STRUCTURE AND FORMATION MECHANISMS OF VEIN-FRACTURE SYSTEMS IN THE NORTH PENNINE OREFIELD

by

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ABSTRACT

The North Pennine orefield in the centre of the Alston Block in northern England, consists of cyclothemic Carboniferous sediments overlying a basement of Lower Palaeozoic metamorphics and granite. Three Pb-Zn-F-Ba vein sets are present in the orefield. The ENE and NNW fractures were initiated as normal faults by shear failure. The ESE fractures post-date the other two sets, and were formed by sinistral strike-slip faulting in the lower parts of the succession. Comparision with model studies show that they were propagated upwards by riedel shearing. The structures produced in each bed or cyclothem unit are related to the physical properties of the rocks. The east-west stresses responsible for the formation of the ESE vein-fractures also caused horizontal movements along the earlier formed ENE and NNW fractures. Statistical analysis shows that the spatial distribution of vein-fractures is related to the larger structures in the Carboniferous and underlying basement.

Mineralization accompanied the horizontal movements and oreshoots on the ESE veins are controlled by changes in strike. The dip of individual ENE and NNW veins vary between different beds in the succession, and are controlled by the mechanical properties of the rocks. The refraction effect, coupled with the initial dip-slip movement on these veins, resulted in the formation of ribbon oreshoots. Joints pre-date the mineralization and have controlled the formation of small veinlets in the harder beds. The joint strikes have been rotated adjacent to the veins, and joint densities increase towards the fractures.

The thesis shows the importance of strike-slip movements in the formation of vein-fractures in the North Pennine orefield. The interpretations of faulting mechanisms has allowed the prediction and assessment of fluorite exploration targets.

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CHAPTER 1 INTRODUCTION

1.1 Geology and topography

The geology of north east England consists of a varied succession of Upper Palaeozoic rocks on the margin of the North Sea Basin. The topography of the region is often spectacularly related to the underlying geology (Hickling et al, 1931). In northern Northumbria, the Cheviot Hills present a bleak landscape of upstanding Devonian granite and lavas. Upper Carboniferous sandstones and shales dominate the low rolling hills of mid-Northumbria and the coalfields of the east. In the south of the region, the tilted plateau of the Alston Block is an area of contrasts; with the high, windswept fell-tops, and the small clusters of dwellings in the sheltered valleys. The climate on the Alston Block is harsh, especially in winter, when the area may be isolated by snow for several days.

1.2 Geological research

The first studies on the geology of north east England commenced at the beginning of the nineteenth century: inspired by the extensive mineral workings in the region. In 1809, Westgarth Forster published his account

on the geological section from Newcastle to Cross Fell, including descriptions of the mineral veins of the Pennines. The Upper Carboniferous strata of the coalfields were identified by Thompson (1814), and Winch (1817). In the mid-nineteenth century, a controversy raged over the nature of the Whin Sill; until its intrusive nature was conclusively proved by Topley and Lebour in 1877. The petrology of the Whin Sill and the other igneous rocks of the region were studied by J.J.H.Teall (1884). At the same time C.T.Clough and W.Gunn were responsible for the Geological Survey's mapping of the Cheviot Hills, and later with Burns, for the mapping of the Alston Block.

Modern palaeontological and sedimentological studies appeared at the beginning of this century in the works of E.J.Garwood, and in more recent times, the papers of G.A.L.Johnson. The mineralization of the northern Pennine orefield was systematically described by Smith in 1923 for the Survey, and later in the many publications of K.C.Dunham. In the last fifteen years there has been a renewed interest in the mineralization of the orefield, partly stimulated by the increase in fluorspar mining activity. Much of this recent work has concentrated on the geochemistry of the ores:- Sawkins (1966), Solomon, Rafter and Dunham (1971), and Smith (1974).

1.3 Aims and methods of research

The aims of the research described in this thesis were:

(i) to give a comprehensive account of the geological structures of the northern Pennine orefield, particulary those associated with the mineralization;

(ii) to interpret the structures of the orefield in the light of modern geological concepts;

(iii) to incorporate the structural interpretations within the tectonic framework of northern England.

The first task in this research was to come to terms with the voluminous literature of the region: it soon became apparent that although the structures of many small areas had been interpretated in detail, previous attempts at describing the structural history of the region as a whole had been unnecessarily cumbersome. Structural data for this research were obtained from published and unpublished sources, and visits to the field. Of the unpublished data, the most useful have been the mine plans produced during the last century by the London Lead and Beaumont Companies. The collection of field data concentrated on two aspects of the structural geology of the orefield: the vein-fractures and the joints. The vein-fractures were recorded by mapping in selected parts of the active fluorspar mines and some of the disused lead-zinc workings. Joints were measured in the mines,

quarries and natural exposures in the orefield.

