwards) can be correlated with the standard zonal/subzonal scheme for the Albian as follows:

Division A: varicosum and auritis subzones of the inflatum Zone; ?rostratum Subzone of the dispar Zone

Division B: cristatum and orbignyi subzones of the inflatum Zone

?Division B or C: nitidus Subzone of the loricatus Zone; intermedius and meandrinus subzones of the lautus Zone

Division C: ?lyelli and ?spathi; subzones of the dentatus Zone

Detailed collecting of in situ material by Mr Morter for the present survey has yielded non-ammonite assemblages that can be correlated with assemblages from the Gault of Norfolk, Suffolk and Cambridgeshire. These latter occur in association with ammonites and belemnites that can be correlated with the standard zonal and subzonal scheme (Section 4.6.4). The in situ fauna, although only a small part of the total known from the Red Chalk, can therefore be used indirectly to allocate the five beds of the formation to zones and subzones. The sequence recognised by Mr Morter can be summarized as follows:-

Bed 5, top part, probably rostratum Subzone; upper part, auritus Subzone; lower part, varicosum Subzone

Bed 4, varicosum Subzone

Bed 3, upper part, probably orbignyi Subzone; middle part, orbignyi

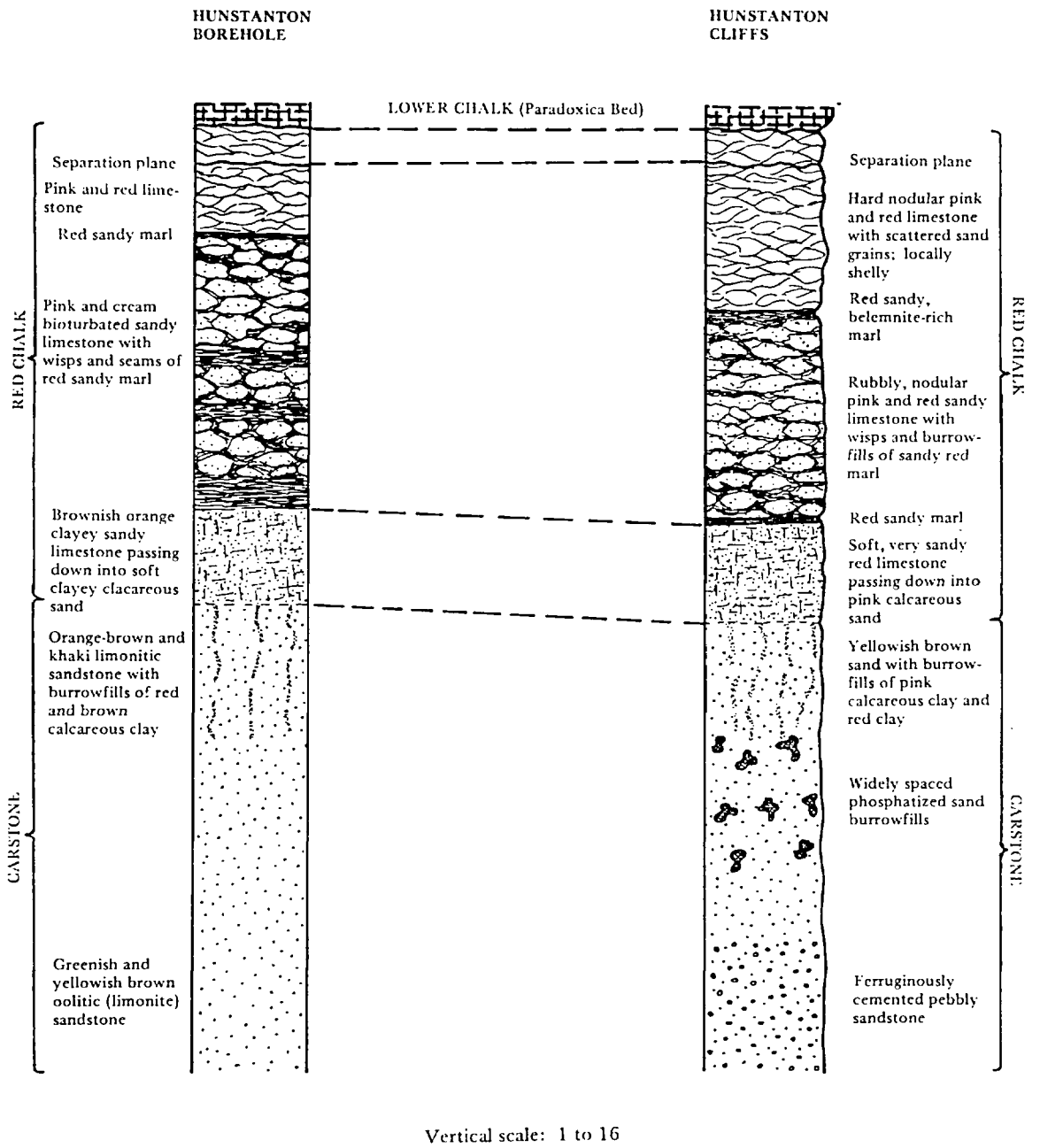


Figure 81. Lithological comparison of the highest Carstone and Red Chalk sequences in Hunstanton cliffs and the Hunstanton Borehole.

and probably cristatum subzones; lower part, possible nitidus, meandrinus and intermedius subzones

Bed 2, no fauna collected

Bed 1, dentatus Zone

Correlation of the Red Chalk sequence with that of the Gault of south-west Norfolk is shown in Figure 77. Further details of the Red Chalk at outcrop are given on open file.

4.6.4 Gault

The outcrop of the Gault in Norfolk can be traced from Sandringham southwards as far as West Dereham, at which locality the formation passes beneath the Recent deposits of Methwold Fens. It occupies low ground that is commonly covered by a veneer of sandy wash derived from the adjacent Chalk escarpment. The lower part of the formation, being farthest from the escarpment, has only a thin covering and is exposed in the deeper drains; the higher part is very rarely exposed. In Victorian times the lower part of the formation was worked extensively, but on a small scale, at outcrop in the county for brick-making and agricultural marl, and in the West Dereham area for agricultural phosphate. All the exposures are now degraded, and few specimens have been preserved. Continuous cores have been obtained from the Gault close to its outcrop at Gayton and Marham and from a site investigation borehole (Ely-Ouse Borehole No. 23) close to the county boundary at Hockwold cum Weeting. Cores were also obtained from the subcrop at Mundford and Great Ellingham (Fig. 80).

At the most northerly point at which it can be recognised as a discrete argillaceous formation, in the Sandringham area, the Gault consists of about 2m of pink and cream-coloured highly calcareous clay. This passes rapidly southwards into brown sandy clay and grey,

cream-coloured and brown silty calcareous clays with thin beds of white and pink nodular chalky limestone (similar to parts of the Red Chalk) in their upper part. These limestones are present as far south as Gayton; thin bands of white chalky limestone also occur at Bilney and Pentney, but these are at lower stratigraphical levels.

The formation thickens steadily southwards from Sandringham and is 9.0m thick at Gayton, 11.6m at Marham and 17.8m at Hockwold. This apparently regular southward thickening is a small part of regional variation that is more complex, and as yet incompletely understood. The Gault thickens southward at outcrop in Suffolk and Cambridgeshire to about 25m in the Soham Borehole [TL 5928 7448], about 30m at Cambridge and about 48m in the Duxford Borehole [TL 469 457]. It thins rapidly eastwards from its outcrop as it oversteps the Palaeozoic rocks of the London Platform. The data is sparse in that subcrop area, but in Suffolk the Culford Borehole [TL 831 710] reputedly proved 15m of Gault resting on Lower Greensand, and the cores and geophysical logs of the Four Ashes Borehole [TM 0230 7187] suggest that it proved a similar thickness of Gault resting on Devonian mudstones. In the Norfolk subcrop (Fig. 80), boreholes at Breckles, Rocklands and Great Ellingham indicate the presence of a broad tract of ground lying between the London Platform (in the south) and the Red Chalk depositional area (in the north) in which the Gault was probably originally about 15 to 20m thick, but where it has locally been reduced by erosion at the base of the Chalk (Fig. 82).

These regional variations in thickness result from a number of interacting factors and their pattern will undoubtedly become more complex as more borehole data become available. The most important factors affecting the preserved thickness are:-

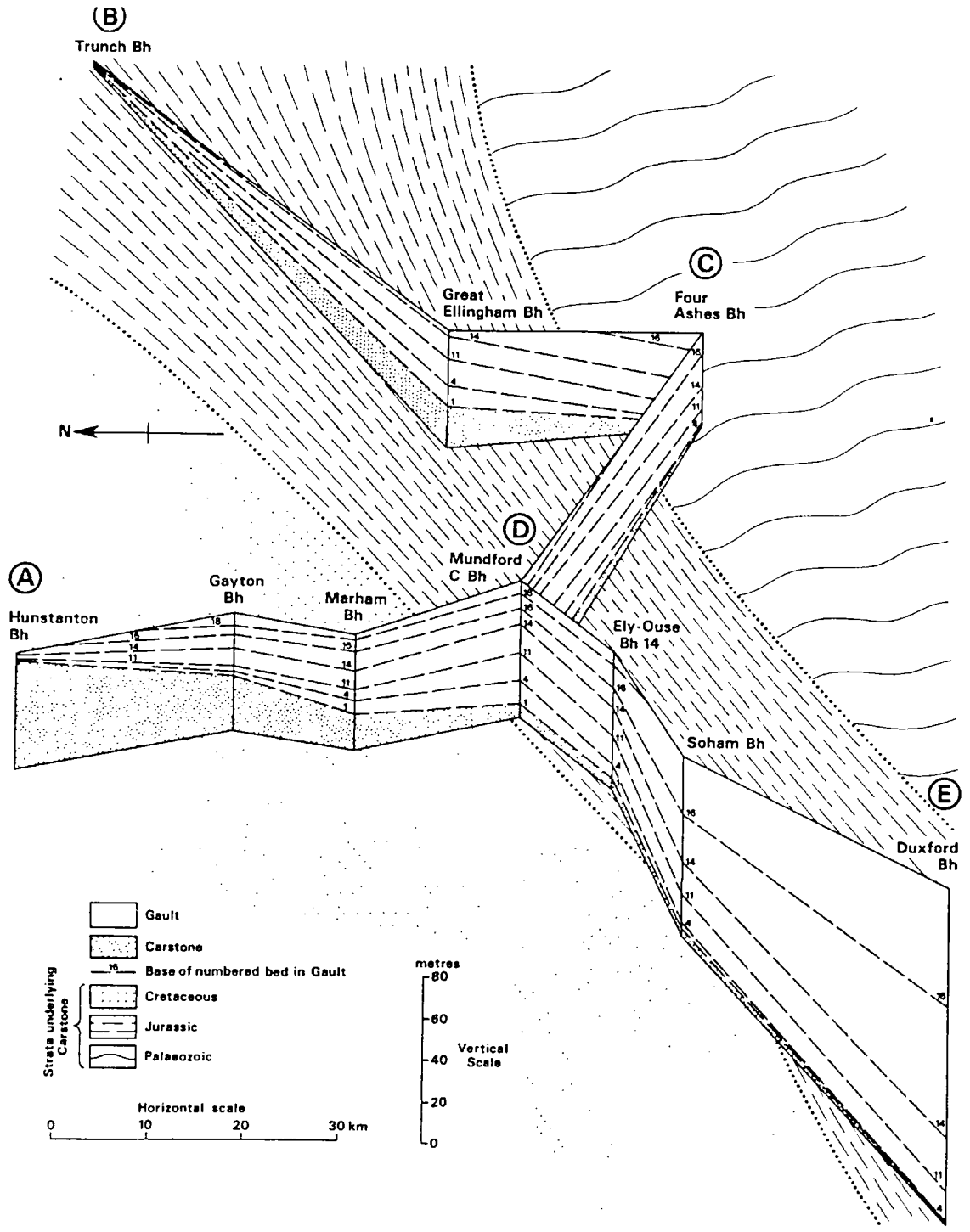


Figure 82. Correlations between the Albian sequences in the northern part of East Anglia (Gallois and Morter, in press).

(i) the attenuation of the whole of the Gault as it passes northwards in Norfolk into the Red Chalk

(ii) the attenuation of the Lower Gault in a southerly and easterly direction in Cambridgeshire and Suffolk as the London Platform is approached

(iii) the rapid expansion of parts of the Upper Gault in a southerly direction in Cambridgeshire

(iv) variations in the amount of erosion that has occurred at the base of the Chalk.

The main outcrop of the Gault in Norfolk runs almost continuously southwards from Sandringham to Gaytonthorpe Common via Roydon, Grimston and Gayton, mostly as low ground with a veneer of pocketed sandy or gravelly wash. Throughout this area the formation can be roughly divided into two parts; a lower part which weathers to medium grey and brown clays and an upper, more calcareous, part which weathers to pale and very pale grey clay with thin bands of soft argillaceous limestone. The outcrop is studded with numerous small, mostly water-filled, pits that were probably dug for agricultural marl and subsequently served as a water supply. Over 70 such pits were recorded between Roydon and Gaytonthorpe Common. The full thickness of the formation was cored in the Gayton Borehole.

The Gault is largely covered by drift deposits associated with the valleys of the River Nar and its tributary the Gaytonthorpe stream between Gaytonthorpe Common and Marham. Relatively drift-free areas of outcrop occur at East Walton, West Bilney, Pentney, Narborough, Marham and Shouldham but these are all on low, poorly drained ground and there are few exposures. Between Shouldham and Crimplesham, the outcrop is overlain by thick Pleistocene deposits. The formation has

a broad outcrop in the Crimplesham, Ryston and West Dereham areas before passing southwards beneath the Recent deposits of Methwold Fens. With the exception of very small inliers at Stubb's Hill and Shrubhill, the latter close to the county boundary, the Gault has no outcrop in Norfolk south of West Dereham.

The Gault was cored in the Marham Borehole and in the Ely-Ouse site investigation boreholes at Hockwold cum Wilton; parts of it were cored in the oil-exploration boreholes at Methwold Common and Severals House (Pringle, 1923, pp. 128-129). The lower beds were formerly worked for brickmaking at Pottrow, Grimston and Ryston; the basal beds were well exposed in the West Dereham area in Victorian times in several large shallow pits dug for agricultural phosphate. No exposure has survived, but it is clear from the descriptions of Teall (1875), Keeping (1883) and Jukes-Browne (MS quoted in Whitaker et al., 1893, p. 13) that the main source of phosphate was large sandy nodules at the top of the Carstone. The Dentatus Nodules and other phosphatic nodules and pebbles in the basal 3m of Gault, usually described as "pale marly clay", were also worked.

The Gault can be divided into two parts on gross lithology and these were termed the Lower and Upper Gault by De Rance (1868). The Lower Gault consists predominantly of medium and dark grey mudstones in which, according to analyses quoted by Perrin (1971, pp. 140-149), illite and kaolinite are the dominant clay minerals. The Upper Gault consists mostly of pale grey mudstones with high calcium-carbonate contents in which smectite is the dominant clay mineral (Perrin, 1971, pp. 140 - 149).

The Lower Gault and the lower part of the Upper Gault of Norfolk

are made up of small-scale rhythms, mostly 1 to 2m thick, that are closely similar to the rhythms of the lower part of the Kimmeridge Clay (Type A of Fig. 5). Each rhythm begins with a medium or dark grey, shelly, pebbly, silty mudstone or muddy siltstone, rich in inoceramid prisms, oysters, belemnites, exhumed phosphatized burrow-fills, and water-worn phosphatic pebbles, that rests on a partially phosphatized and glauconitized, burrowed surface. This basal bed passes up into medium and pale grey calcareous mudstones by a decrease in the coarser clastic (including bioclastic) content and an increase in calcium carbonate (Fig. 83). This lithological change is commonly accompanied by a decrease in faunal diversity and numbers. The upper part of the Upper Gault shows weakly developed rhythms that are made up of paler, more calcareous mudstones than those of the Lower Gault and the sequence contains fewer major erosion surfaces. The higher rhythms resemble parts of the Upper Kimmeridge Clay of Dorset (Type C rhythms of Fig. 46). Hill (1900, pp. 330 - 335) recognised that much of the calcium carbonate in the Upper Gault was derived from coccoliths and this has been confirmed by later workers such as Black (1972 - 75).

In their descriptions of the Folkestone succession both De Rance (1868, 1875) and Price (1874, 1876) subdivided the sequence on the basis of a combination of lithological and faunal characters. De Rance (1868) recognised 11 lithological units that could be distinguished by their faunas. Price (1875) also recognised 11 beds; the youngest of these was subsequently divided into three by Jukes-Browne (1900, pp. 71 - 81) and the resulting 13 beds (numbered I to XIII) have formed the basis of subdivision of the Gault of the type section since that time. Several of these beds have erosion surfaces

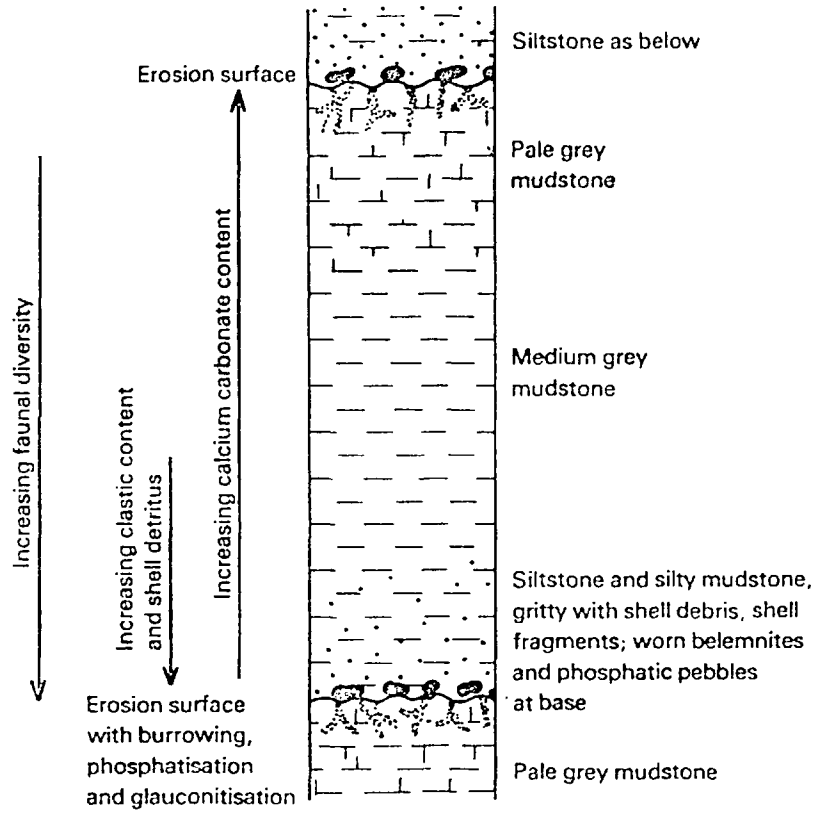


Figure 83. Idealized rhythm for the Gault of East Anglia.

marked by phosphatic pebble beds at their bases, and this largely explains why subsequent detailed work on the ammonite succession (mostly by L.F. Spath) showed many of the more pronounced faunal changes to coincide with bed boundaries. The boundaries of ten of the original 13 beds corresponded with ammonite zonal/subzonal boundaries for many years (e.g. Casey, 1966). In more recent work (Owen 1971, 1976) the subzonal boundaries have been modified so that now only one of Price's beds is coincident with a subzone.

The main difficulty in attempting correlations within the Gault is that of recognising the bases of those individual rhythms that are erosive and which may locally cut out all or part of the underlying rhythms. In the Gault sequences proved in cored boreholes in East Anglia, correlations can be made with confidence over relatively large distances by comparing the sequences of lithological and faunal events in the same manner as that described in Section 2.3 for the Kimmeridge Clay. These comparisons have enabled a standard sequence of 19 distinctive beds to be devised that is applicable to the Gault of the central and northern parts of East Anglia (Fig. 84; Gallois and Morter, in press, Fig. 3).

The bases of 13 of these beds have been taken at erosion surfaces that mark the bases of complete or incomplete rhythms. In nearshore areas such as that in which much of the Gault of East Anglia was probably deposited, these sedimentary breaks commonly coincide with faunal changes. It is therefore no surprise to find that the majority of the zonal/subzonal boundaries are coincident with bed boundaries. The remaining 6 beds are so lithologically distinctive as to suggest that they are also related to widespread sedimentary events. All except one of the 19 beds have been shown to be persistent over large

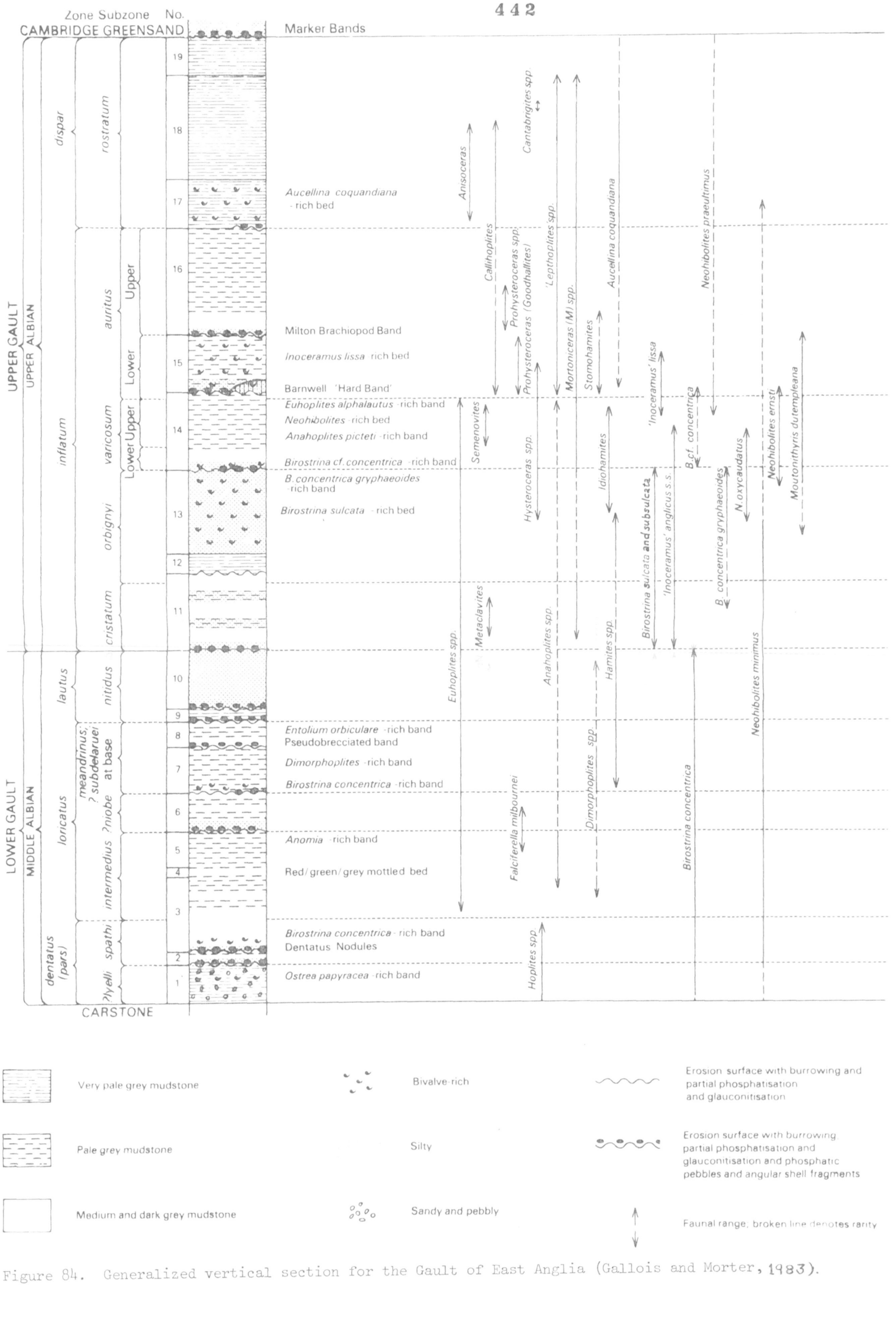


Figure 84. Generalized vertical section for the Gault of East Anglia (Gallois and Morter, 1983).

areas of East Anglia and it seems likely that many of them will be recognisable throughout much of southern England. Bed 19, the youngest in the sequence, has only been recorded in the Gayton Borehole.