Analysis of the structures of the orefield was undertaken empirically by comparing the structures with published experimental and theoretical models, and statistically using a computer. Mathematical modelling on the computer was used to simulate the stresses associated with the formation of some of the vein-fractures. The structural interpretations of the orefield derived from these analyses were used in the broader interpretation of the structural history of northern England during the Upper Palaeozoic.

CHAPTER 2 GEOLOGY AND MINERALIZATION OF THE ALSTON BLOCK

The general succession of strata on the Alston Block is shown in figure 2.1

2.1 Lower Palaeozoic

Lower Palaeozoic sediments and minor extrusive igneous rocks form much of the basement of the Alston Block, but are only exposed in the inliers of Cross Fell (NY687344) and Teesdale (NY850300). The early sediments are highly deformed, with tight folds and locally intense cleavage, making correlation difficult.

The Cross Fell inlier consists of a NW trending series of outcrops along the western margin of the Alston Block, between the Inner and Outer Pennine faults. The Ordovician rocks of the inlier range in age from Arenig to Ashgill. All three main divisions of the Lake District sequence are present: Skiddaw, Borrowdale Volcanic and Coniston Limestone groups (Burgess and Holliday, 1979). In the Teesdale inlier only rocks of the Ordovician Skiddaw and Borrowdale Volcanic groups are present. Rocks of the Skiddaw Group are also believed to underlie much of the Carboniferous cover of the Alston Block (Burgess and Holliday, 1979), and have been proved in boreholes at

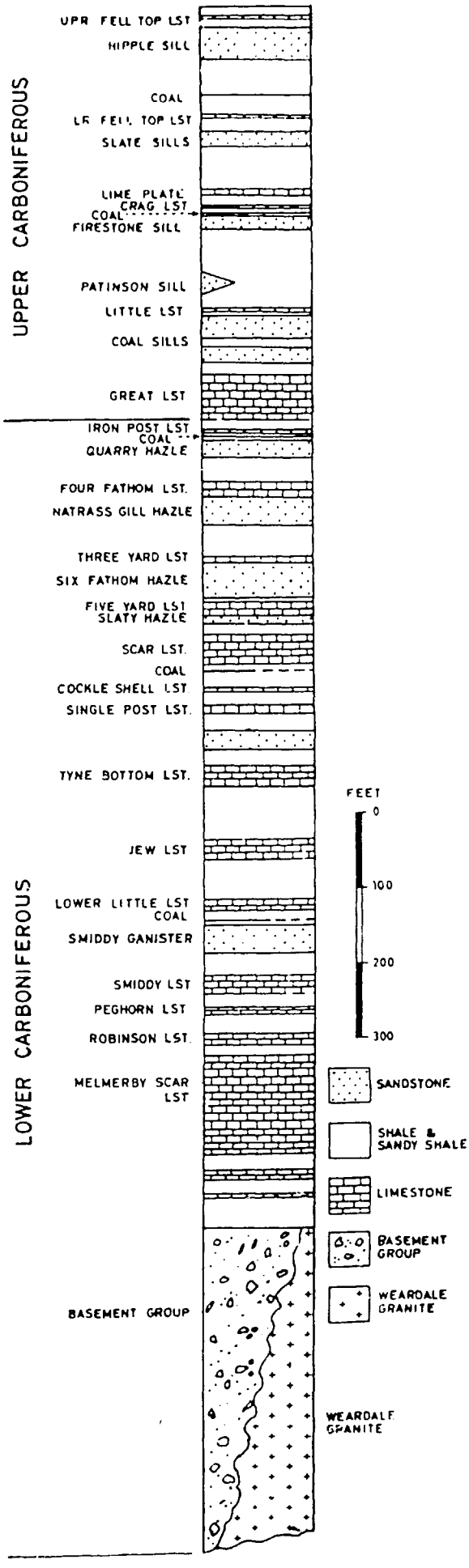


Fig. 2.1 General stratigraphic succession on the Alston Block (from Smith, 1974)

Roddymoor (NZ151363) and Allenheads (NY861453).

2.2 Dinantian

Lower Carboniferous Dinantian sediments crop out along the Lunedale and Pennines fault escarpments, and in the main river valleys; Tyne, Tees and Wear. During the Lower Carboniferous peroid, the Alston Block remained uplifted until the Arundian transgression (George et al, 1976).