The Gayton sequence is summarized below (faunal identifications by Mr Morter):

Chalk; hard bioturbated limestone with green-coated phosphatic pebbles at base

Gault

Bed 19; limestone, soft bioturbated chalky, almost white but with disseminated pale yellow and orange staining; shelly with common Neohibolites spp. and Aucellina; marked lithological change at base 0.51m

mudstone, soft pale grey, highly calcareous; bioturbated throughout; sparsely shelly with Neohibolites the only common fossil 0.25m

Beds 17 and 18; mudstone, soft bioturbated; pale, medium and brownish grey, highly calcareous, band of soft argillaceous chalky limestone (0.11m thick) in lowest part; shelly in lower part and at several levels in upper part with abundant Aucellina; other fauna includes Nielsenicrinus, Kingena, Plicatula, Terebratulina, Entolium, and Neohibolites; passing down into 1.30m

Bed 16; mudstone, soft bioturbated pale and dark grey; band of argillaceous chalky limestone (0.08m thick) in lower part of bed; sparsely shelly with Aucellina the only common fossil;

Inoceramus chips and fish debris also present; phosphatic pebble bed at base with green coated phosphatized mudstone pebbles up to 37mm diameter, and with common brachiopods including Moutonithyris .. 0.94m

Bed 15; mudstone, soft bioturbated pale and medium grey in upper part, reddish brown and pale green in middle part and silty medium grey in lower part; fossiliferous at several levels with Isocrinus, Nielsenicrinus, Pycnodonte, Moutonithyris and other terebratulids, and Inoceramus chips; passing down into 0.81m

Bed 14; mudstone, soft silty, bioturbated medium grey passing down into pale and medium grey bioturbated mudstones with band of pale grey shelly chalky limestone (0.10m thick) in lower part of bed; Neohibolites spp. abundant in upper part of bed, and Birostrina concentrica abundant in chalky limestone and lower part of bed; other fauna includes Monticlarella, Moutonithyris and Pycnodonte; glauconitized surface at base 1.17m

Bed 13; mudstone, soft bioturbated; medium grey; silty passing down into siltstone with much shell debris (0.3m) and then into pale and medium grey bioturbated mudstones; shelly at severa levels especially in top part of bed; Birostrina sulcata (Parkinson) common throughout; other fauna includes Nielsenicrinus, ?Metaclavites, Plicatula,

Terebratulina, Birostrina concentrica gryphaeoides (J. de C. Sowerby), Neohibolites and, in upper part of bed only, Euhoplites, Hysteroceras, and Mortoniceras (Deiradoceras); passing down into 1.34m

Bed 12; limestone, very soft and muddy; bioturbated pale grey with darker grey infillings of Chondrites and other burrows; sparsely fossiliferous 0.16m

Bed 11: mudstone, soft bioturbated; interbedded pale and medium grey; silty in lower part with band of medium grey siltstone at base; shelly in lower part, less so in upper; fauna includes Isocrinus, Nielsenicrinus, Kingena, Moutonithyris, Plicatula, Terebratulina, 'Anomia', Birostrina subsulcata (Wiltshire), B. concentrica gryphaeoides, Inoceramus, Pseudolimea, Neohibolites and cirripede valves; phosphatic pebble bed at base with rolled and worn belemnites resting on intensely burrowed surface 1.04m

Beds 5, 7 and 8 condensed; mudstone, soft intensely bioturbated pale green, grey and yellowish grey with some streaks of dull reddish brown; burrow infillings of overlying silt extend down almost to base of bed; becoming very pale grey highly calcareous in lower part; phosphatic pebble beds at two levels; rare limonite-coated sand grains (cf. Carstone) scattered throughout; sparse fauna with Birostrina concentrica Parkinson and Neohibolites the only common fossils; passing down into 0.33m

Bed 4; mudstone, soft intensely bioturbated pale green, dull reddish brown and grey; rare sand grains, shelly in upper part with common Birostrina; other fauna includes Kingena, Pycnodonte (Phygraea), Pseudolimea and common Neohibolites; bed of green and red phosphatized mudstone pebbles at base resting on burrowed surface 0.23m

Bed 3; mudstone, soft bioturbated medium grey; burrow infillings and wisps of shell debris and limonite-coated sand grains present throughout and becoming more abundant with depth; sparsely shelly with Pycnodonte (Phygraea), and Neohibolites the only common fossils; pebble bed at base with hard black phosphatic nodules, some enclosing Hoplites spp. including H. (H.) dentatus (J. Sowerby) (Dentatus Nodules) 0.25m

Bed 2; mudstone, soft medium grey, silty with scattered grains and burrow concentrations of sand; shelly with much shell dust and many larger fragments and whole shells; fauna includes Moutonithyris, common Birostrina concentrica, Neithea, Pseudolimea, Rastellum, and Hoplites (H.) dentatus; plaster of B. concentrica at base resting on burrowed surface 0.29m

Bed 1; mudstone, soft intensely bioturbated pale grey with much limonite-coated sand and scattered small pebbles of quartz and rotted ironstone and, at one level, clasts of pale grey soft mudstone;

sparsely shelly except for concentration of Birostrina concentrica at one level; Pycnodonte, Neohibolites and Hoplites also present; passing down with bioturbation into 0.46m

Carstone; intensely bioturbated clayey, pebbly soft sandstone with large phosphatized burrow infillings

The Gault sequence at Gayton is the most attenuated that has yet been completely sampled. Despite this, it can be correlated in lithological and faunal detail with the sequence at Marham and with the much thicker sequences of south-west Norfolk (Fig. 77) and Cambridgeshire (Fig. 82). The Lower Gault (Beds 1 to 10) is especially thin at Gayton and contains several prominent erosion surfaces. The correlation of these surfaces with the comparable surfaces at Marham and Mundford (Fig. 85) provides a good example of the complex nature of the attenuation that occurs at this stratigraphical level.

Local lithological variations are present in the Gault in Norfolk, especially in the northern part of the outcrop. Thin beds of dark red to pink mudstone occur at several levels. The most intensely coloured of these, Bed 4 in the standard sequence, can be traced southwards as far as Cambridgeshire, via the Gayton, Marham, Mundford and Hockwold boreholes, its colour becoming fainter as the distance from the Red Chalk area of deposition increases. A less obvious lithological change takes place in the opposite direction. Close to the edge of the London Platform the Lower Gault is predominantly silty and grey; northwards from there the beds at any particular level become paler, more calcareous and less silty. In the Upper Gault, thin bands of very calcareous mudstone that are present in Beds 14, 16 and 17 of the Cambridgeshire outcrop pass northwards into laterally impersistent

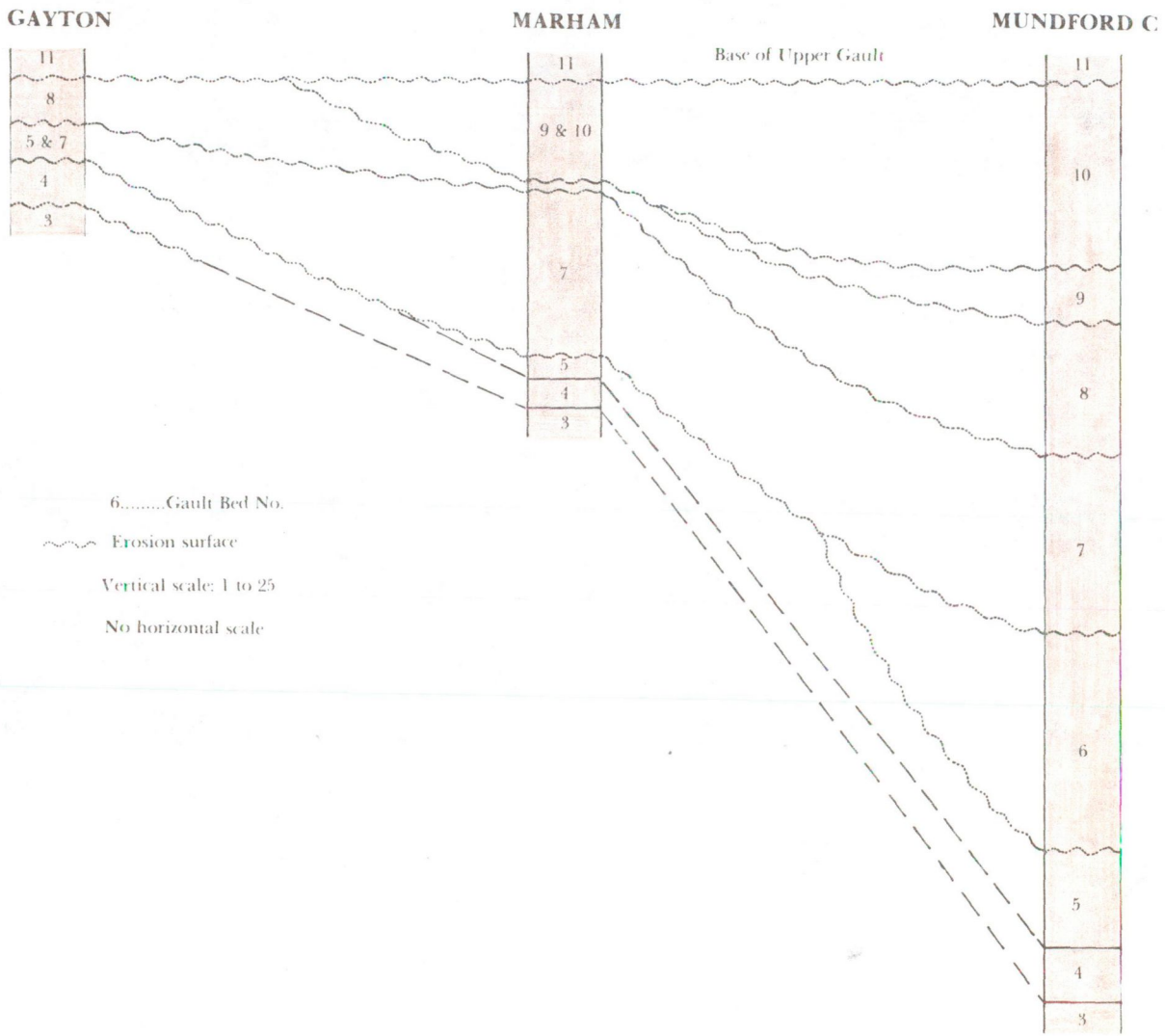


Figure 85. Diagrammatic correlation of erosion surfaces in the upper part of the Lower Gault between Gayton and Mundford.

thin, muddy chalky limestones at Gayton (at the base of Bed 14), Pentney (at the base of Bed 16) and Bilney (in Bed 17). The two younger beds were referred to as the 'Pentney Limestone' and the 'Bilney Limestone' by Seeley (1861).

The Gault contains a rich marine fauna dominated by bivalves, but includes relatively common solitary corals, serpulids, gastropods, scaphopods, ammonites, belemnites, crinoids and echinoids together with an abundant microfauna of ostracods and foraminifera. Ichnofossils are represented by common Chondrites, possible thalassinoid burrows and a variety of trails. The modern zonal and subzonal scheme for the Gault in England is based on ammonite assemblages from the work of Spath (1923a, 1923b, 1926, 1941), subsequently modified by Casey (1961b, 1966) and Owen (1971, 1976). The ammonite assemblages can be supplemented by the use of other groups notably belemnites (Spaeth 1971, 1973) inoceramid bivalves (Kauffman, 1976), ostracods (Wilkinson and Morter, in press), foraminifera (Carter and Hart, 1977; Price, 1977) and coccoliths (Black, 1972 - 75). The zones and the subzones for that part of the Albian which is represented by the Gault in Norfolk have been determined by Mr Morter and are shown in Figure 84.

The recognition of zones and subzones is difficult in borehole cores in the Gault, despite the generally fossiliferous nature of the formation, because of the limited amount of material available from any particular horizon. Additionally in Norfolk, where the sequence is poorly exposed and attenuated in comparison with other parts of England, very few of the characteristic ammonite assemblages have been recognised at outcrop. The subzonal/zonal scheme has, however, been applied to the Gayton and Marham borehole sequences

by comparing them with the standard faunal and lithological sequence worked out for East Anglia. A detailed description of the faunal sequence of the standard succession is given, subzone by subzone, by Morter (in Gallois and Morter, in press); the faunas of the individual beds are included in the individual bed descriptions in the same account.

Correlation of the most complete Gault sequences yet proved in Norfolk, those in the Gayton, Marham and Mundford C boreholes, with one another and with the Red Chalk sequence at Hunstanton is shown in Figure 77. Details of the sequences proved in the subcrop area at Great Ellingham and in the partially cored sequence at Hockwold (Ely - Ouse Bh. 23) are given elsewhere (Gallois in Cox and others, in press; Gallois, in press). Correlation of the Great Ellingham sequence with those proved elsewhere in the subcrop is shown in Fig. 82 (from Gallois and Morter, in press). The depositional environments of the Gault are discussed below.

4.7 Depositional environments

The top Jurassic-Lower Cretaceous rocks of Norfolk contain lithological and faunal evidence indicative of deposition in shallow marine environments during a repetitive sequence of transgression and regression. Many of the younger sediments contain material derived from the older, and in the southern part of the county, close to the London Platform, the sequence is greatly attenuated due to unconformities in the Cretaceous. The closer one approaches to the London Platform the less evidence there is available for study and the palaeogeography can only be deduced from an examination of contemporaneous deposits elsewhere in southern England.

4.7.1 Evidence for palaeogeography

Casey (1967, Fig. 4) has suggested that the Kimmerian earth movements caused the open-marine environment of the Kimmeridge Clay, which had covered much of eastern England, to be replaced in the mid Volgian by a marine strait that ran from Lincolnshire to Wiltshire. This strait was bounded in the east by land formed by the London Platform and in the west by a Midlands land area. It was open at the time of deposition of the Roxham Beds (in the north) and Portland Stone (in the south), closed during deposition of the Runcton Beds and their southern equivalent the Lower Purbeck Beds, briefly open in early Mintlyn Beds (= Cinder Bed) times, and closed during deposition of the Mintlyn Beds to Roach (in the north) and the Wealden (in the south).

No Cretaceous rock is preserved west of their modern eastern England outcrop and the existence of a Midlands land area in the latest Jurassic and early Cretaceous in speculative. The marked faunal and lithological differences between the marine Roxham Beds and the marine Portland Stone have been suggested by Casey (1967) to be due to slight differences in salinity. The differences between the freshwater to hypersaline Purbeck Beds and Wealden and their marine equivalents in Norfolk can be explained without the need to invoke a Midlands land area by assuming that the former were deposited in coastal-plain environments adjacent to the southern margin of the London Platform, with open sea to the north west and west.

Evidence from the intervening area, the western edge of the London platform between Cambridgeshire and Wiltshire, is poorly known. Patches of early Cretaceous sand occur at numerous localities, but few have yielded sufficient faunal data for them to be

correlated with either the marine (northern) or non-marine (southern) Cretaceous sequences.

Evidence for the positions of the early Cretaceous shorelines is limited in Norfolk because of the common absence through erosion of the more near-shore deposits. At several levels, however, contemporaneous marine deposits of markedly different lithology are present and these can be used to indicate the directions in which the shorelines lay (Fig. 86). Details of the deposits and their presumed depositional environments are discussed in Section 4.7.3.

4.7.2 Sources of the sedimentary components

The top Jurassic-Lower Cretaceous rocks of Norfolk include a great variety of lithologies ranging from pebble beds to mudstones, but these are made up of a relatively small number of components that occur in varying proportions throughout the sequence (Plate 30). These are qualitatively summarized in Table 19; their possible sources are discussed below.

4.7.2.1 Pebbles

Pebbles occur at many stratigraphical levels in the Norfolk sequence. In the older formations they are predominatly phosphatic and rest on erosion surfaces; they commonly enclose phosphatized ammonites derived from the underlying formations and their stratigraphical (but not necessarily their geographical) provenance is usually obvious. Examples include the phosphatic pebbles at the bases of the Roxham Beds (with *Pavlovia* derived from the Kimmeridge Clay), Runcton Beds (*Subcraspedites* derived from the Roxham Beds) and Mintlyn Beds (*Subcraspedites* and *Runctonia* derived from the Runcton Beds). Similar phosphatic pebble beds occur at the base of

Plate 30. Selected Lower Cretaceous lithologies, all of which weather at outcrop to ferruginous sandy clay or clayey sand. All photographs at natural size.

A. Bioturbated clayey, glauconitic fine-grained sand with phosphatic pebbles. View normal to bedding, Specimen no. BDD 3426, Hunstanton Borehole, 316 ft 2 in., low Mintlyn Beds.

B. Bioturbated clayey, glauconitic fine-grained sand densely cemented in part by phosphatic ironstone; prominent burrow at left is lined with glauconitic clayey sand and filled with clean brown sand. View parallel to bedding, Specimen no. BDC 1049, Marham Borehole, 217 ft 5 in., low Mintlyn Beds.

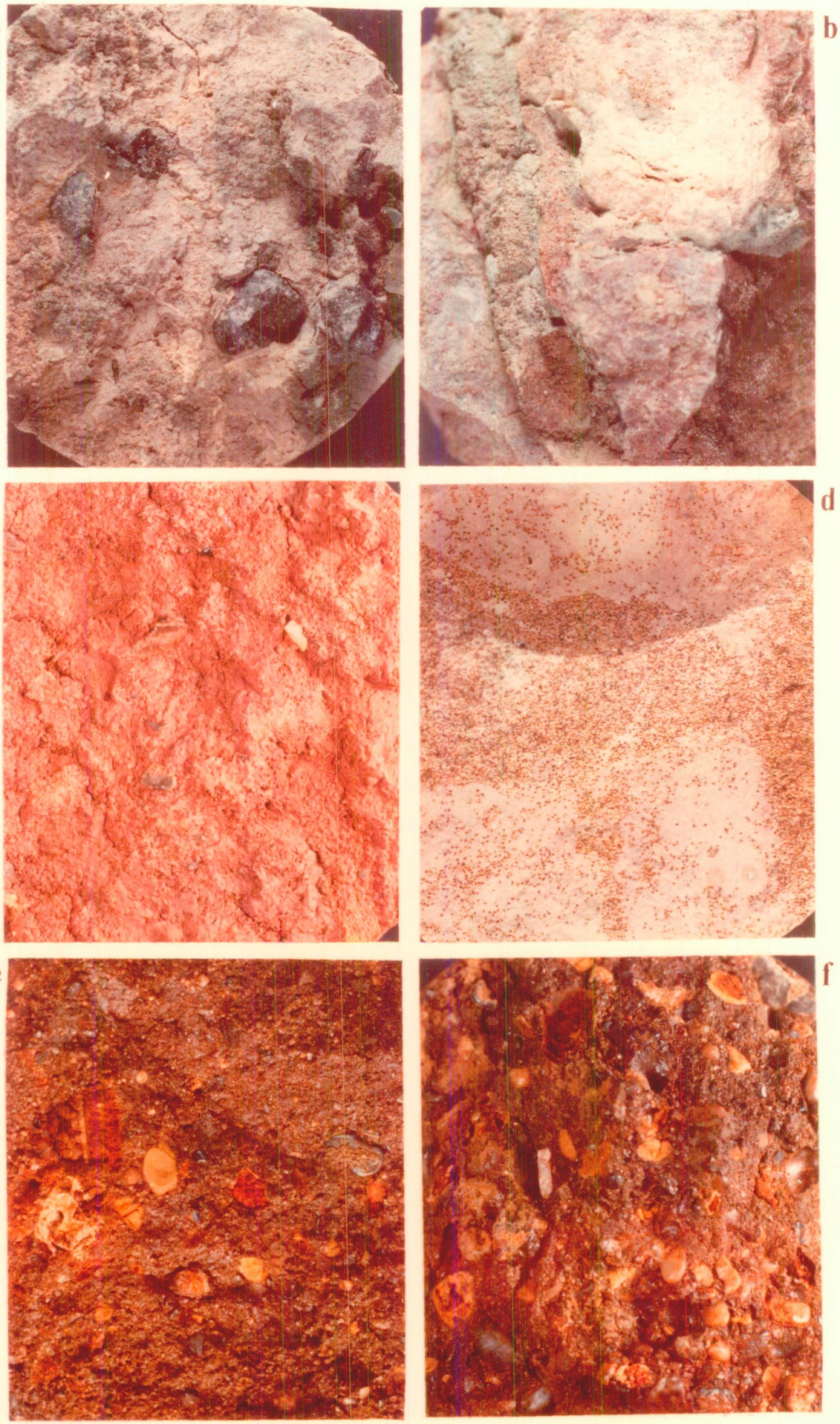
C. Bioturbated sparsely pebbly, faintly sandy, oolitic (limonite) silty clay. View normal to bedding, Specimen no. BDD 2853, Hunstanton Borehole, 176 ft 2 in., high Dersingham Beds.

D. Faintly sandy, silty clay with burrowfill concentrations of limonite ooids and densely cemented by phosphatic ironstone. View normal to bedding, Specimen no. BDD 2758, Hunstanton Borehole, 160 ft 11 in., Roach.

E. Bioturbated, pebbly, intensely oolitic sandstone with limonite/chamosite cement; pebbles dominantly ironstone. View normal to bedding, Specimen no. BDD 2361, Hunstanton Borehole, 69 ft 0 in., Carstone.

F. Bioturbated intensely pebbly, oolitic sandstone with ferruginous cement as E. Pebbles mostly ironstone and vein quartz. View normal to bedding, Specimen no. BDD 2357, Hunstanton Borehole, 67 ft 6 in., Carstone.

Plate 30



- not recorded

Ma .... major, < 10% Mi .... minor, 1 to 10% T .... trace, >1%

Formation	Pebbles		Quartz		Clay minerals (mud)	Ooliths (limonite, chamosite)	Glauconite	Calcite (shells, cements)	Siderite (mudstones, cements)
	Phosphatic	Others	Sand	Silt					
Red Chalk	T	Mi	Mi	-	Mi	T	-	Ma	-
Gault	T	-	T	Mi	Ma	T	T	Ma	T
Carstone	T	Ma	Ma	T	Mi	Ma	T	Mi	Mi
Woburn Sands	T	Mi	Ma	T	Mi	T	Mi	Mi	-
Sutterby Marl	T	-	-	Mi	Ma	-	T	Ma	-
Skegness Clay	-	-	-	Mi	Ma	T	-	Mi	-
Roach	T	Ma	Ma	Mi	Ma	Ma	T	Mi	T
Dersingham Beds in north	T	Mi	Ma	Ma	Ma	Mi	T	Mi	T
Dersingham Beds in south	-	T	Ma	Ma	Mi	Mi	T	Mi	Mi
Leziate Beds	-	-	Ma	Mi	T	T	Mi	-	-
Mintlyn Beds	Mi	T	Ma	Ma	Ma	T	Ma	T	Ma
Runcton Beds	Ma	T	Ma	Ma	Ma	T	Ma	T	-
Roxham Beds	Mi	Mi	Ma	Mi	Mi	T	Mi	Mi	-

Table 19. Qualitative summary of the gross mineralogy of the top Jurassic-Lower Cretaceous rocks of Norfolk.

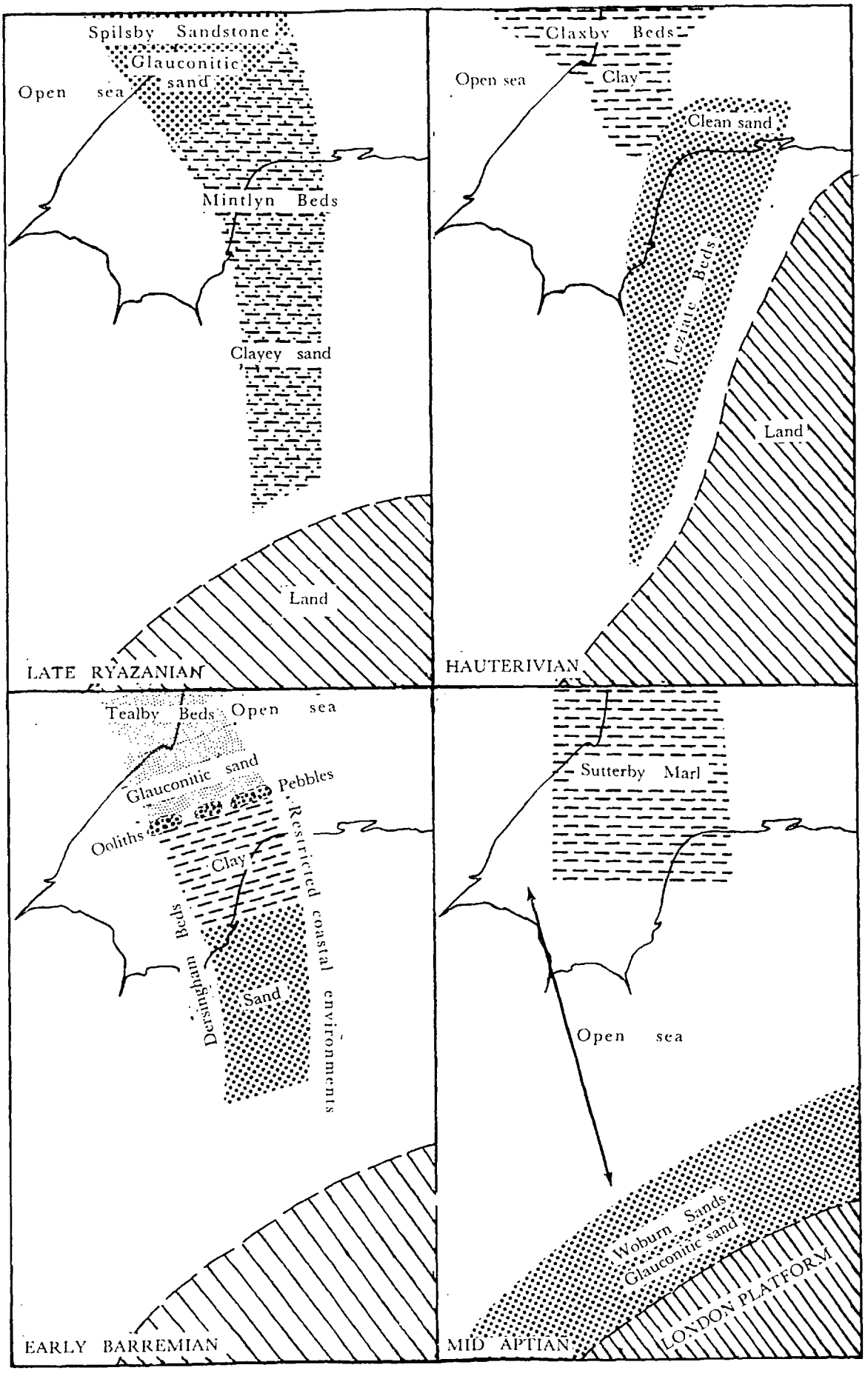


Figure 86. Geographical distribution of lithologies at selected times in the early to mid Cretaceous.

the Woburn Sands (ammonites derived from Oxfordian to Aptian deposits) and Carstone (Prodeshayesites, Cheloniceras and Dufrenoyia derived from the Skegness Clay and Sutterby Marl). The Roxham Beds, Runcton Beds, Skegness Clay and Sutterby Marl have relatively small subcrops and the faunas derived from them into the overlying formations are probably of local origin.

The geographical origin of the Pavlovia faunas in the basal bed of the Roxham Beds is more difficult to determine. Phosphatized casts of body chambers of Pavlovia spp. and casts of Kimmeridgian myid and other bivalves are also abundant in the basal beds of the Speeton Clay (Ryazanian) in North Yorkshire, the Spilsby Sandstone (Volgian) in Humberside and Lincolnshire, and the Portland Beds (Volgian) in Oxfordshire and Wiltshire. Kimmeridge Clay with in situ partially phosphatized Pavlovia Zone faunas is locally present around the edge of the London Platform in Buckinghamshire and Berkshire and, at outcrop, occurs as far south as the Vale of Wardour. Away from the London Platform, the thicker sequences of south Dorset and the Weald contain in situ Pavlovia Zone faunas in aragonitic and calcitic preservation. The abundance of the derived Pavlovia faunas suggests that the youngest part of the Kimmeridge Clay was formerly present everywhere around the edge of the London Platform, but that it may have been a condensed sequence with numerous phosphatized horizons. Large numbers of black Carboniferous cherts ('lydites') that occur with the derived Pavlovia faunas in Norfolk and other eastern counties are thought to have come from outcrops in northern England. The origin of the only other common constituent of the basal Roxham Beds pebble bed, clear and vein quartz, is unknown.

The Dersingham Beds, Roach, Woburn Sands and Carstone contain

large numbers of pebbles that can be lithologically matched with Lower Cretaceous rocks in Lincolnshire and Yorkshire, together with a large proportion of quartz pebbles of indeterminate origin and a few pebbles of presumed far-travelled origin. Pebbles are rare in the more southerly outcrops of the Dersingham Beds except in the pebble bed that marks the base of the Snettisham Clay. This contains pebbles of quartz, quartzite and chert of unknown origin, rotted limestone from the Tealby Beds and phosphatic pebbles thought to have been derived from more northerly outcrops of the Dersingham Beds. The Dersingham Beds at Hunstanton, the Roach and Carstone contain a similar suite of pebbles, but in greater abundance and at many stratigraphical levels. In addition, the Carstone contains abundant pebbles of ironstone and oolitic mudstone that can be matched with lithologies in the Mintlyn Beds, Dersingham Beds and Roach in Norfolk, and with the Claxby Beds, Tealby Beds and Roach in Lincolnshire. In south-west Norfolk the Woburn Sands contain fragments of rotted ironstone that were probably derived from local outcrops of Sandringham Sands.

At Hunstanton, the Leziate Beds contain grains of mudstone and ironstone that appear from their degree of induration to be Jurassic in origin; the nearest probable source is now hidden beneath north-east Norfolk. The Carstone at Hunstanton contains rare fragments of far-travelled material of unknown origin that includes metamorphic and volcanic rocks.

4.7.2.2 Heavy minerals and quartz sand

Rastall (1919) recorded similar suites of heavy minerals in the Leziate Beds at Castle Rising, the Woburn Sands in Cambridgeshire and

the Carstone at Hunstanton. Ingham (1929) subsequently described a similar assemblage from the Spilsby Sandstone of Lincolnshire. The principal heavy minerals in all four formations are kyanite, tourmaline, stauralite, rutile, pyroxene, muscovite, ilmenite, garnet and zircon, with rarer blue amphibole, biotite, hornblende, apatite, anatase, barytes and sillimanite. Many of the commoner grains are fresh, large and angular.

The similarity of the assemblages suggests a common source(s) that was available for erosion throughout much of the late Jurassic to mid Cretaceous interval. Variations occur in the relative abundances of the minerals within and between formations. For example, Rastall (1919) noted that garnet and blue amphibole were abundant in the Sandringham Sands [Leziate Beds], were rare in the Woburn Sands in Cambridgeshire, and very rare in more southerly outcrops of the Woburn Sands. He suggested, therefore, that in the Woburn Sands these minerals were secondarily derived from the Sandringham Sands. However, the possibility that the younger formations have obtained most of their heavy minerals from the older formations can be largely discounted because of the size and freshness of many of the mineral grains at all stratigraphical levels.

The occurrence of large, angular grains of minerals derived from igneous or high-grade metamorphic rocks remains an enigma at all four stratigraphical levels because no suitable nearby source rocks are known that could have either cropped out in the late Jurassic and early Cretaceous or supplied these minerals via a sediment of intermediate age. Rastall drew attention to the abundance in some samples of kyanite, tourmaline, garnet and a bluish-green amphibole (cf. arfvedsonite) and suggested (1919, p. 272) that they were possibly

derived from Scandinavia. Sphene, tourmaline and possible cassiterite were recorded by him as more common in the more south westerly (Bedfordshire) outcrops of the Woburn Sands and he suggested that these minerals might indicate a source area in south-west England. In a subsequent study Rastall (1925) concluded that the petrography of the Woburn Sands suggested derivation from Millstone Grit or Coal Measures rather than from Lower Palaeozoic or Precambrian rocks. Boswell (1927) considered the kyanites to be too fresh to have travelled far and suggested a near-by, but as yet unknown, source.

The nearest, and most obvious places to look for sources of these minerals are the London Platform and the Pennines; neither offers a satisfactory solution. All the pre-Permian rocks proved to date on the London Platform are unmetamorphosed sediments. Igneous and metamorphic rocks occur beneath west Norfolk but these are everywhere overlain by Triassic and Jurassic sediments and could not have cropped out in the late Jurassic or Cretaceous. Parts of the Pennines may have been land during the Cretaceous, but it seems likely that there also the igneous and metamorphic rocks were overlain by Upper Palaeozoic and Mesozoic rocks at that time.

Sources as far distant as Scandinavia can be discounted now that the presence of continuous, thick sequences of predominantly argillaceous marine Lower Cretaceous deposits are known from the intervening North Sea. No Cretaceous rock has survived in the Midlands or Wales, the nearest areas in which igneous and metamorphic rocks crop out at the present day, so the likelihood of suitable source rocks being available there during the Cretaceous cannot be readily assessed. It is interesting to note that large blocks of unweathered igneous and metamorphic rocks occur in the basal bed of the Chalk in the Cambridge

area and that these were believed by Hawkes (1943) to have been derived largely from Wales and the Midlands. The most favourable suggestion still seems to be that the fresher heavy minerals in the Jurassic and Cretaceous were derived from igneous and metamorphic source rocks not far distant from the present day outcrop of the Jurassic and Cretaceous as suggested by Boswell (1927). The recent discoveries of coarse, clastic Carboniferous rocks around the edges of the London Platform in east Norfolk (e.g. Somerton Borehole), Berkshire (Esso Strat. B Borehole) and Oxfordshire (NCB boreholes), has added weight to Rastall's (1925) suggestion that much of the quartz in the sands could have been derived from Carboniferous rocks. These rocks having been rapidly deposited in fresh- or brackish-water environments probably also contain relatively fresh heavy minerals derived from Pre-cambrian and Palaeozoic rocks in the region. The London Platform is likely to have also been fringed by coarse Triassic terrestrial sediments that were available to be eroded in the early Cretaceous. These rest on a variety of igneous and metamorphic rocks elsewhere in the region and contain unweathered fragments of these rocks together with fresh mineral grains derived from them.

Carboniferous and Triassic sands may also have provided much of the quartz in the Sandringham Sands and Dersingham Beds. According to Suttner and Basu (1981) the compositions of newly formed sands, expressed in terms of their quartz, feldspar and rock-fragment contents, are primarily controlled by the parent rock type and weathering pro-cesses, except in shallow marine environments where these compositional differences are destroyed. In a review of ancient sediments, they concluded that almost all relatively pure quartz sands (> 95% quartz) were multicyclic in origin and that first-cycle pure sands were likely

to form only in shallow-marine environments with slow sedimentation rates that receive their sediment from a low-relief area with a tropical, deep-weathering climate. The pure sands of the Leziate Beds probably represent the fastest rate of deposition in the Lower Cretaceous in Norfolk and they are therefore presumed to have been derived from older sands or sandstones.

4.7.2.3 Clay minerals

No systematic detailed study has yet been made of the clay mineralogy of the top Jurassic - Lower Cretaceous rocks of Norfolk. The following note on the major trends, based on XRD analyses of a representative selection of samples from the Hunstanton Borehole, has been provided by Dr C.V. Jeans of Cambridge. "There is a fairly marked change in the composition of the clay-mineral assemblages across the Kimmeridge Clay-Sandringham Sands junction. Kaolinite is more abundant in the Roxham and Runcton beds than in the Kimmeridge Clay and its concentration increases up the sequence until it is the dominant clay mineral in the Leziate Beds, where it may be partly neoformational in origin. The proportion of clay mica decreases up the sequence. Small amounts of vermiculite and larger amounts of irregular mixed-layer minerals including vermiculate/clay mica and clay mica/smectite mixtures occur throughout the Sandringham Sands. Chlorite is absent. Clay mica again becomes the dominant clay mineral in the Dersingham Beds and Roach, with kaolinite and irregular mixed-layer minerals such as clay mica/smectite and clay mica/vermiculite making up most of the rest of the assemblages. Small amounts of vermiculte and, at some levels, chlorite are also present".

The major change in the clay-mineral assemblage with time is the variation in the clay mica/kaolinite ratio. Possible causes of changes

in this ratio have been discussed in Section 2.4.3 with respect to the changes that occur in the Kimmeridge Clay. The presence of high kaolinite concentrations in the Sandringham Sands suggests a nearby terrestrial source. Variations in their kaolinite contents, and between those of the Sandringham Sands and the Dersingham Beds and Roach, are probably related to differing rates of deposition; the most rapidly deposited formation, on the basis of the sedimentological evidence, was the Leziate Beds and this has the highest kaolinite content.

4.7.2.4 Chamosite and siderite

The origin of chamosite and other iron-mineral ooliths has been much discussed. Sorby (1857) suggested that some were formed by the diagenetic replacement of calcareous ooliths, and this hypothesis was greatly extended by Cayeux (1922). However, Hallimond (1925), Taylor (1949) and Knox (1970), working with the same Jurassic ironstones that Sorby had examined, and many others workers worldwide examining oolitic ironstones that range from Precambrian to Tertiary in age, have produced convincing petrological evidence for a primary origin. Despite this, Kimberly (1979) has recently suggested that the replacement theory is universally applicable.

There is no published account of primary ferruginous ooliths forming in a modern environment. Porrenga (1965) has described chamosite forming within the Holocene sediments of the Niger and Orinoco delta cones, and Allen et al. (1979) have recorded scattered concentrically structured ferruginous pelloids forming in marine organic-rich muds at shallow depths on a delta front in Borneo.

Despite the absence of a modern analogue, there is agreement

among most modern authors concerning some of the factors required for the formation of oolitic ironstones. There is general agreement that a warm humid climate is needed to produce the necessary concentrations of iron in the source area and that some mechanism is required to maintain those concentrations in the depositional area. Many oolitic ironstones contain marine fossils or are thinly interbedded with fossiliferous marine strata and there is no satisfactory theory to explain how iron-rich solutions can remain sufficiently concentrated in a marine environment for ooids to form. Huber and Garrels (1953) have suggested that, under favourable conditions, siliciclastic materials can settle in hollows ('clastic traps') on the sea bed and that iron minerals can become concentrated on the intervening rises and form shoals of accreting ferruginous ooliths.

An alternative mechanism was suggested by Brookfield (1971), based on a study of the Kimmeridgian Abbotsbury Ironstone, in which siliciclastic materials and ferruginous ooliths were deposited together and were subsequently separated by differential winnowing by currents. The sedimentological flaws in this argument were pointed out by Knox (1971). Kimberly's (1979) alternative solution is that aragonite ooids were formed in conditions directly analogous to those of the present day Bahama Banks, and that these were subsequently replaced by iron minerals derived from iron-rich pore-water percolating down from an overlying layer of subaerially exposed organic-rich deltaic mud. Bradshaw et al. (1980) have challenged this theory on petrological grounds and drawn attention to the absence of deltaic deposits or evidence for their former existence above the vast majority of oolitic ironstones.

There is also broad agreement concerning the depth of water (no

more than a few tens of metres) and great length of time required to form chamosite ooids and muds. There is less agreement about their significance within rhythmic sequences; Hallam and Bradshaw (1979) and Kimberly (1979) consider them to characteristically mark the late stages of regional regressions, but Knox (1971) thought they more commonly marked the early stages of regional transgressions. Among those in favour of a primary origin, there is some agreement that ooids form in a muddy environment and may then be concentrated in shoals by current action. There are numerous published examples of muddy-oolitic and concentrated-oolitic ironstones; the two described below are lithologically similar to examples in the Lower Cretaceous or Norfolk.

Talbot (1974) described argillaceous oolitic ironstones in the southern English Corallian which he thought had formed from concentrations of iron-bearing colloids in lagoons or quiet marine embayments. The iron minerals were thought to be supplied by rivers draining a deeply-weathered landscape under a tropical or sub-tropical climate. The faunal and sedimentary evidence (mostly bioturbation) suggested aerobic bottom conditions and it was therefore postulated that the colloids had been transformed to chamosite in a reducing environment at some time after burial. This type of ironstone, an intensely bioturbated mud with concentrations of ferruginous ooliths that rarely have detrital cores, is similar to the more oolitic parts of the Dersingham Beds and Roach in Norfolk.

Van Houten and Karasek (1981) have described a sequence of clayey, sandy and pebbly oolitic ironstones, the Devonian Shatti Formation of Libya, whose transgressive nature and bedding and bioturbation features can be closely matched with those of the Carstone of Norfolk. They

concluded that these Devonian ooids formed in low-energy sand-starved environments in very shallow coastal waters with an abundant burrowing fauna, either on mudflats behind a coastal barrier or on an abandoned delta front. The iron minerals were supplied by runoff from a low-relief, deeply-weathered, vegetated source area in a hot, humid climate. A low tide range and little wave action are suggested by the poorly sorted nature of the more argillaceous parts of the sequence. Many of the ooids are thought to have been transported from their place of origin by coastal currents during marine transgressions and were concentrated in cross-bedded bars that were extensively colonised by a deep-burrowing fauna (mostly of Skolithos; op. cit., Fig. 6B). Oolite formation and growth of the bars ceased as the transgression continued and muddy, shallow, marine sedimentation returned to the area.

The origin of sideritic concretions is less problematical than that of chamosite. Most workers agree that siderite forms in relatively well-oxygenated sediments close to the sediment-water interface; in comparable anaerobic sediments pyrite is formed. The bioturbated and permeable nature of the sands that enclose the siderite mudstones in the Mintlyn Beds is in accord with this presumed origin.

4.7.2.5 Glauconite

Glauconite has been described from sediments ranging from Precambrian to Recent in age, but in Britain appears to be common only in the Cambrian, Jurassic, Cretaceous and Tertiary. It is especially abundant in late Jurassic and early Cretaceous marine sands throughout the Boreal province and is very common worldwide in the mid Cretaceous, early Tertiary and Quaternary.

For many years its origin was considered to be more or less proven, following the suggestion by Murray and Renard (1891) who collected samples from modern sediments during the Challenger expeditions, and it was believed to form from the breakdown of biotite and other iron-rich micas in the sea. Galliher (1935) expanded on this theory and considered glauconite to be characteristic of continental shelves adjacent to land masses rich in plutonic and metamorphic rocks. The subsequent recognition of glauconitic muds, grains and peloids and glauconitized hard-grounds in a great variety of marine environments led to the recognition that the mineralogy and origin of so-called 'glauconites' was complex.

In a recent review of modern glauconite occurrences Odin and Matter (1981) have suggested that glauconitized sediments should be called 'glaucony' and that pure mineral grains should be referred to as 'glauconitic smectite' or 'glauconitic mica' depending on their position in the glauconitic mineral family. Other green minerals that can usually only be differentiated by X-ray diffraction in sediments, and which have therefore commonly been mistaken for glauconite, include chlorite and chamosite. All modern glauconites are forming in open marine environments, mostly on the outer edges of continental shelves in water depths of 200 to 300 m. The more evolved glauconites have required 10^5 to 10^6 years to form according to Odin and Matter; for long periods of time in the Pleistocene, when sea levels were 100 to 150 m lower than at present, these grains must have been forming in water 50 m to 200 m deep.

The growth of glauconite grains is governed by the availability of dissolved iron and potassium; they are therefore preferentially formed in areas with low sedimentation rates and subjected to constant

winnowing and sea-bed exposure of the grains. In very shallow, turbulent water glauconite formation is inhibited by the presence of available oxygen. In ancient sediments, transgressions are thought to have commonly produced conditions favourable to glauconite formation in quiet-water conditions that followed the transgression.

Glauconite is abundant at many levels in the top Jurassic-Lower Cretaceous rocks in Norfolk, especially in the condensed sequences close to the Jurassic-Cretaceous boundary and in parts of the Leziate Beds. A variety of forms occurs including glauconitic mud, replacement of shell fragments, opaque impure grains, clear bright green 'pure' grains and grains of composite origin. Many grains have clearly been reworked and include several growth stages. For this reason the radiometric dates of 131.9 and 131.4 m.y. determined by Dodson et al. (1964, p. 148) on glauconites from just below and just above the Jurassic-Cretaceous boundary at West Dereham, should be regarded with caution.

4.7.2.6 Phosphate

The origin of the phosphates that replace fossils and sedimentary features such as burrows in the muds of the Kimmeridge Clay is discussed in Section 2.4.3.3. The best documented analogue of the sandy, glauconitic phosphatic nodule and pebble beds that occur at several levels in the Roxham Beds, Runcton Beds and Mintlyn Beds are extensive areas of phosphatic rocks that crop out on the continental shelf adjacent to the western (Birch, 1979) and southern (Parker, 1975) coasts of South Africa. There, extensive re-working of phosphate-rich rocks during repeated regressive/transgressive rhythms in the Tertiary has produced a complex heterogeneous mixture of authigenic, terrigenous and biogenic components (Birch, 1979). The main period of phosphatisation is believed to have been in the Miocene, although mineralisation

occurred at many other periods in the Tertiary and continued to occur until at least the late Pleistocene (Baturin et al., 1972).

The main source of the phosphate is thought to have been large quantities of zooplankton that fed on nutritious upwelling waters at the shelf edge. Initially a phosphatised pavement was formed by replacement of calcareous mud. This was subsequently broken up during a regressive phase, and pebbles of it and grains of glauconite that had formed during the first phase of phosphatisation, were incorporated in a second-generation phosphatic pavement during the next transgression. The resulting rocks are petrologically very similar to those that occur close to the Jurassic-Cretaceous boundary in Norfolk. Similar rocks are common at this stratigraphical level throughout the Boreal province and Ronov and Khain (1962) have suggested that those on the Russian Platform were formed in response to a change to a more arid climate.

4.7.3 Summary of geological history

After a period of erosion in the late Jurassic, the sea returned to Norfolk in the mid Volgian. The basal bed of the Roxham Beds (Sandringham Sands) rests with marked, but almost planar, unconformity on a wave-cut platform of Kimmeridge Clay. Borehole and seismic evidence from The Wash suggests that the thin limestone bands in the Kimmeridge Clay formed extensive ledges on this platform in much the same way that the 'stone bands' in Dorset give rise to the present day 'Kimmeridge Ledges'. Strata represented elsewhere in southern England by the top part of the Kimmeridge Clay and much of the Portland Beds are absent through erosion or non-deposition in Norfolk. The phosphatised derived fauna in the basal bed of the Roxham Beds suggests that the early part of this interval was represented by condensed deposition.

The coarse pebbly lithology of the basal bed of the Roxham Beds

and its abundant and varied fauna show that it was deposited in a well-aerated, current- or wave-agitated marine environment; the presence of long, vertical Skolithos-type burrows penetrating the underlying Kimmeridge Clay indicate that the water was initially very shallow, possibly intertidal. Water depth increased with time and the basal pebble bed was replaced by intensely bioturbated sands with Ophiomorpha and then by glauconitic and pyritic sands, and highly glauconitic sands with several erosion surfaces marked by phosphatic nodule/pebble beds. The peak of phosphate and glauconite production occurred in the Runcton Beds and lowest Mintlyn Beds in intensely bioturbated and winnowed sands in a current-swept, probably shallow, clear sea.

There is insufficient evidence to comment on lateral lithological variations, and hence on the probable palaeogeography, in the earliest part of the Sandringham Sands. The Roxham Beds show little lithological variation at outcrop or when traced beneath The Wash into Lincolnshire, except that in their most southerly outcrop, in south-west Norfolk, they contain thin bands of highly carbonaceous clay that may indicate the proximity of a fluviatile source.

No precise radiometric date is available for sedimentary sequences in the late Jurassic and early Cretaceous, but there is general agreement that the mid Volgian to early Ryazanian interval lasted about 6 m years (e.g. Lambert, 1971). It is represented in Norfolk by about 12 m of sands (Roxham Beds, Runcton Beds and Lower Mintlyn Beds). There is no direct evidence for palaeotemperatures at that time now that doubt has been thrown on the reliability of oxygen-isotope analyses of calcareous fossils for this purpose. However, the Norfolk sands are contemporaneous with beds elsewhere in southern England that include

shelly limestones with corals (Portland Beds of Wiltshire) and sabkha sequences with evaporites (Purbeck Beds of Dorset and the Weald) that must have formed in sub-tropical or tropical environments.

The current-swept environments in which the condensed sequences of the earliest Cretaceous rocks were deposited in Norfolk were replaced by quieter conditions in which the bulk of the Mintlyn Beds were laid down. Thin undisturbed bands of glauconitic clay indicate quiet conditions at some levels, and cross-lamination picked out by clay wisps or glauconite grains shows that weak currents were present at others. Bioturbation is present at many levels with common vertical and high-angle burrows in the lower part of the formation replaced by low-angle and sub-horizontal burrows in the higher part. The fauna is wholly marine but although the total number of ammonite and bivalve species is high, the diversity at most levels is low. Kelly (1977) concluded from a study of the bivalves of the Roxham Beds, Runcton Beds and Mintlyn Beds and their Lincolnshire correlative - the Spilsby Sandstone, that the faunas were indicative of shallow marine environments and that they formed assemblages that were controlled by the substrates.

The absence of brachiopods, corals, crinoids and echinoids may indicate a lack of suitable substrate; the absence of belemnites, common at the same stratigraphical (in the Speeton Clay) in North Yorkshire, may indicate a restriction of water movement. The presence of almost ubiquitous bioturbation, abundant glauconite and siderite concretions at several levels proves that the upper layers of the sediment were well aerated. Small coarsening-upward rhythms in the upper part of the sequence provide a passage upwards into the Leziate Beds and probably minor transgressions followed by regressions.

The geographical distribution of the Leziate Beds suggests that they were deposited as a linear sand body bounded to the east or south-east by land and to the west and north-west by a shallow sea in which the predominantly muddy sediments of the Claxby Beds were being deposited. The sparse faunal evidence shows that the Leziate Beds are marine and this is confirmed by the sedimentary structures. The local abundance of pyritized mats of woody debris and thin carbonaceous clay seams suggests the proximity of a wooded landscape, or the nearby outfall of a river draining such a landscape, and a relatively rapid rate of sedimentation to allow the organic material to be preserved. A relatively high rate of sedimentation in shallow water is also indicated by the common occurrence of vertical Skolithos and Arenicolites burrows.

The cross-bedding orientations recorded by Schwarzacher (1953) show evidence of tidal currents and the overall pattern (Fig. 87) is consistent with that of a prograding sand body that accreted by shoreward (eastwards) migration of sand under tidally influenced conditions in which the flood tides were stronger than the ebbs. The presence of oscillation ripples with clay drapes in the youngest part of the Leziate Beds may indicate that the sands locally accreted to the point where their upper surface was in the intertidal zone.

The clean, well-sorted nature of the bulk of the Leziate Beds sands suggests that they were derived from quartzitic sediments rather than from igneous or metamorphic rocks. The most likely outcrops of such sediments were Carboniferous and Triassic rocks around the edges of the London Platform; the abundance of grains of soft mudstone and ironstone at Hunstanton and of rotted limestone at Snettisham suggests that outcrops of Jurassic rocks were also being eroded, probably in north-central Norfolk, at that time. A preliminary study of the surface

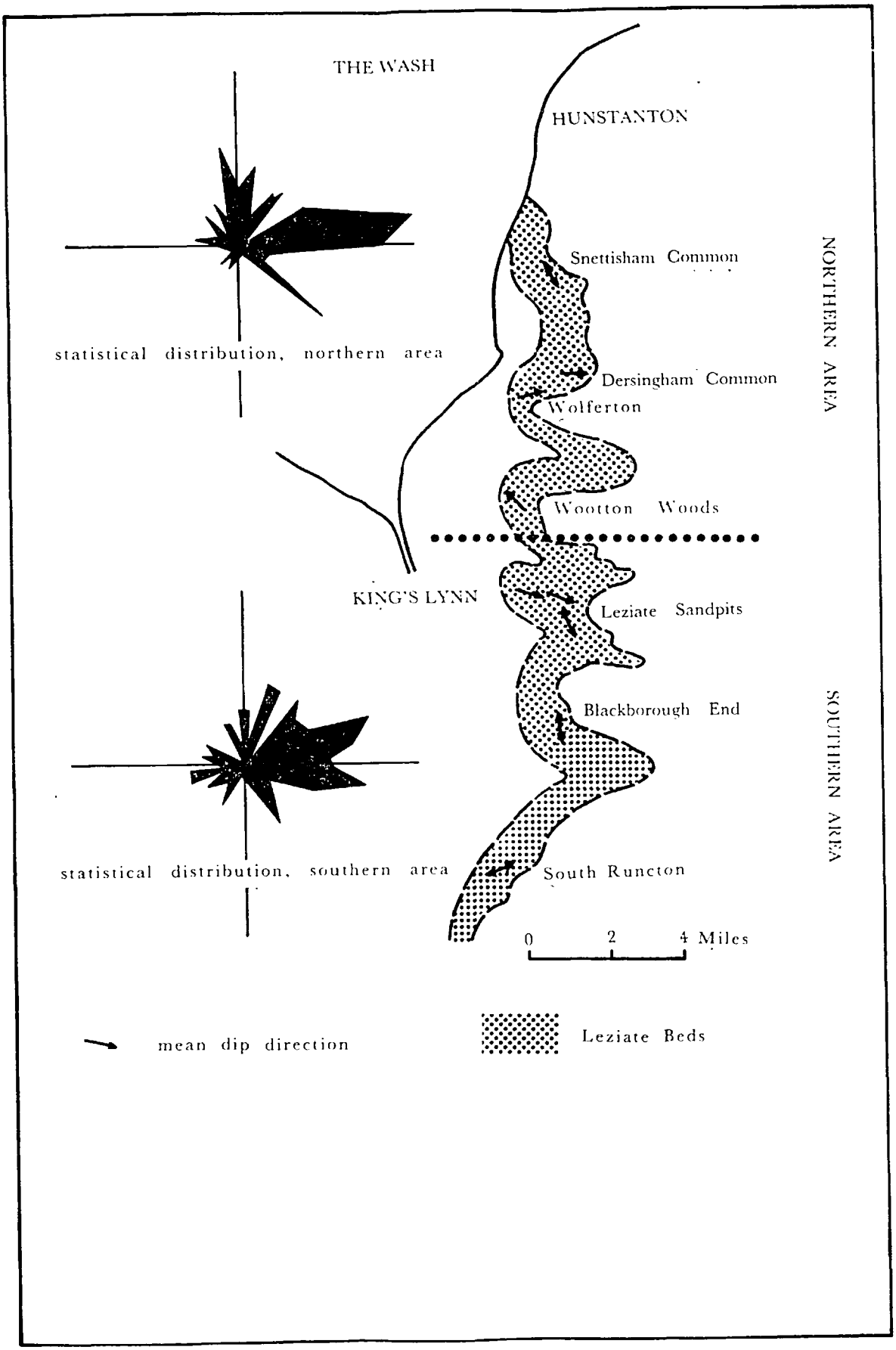


Figure 87. Cross-bedding orientations in the Leziate Beds (after Schwarzacher, 1953).

textures of the quartz grains has shown them to have features indicative of deposition in several environments, together with common secondary precipitation and dissolution features.

The Dersingham Beds overlie the Leziate Beds with sharp lithological contrast and minor unconformity and cut across sedimentary features in the underlying formation. The younger formation is finer-grained than the older at most stratigraphical levels and its basal beds contain a marine fauna that includes bivalves, ammonites, brachiopods and echinoids. The lithological passage from predominantly arenaceous Dersingham Beds in the southerly part of the outcrop to predominantly argillaceous in the north, and into the argillaceous Tealby Beds in the north-west (beneath The Wash and into Lincolnshire) mimics the lithological change in the same direction in the underlying beds (the Leziate Beds passage into the Claxby Beds) except that the change from argillaceous to arenaceous occurs in a more southerly area (Heacham instead of beneath The Wash) in the younger formations. The fauna, lithology and field relationships all suggest that the basal Dersingham Beds were transgressive across the Leziate Beds in an easterly or south-easterly direction.

In Lincolnshire, the Tealby Beds contain a richer and more varied marine fauna than the Dersingham Beds, and do so at many more stratigraphical levels, demonstrating that more open marine conditions were present in Lincolnshire than in Norfolk. In their more southerly outcrops, around King's Lynn, much of the upper part of the Dersingham Beds is lithologically indistinguishable from the Leziate Beds and is presumed to be a regressive sequence. In their most northerly occurrence, at Hunstanton, the Dersingham Beds are made up of predominantly argillaceous rhythms that can be correlated with similar rhythms in the Tealby Beds.

Each rhythm is transgressive with a basal bed of pebbly oolitic shelly clay resting on an erosion surface. The fauna is dominated by small bivalves, but locally includes crinoids, echinoids, serpulids, bryozoa, brachiopods, scaphopods, gastropods, wood fragments and rare ammonites. The sequence becomes finer grained and less shelly with time and each rhythm ends with red or brown clay that contains only pyritized trails and burrow concentrations of small bivalves. The basal parts of the Dersingham Beds rhythms are unusually poorly sorted for a marine sediment. The pebbles and clay minerals must have been transported and deposited by high- and low-energy processes respectively and the sediment subsequently intimately mixed by bioturbation. The abundance of limonite ooliths suggests, by comparison with modern occurrences, slow deposition in a low energy, shallow muddy marine environment. The pebbles were introduced into this environment either by fluviatile floods breaking down riverine or estuarine gravel bars or by storms dispersing beach shingle or offshore gravel bars. The varied and mostly thick-shelled nature of the fauna suggests that much of it was also swept into the depositional area with the gravel. When traced north westwards into Lincolnshire, the pebbly oolitic clays pass into glauconitic sands (at the bases of the Tealby Beds rhythms) indicative of an open marine shelf. The distribution of environments can be best explained by assuming that the pebbly argillaceous Dersingham Beds were deposited in shallow coastal environments that were partially separated from open marine environments in Lincolnshire by discontinuous gravel bars that were, from time to time, broken up by storms that spread their pebble content landward (Fig. 86). To the south east, the pebbly clays passed into near-shore, marine sands.

The red, almost barren clays of the top parts of the rhythms are

common to both the Dersingham Beds and Tealby Beds. No evidence of emergence has been recorded in them and their faunas continued to be marine, but they clearly represent widespread regressive phases caused either by slow progradation or by falls in sea level. Their red colour, and that of parts of the overlying Roach and Red Chalk, has generally been assumed to result from tropical lateritic weathering in the source areas. However, it has been suggested by Kent (1967) that the red muds in the Red Chalk could have been derived from Triassic rocks exposed by salt domes rising in the North Sea, and the same explanation could account for the earlier occurrences. In all three formations, highly oxygenated environments would be necessary for the red colour to be preserved.

One particular rhythm in the Dersingham Beds deserves additional comment. At outcrop in Norfolk the Snettisham Clay rests unconformably on earlier parts of the Dersingham Beds and it appears to be the most extensive of the transgressive rhythms of the argillaceous Dersingham Beds. Between Heacham and Dersingham the Snettisham Clay contains a marine fauna, scattered limonite ooliths and ironstone nodules and is lithologically similar to the deposits described above as having formed in a shallow coastal environment. Southwards from Dersingham the clay changes from predominantly brown and red to grey, is almost barren except for tracks, trails and a few pyritized burrows, and contains sand partings and isolated ripples and small erosional scours infilled with silt or fine-grained sand. Unbroken lamination, picked out by silt and very fine-grained sand, occurs at many levels. The presence of common pyritic concretions, the sedimentary structures and the lack of fauna indicate deposition in a quiet, poorly oxygenated environment.

The geographical distribution of the Snettisham Clay and its correlatives suggest that this may have been a lagoon or tidal flat, possibly with some fluviatile influence.

The Roach overlies the Dersingham Beds and Tealby Beds with minor unconformity, but its lithologies and fauna are so similar to those of the underlying beds that it can be considered to form an unbroken rhythmic sedimentary sequence with them and to have been deposited in the same range of transgressive/regressive environments. In Norfolk, the higher parts of the Roach contain beds of very fine-grained sand and silt and the overall sequence combines features of both the arenaceous and argillaceous parts of the Dersingham Beds. Beneath The Wash and in east Lincolnshire the upper part of the Roach consists of almost barren, intensely bioturbated uniform pebbly oolitic clays that are absent through erosion in Norfolk. They are presumed to have formed in a very shallow coastal marine environment with restricted circulation, similar to that envisaged for the pebbly oolitic clays of the Dersingham Beds.

Beneath The Wash the Roach is conformably overlain by the dark grey sparsely shelly clays of the Skegness Clay. The latter is overlain unconformably by the calcareous clays of the Sutterby Marl with their abundant and varied fauna of ammonites, belemnites, bivalves, brachiopods, echinoids and ostracods and rich coccolith flora that could only have tolerated fully marine conditions. Taken together, the Skegness Clay and Sutterby Marl represent a progressive transgression that replaced the restricted environment of the Roach with a shallow open marine environment, probably with a restricted circulation, and then with an open shelf environment.

The Skegness Clay has no known correlative in Norfolk and is presumed to have been rather limited in its easterly extent. The

Sutterby Marl, however, is probably represented in the south west of the county by the glauconitic sands of the Woburn Sands. There has been much discussion in recent years concerning the depositional environment of these sands which are well exposed in Bedfordshire where they have been extensively worked.

The sedimentological evidence for the source of the Woburn Sands is inconclusive. The cross-bedding at outcrop in the Buckinghamshire to Cambridgeshire area has been studied by Schwarzacher (1953) and Narayan (1963) who respectively concluded that the sand had been transported from the north and the north west. Narayan (1971) interpreted the cross-bedding as that of tidally influenced sandwaves moving parallel to a shoreline that trended north-west to south-east with land on its south western side. This conclusion is at variance with the evidence provided by the field relationships of the Woburn Sands, which appear to be marine, shallow-water and beach deposits banked up against a shoreline of Palaeozoic rocks (the western edge of the London Platform) that trended NE-SW in Bedfordshire and Cambridgeshire.

The problem of interpretation has arisen largely because the nature and mode of movement of the sand bodies that make up the Woburn Sands cannot be clearly demonstrated. They may have been sand-waves aligned at high angles to the coastline, as described by Stride (1963) from parts of the English Channel at the present time, or sand-ridges aligned roughly parallel to the coastline such as those in parts of the southern North Sea (Houbolt, 1968). Until such time as the sedimentological evidence is better understood, the suggestion by Middlemiss (1976) that the Woburn Sands shoreline lay a little south east of a line from Brickhill, Buckinghamshire, to Upware, Cambridgeshire, seems the most satisfactory in terms of the lithological and faunal evidence.

Northwards from Cambridgeshire the original extent of the Woburn Sands is now poorly known due to their overstep by, and incorporation in, the Carstone. Possible patches of Woburn Sands have been recorded in boreholes close to the northern edge of the London Platform in south Norfolk and it is likely that sandy near-shore Aptian deposits fringed the platform. In Cambridgeshire, Suffolk and south-west Norfolk the Woburn Sands rest with marked unconformity on late Jurassic rocks, but in north-west Norfolk and Lincolnshire their lateral equivalent rests with minor unconformity on early Aptian rocks. The London Platform appears therefore to have undergone some rejuvenation in the Aptian, but of a local nature that may have been related to faulting around its margins.

The lithology, fauna, bedding features and an abundance of erosion surfaces with long vertical burrows suggest that the Carstone was deposited in a high-energy marine environment. The formation rests with increasing unconformity on older Cretaceous rocks when traced southwards at outcrop in Norfolk and on Jurassic rocks in its Suffolk subcrop. The Carstone sea appears to have reoccupied a broad area of coastal plain and shallow marine environments in Norfolk that had become emergent during the late Aptian. At its maximum extent the Carstone transgression reached the northern flank of the London Platform in Suffolk.

The lithological and thickness variations in the Carstone at outcrop suggest that it formed an offshore bar composed largely of sand, ooliths and pebbles in the Hunstanton area, with marine glauconitic sands and clayey sands on its southern (Norfolk) side and marine sands on its north-western (Lincolnshire) side. The lateral extent of this bar is unknown, but it was clearly limited or discontinuous because the

deposits on its landward side show no indication of deposition in a restricted environment.

In south Norfolk the Gault overlies the Carstone without any obvious major break in sedimentation. Phosphatisation at the junction suggests a slowing of the depositional rate and this and deeper water is also indicated by the rapid change to argilllaceous sedimentation. The rhythms of the Gault are closely similar with those of the Lower Kimmeridge Clay (Type A of Fig. 5) and both are interpreted here as transgressive. The presence of silt, coarse angular shell debris, phosphatic pebbles and a diverse fauna in the basal beds of the Gault rhythms indicates a well-aerated environment with current winnowing. The higher beds in the rhythms represent quieter environments and deposition in deeper water.

The transgressive nature of the lower part of the Gault can be demonstrated in boreholes in its Norfolk and Suffolk subcrop. In areas adjacent to the London Platform, Bed 1 of the Gault rests conformably on the Carstone; on the edge of the platform beneath north Suffolk,the Four Ashes Borehole [TM 0230 7187] proved Bed 5 resting on 0.4m of pebbly muddy sand with angular fragments of Palaeozoic mudstone that rested on Palaeozoic mudstone. Beneath central Suffolk, the Clare Borehole [TL 7834 4536; Millward, 1980] proved Upper Gault with angular cobbles of Palaeozoic mudstone, resting on a very irregular surface of the same Palaeozoic mudstone.

The depth of the Gault sea in Norfolk cannot be directly determined, but its lateral equivalent, the Red Chalk, provides an important clue because its own conditions of deposition have been demonstrated. Jeans (1973, 1980) described algal stromatoliths in the Red Chalk at Hunstanton and in Lincolnshire and concluded that the upper part of

the formation was deposited in the photic zone. Most modern authors interpret such structures as indicative of deposition in an intertidal or shallow subtidal environment by analogy with modern stromatoliths. Jean's observations have been confirmed in the present work in which algal mats have been recorded in the cores of Red Chalk from the Hunstanton and Trunch boreholes. The statement by Anderton et al., (1979, p. 239) that the main area of Red Chalk deposition coincides with the Market Weighton horst (Axis) is incorrect and their suggestion (Fig. 15.11a) that the Red Chalk might have been deposited in deep water on a seamount surrounded by even deeper water shales with turbidites, is incompatible with the sedimentology and distribution of the Red Chalk, Gault and Carstone in Norfolk.

A reconstruction of the depositional environment immediately prior to the Upper Gault (basal Bed 11) transgression, along a line of section running from north Norfolk to central Suffolk, in which it is suggested that the shallow-water limestones of the Red Chalk pass south into Gault muds and then reach a shoreline of Palaeozoic rocks, is shown in Fig. 88. Within the northern part of East Anglia, the Carstone shoal (in the north) and the London Platform (in the south) appear to have acted as physical barriers to form a shallow marine embayment or strait with an east-west trend in which the Lower Gault was deposited. In the Hunstanton area the Carstone formed an offshore bar. Eastwards from there, there is little borehole data until the Trunch Borehole is reached where an attenuated Red Chalk sequence rests unconformably on Middle Jurassic rocks. In that area, the northern limit of the Gault seems to have been controlled by an island or shoal of upfaulted Jurassic rocks. Within this embayment the Gault fauna is fully marine at all stratigraphical levels and at no time was any restriction of

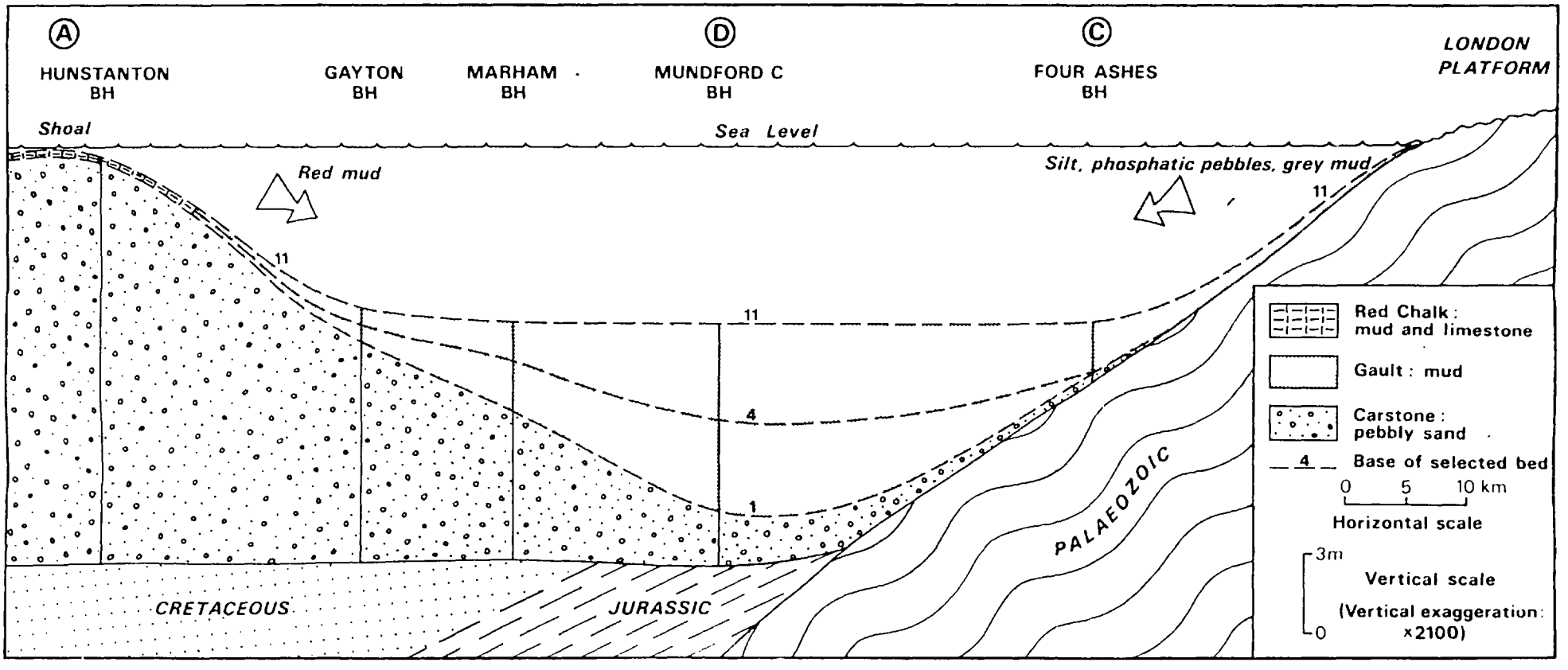


Figure 88. Reconstruction of the presumed depositional environment in the northern part of East Anglia immediately prior to the Upper Albian transgression.

water movement caused by the northern or southern barriers.

The rhythms in both the Gault and the Lower Kimmeridge Clay contain sedimentary and faunal evidence of the repetitive replacement of high-energy (presumed shallow water) by low-energy (presumed deeper water) environments. As with the Kimmeridge Clay, the highest parts of the Gault rhythms are presumed to be regressive and to have been subject to erosion prior to the onset of the succeeding transgressive rhythm. The maximum extent of transgression in the Gault may have been at the onset of the Upper Gault (base of Bed 11) when the London Platform was finally inundated (Fig. 89). The highly calcareous upper part of the Upper Gault, with its fauna restricted almost solely to oysters, appears to represent the last regression before the great Cenomanian transgression that brought pelagic chalk sedimentation to the whole of eastern England.

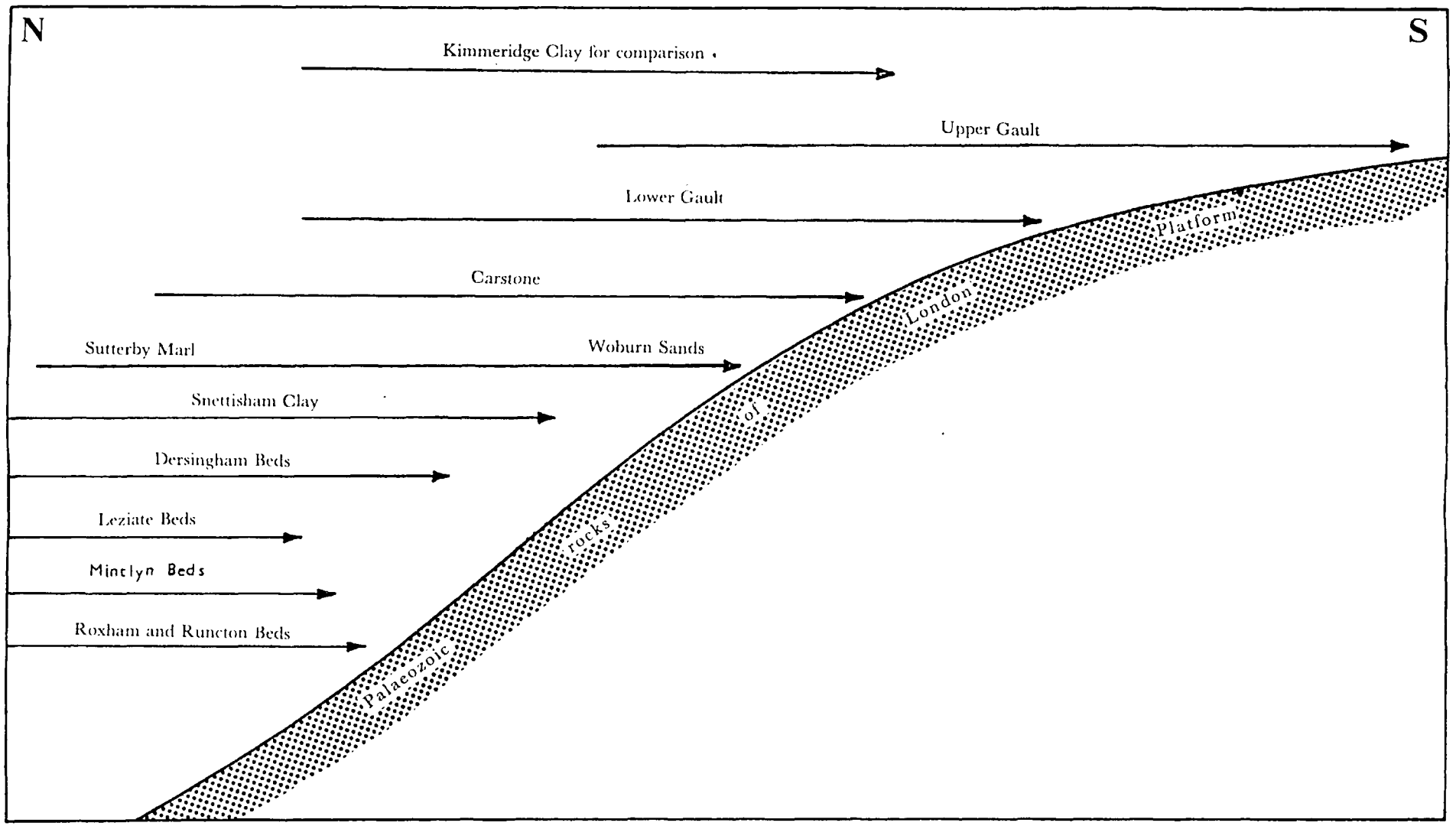


Figure 89. Presumed maximum extensions of the late Jurassic to mid Cretaceous formations onto the northern edge of the London Platform.

CHAPTER 5

CONCLUDING REMARKS

The Upper Jurassic and Lower Cretaceous rocks of Norfolk consist at their maximum of about 250m of predominantly siliciclastic sediments that were deposited over an interval of about 50 million years. The sequence is composed wholly of marine sediments and contains only one major unconformity; it is therefore unusually complete by comparison with marine sequences at this stratigraphical level elsewhere in Britain.

The lithologies range from muds to pebble beds and are indicative of low- to high-energy environments in shallow to very shallow shelf seas. Sedimentation in Norfolk was influenced throughout this period by the nearby presence of the London Platform, and at several stratigraphical levels it was probably controlled by the type and amount of siliciclastic material that could be supplied by Palaeozoic rocks exposed on the platform.

The late Jurassic sequence in England is regressive, but within this overall trend the Kimmeridge Clay contains a complex sequence of transgressive, stillstand and regressive rhythms that probably formed in response to eustatic changes in sea level. Similarly, although the latest Jurassic to mid Cretaceous sequence is predominantly transgressive, it contains transgressive and regressive events.

The change in trend from regression in the late Jurassic to transgression in the early Cretaceous reflects long-term erosion cycles interrupted by widespread tectonic events that caused regional changes in the palaeogeography. In Norfolk, the Kimmeridge Clay ended a long period of predominantly argillaceous sedimentation during which the land areas supplying the sediment became progressively more mature.

Earth movements in the late Jurassic rejuvenated the source areas and, in the case of the London Platform, probably caused large areas of arenaceous Palaeozoic and Triassic rocks to be exposed for the first time since the Triassic. A phase of slow maturation of the source areas followed, punctuated by episodes of rejuvenation in the Aptian and Albian.

Although the transgressive and regressive events in the early Cretaceous gave rise to a repetition of similar environments, long-term changes in the geography of the source areas are reflected in the lithologies. For example, the passage in the Valanginian from the sandy, nearshore Leziate Beds into the clayey restricted marine Claxby Beds and the open marine Speeton Clay is similar to the change in the Hauterivian from the sandy nearshore Dersingham Beds into the clayey restricted marine Dersingham Beds and the open marine Tealby Beds. But, in the Aptian, the nearshore sands of the Woburn Sands and the open marine clays of the Sutterby Marl have no known clayey restricted marine correlative, presumably because the land areas were by that time smaller and the water depths and/or tidal currents between them were too great for restricted muddy sedimentation to develop. In the Albian, the London Platform was so reduced in size and relief that the open marine clays of the Lower Gault formed a muddy shoreline against it without any intervening arenaceous deposit.

A similar situation to that of the Albian had probably existed in the late Jurassic when the Kimmeridge Clay reached the maximum extent of its transgression and its muddy shoreline reached the argillaceous Palaeozoic rocks that form the core of the platform. In the late Jurassic the platform had been rejuvenated by earth movements, but in the mid Cretaceous the transgression continued and the platform was

inundated by the Upper Gault. Thereafter it had little influence on Cretaceous or later sedimentation.

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