2.2.1 Arundian: -Basement Beds and Orton Group

Burgess and Holliday (1979) have subdivided the Arundian sediments into the Basement Beds and the Orton Group (Fig 2.2). These two divisions are equivalent to the Basement Group of Dunham (1948). The Basement Beds are only present at outcrop along the northern edge of the Stainmore Trough and the Pennine escarpment. They consist of conglomerates and sandstones locally split by shale bands, infilling hollows on the pre-Carboniferous surface of the block. They are not present around the Teesdale inlier. South of the Lunedale fault, the succession rapidly thickens into the Stainmore Trough: there are over 250m of basal sediments at Roman Fell (NY755200). This thickening suggests that the southern boundary of the

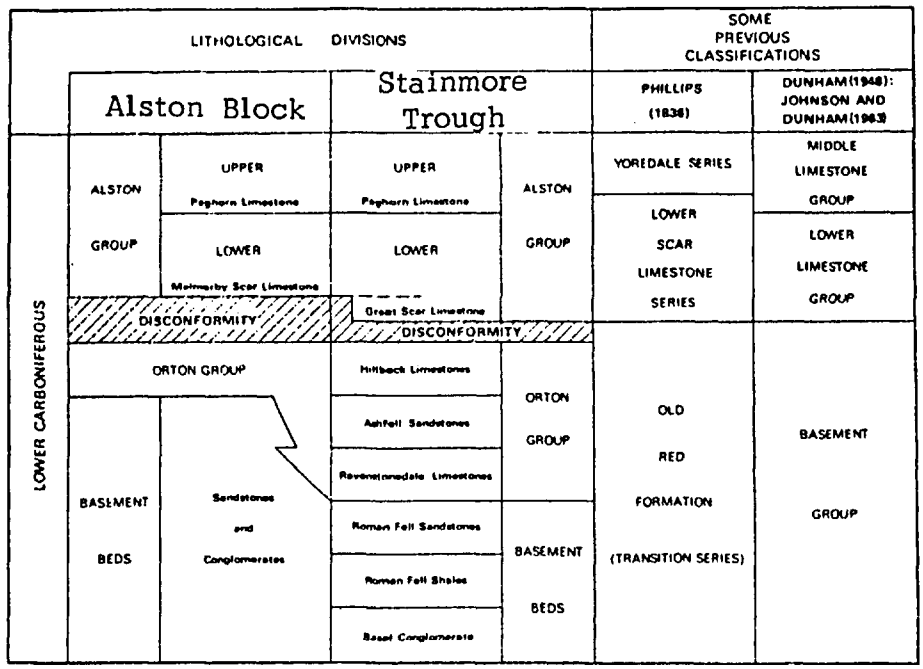


Fig. 2.2 Main subdivisions of the Lower Carboniferous on the Alston Block and in the Stainmore Trough (from Burgess and Holliday, 1979)

Alston Block acted as a contemporary hinge line during Carboniferous times. Sediments of the Orton Group overlie the Basement Beds along the escarpment, and unconformably overlie the Lower Palaeozoic rocks in the Teesdale inlier. As with the Basement Beds, the sediments of the Orton Group thin northwards from the Lunedale Fault, and are no more than 20m thick over most of the block (Burgess and Holliday, 1979). The group consists of alternations of sandstone, marine limestone and shale, which mark the beginning of rhythmic sedimentation which continued throughout the Carboniferous.

2.2.2 Alston Group

The Alston Group spans the Asbian and Brigantian stages; the boundary between which is marked by the base of the Peghorn Limestone. The lower part of the group, below the Peghorn Limestone, is equivalent to the Lower Limestone Group of Dunham (1948). The upper part is equivalent to the Middle Limestone Group.

The base of the Alston Group is a disconformity marked by the erosion and dolomitization of the underlying Orton Group strata. Sediments of the intervening Holkerian stage are absent on the block. The Alston Group consists of rhythmic alternations of limestone, shale, and sandstone, forming cylothem units. A complete cyclothem

comprises of the following lithologies (Hudson, 1924; Johnson and Dunham, 1963):-

	1 Limestone, with sharp base
TOP	7 Transition beds; sandstones and shales
	6 Coal
	5 Seat earth
	4 Sandstone
	b Massive, and/or cross-bedded
	a Flaggy, ripple marked
	3 Siltstones
	2 Mudstones
	c Silty
	b With ironstone nodules
	a Calacerous
BOTTOM	1 Limestone

The thickness and proportion of each lithology varies between cyclothems and certain lithologies may be absent. In the lower part of the group, the limestone (1) often rests directly on the sandstone (4b). Locally the sandstone member infills wash-out channels which may cut across several cyclothem units (Smith, 1974). The total thickness of the Alston Group sediments on the block is about 300m. The major cyclothems average 30m thickness, and can be correlated across most of the Carboniferous of northern England (Ramsbottom, 1973).

2.3 Namurian

Cyclic sedimentation continued during the Namurian, but with increasing emphasis on the regressive end of the cycle (Ramsbottom et al, 1978). Limestones are generally rare, whilst sandstone and coal increase in importance. Thick sandstones locally infill wash-out channels.

2.3.1 Great Limestone

The Great Limestone marks the base of the Namurian. It is the thickest Upper Carboniferous limestone and the most economically important. It is laterally equivalent to the Main Limestone of the Askrigg Block. On the Alston Block the Great Limestone averages a thickness of 18m. It is a blue-grey, fine-grained limestone, with several persistant biostromes (Johnson, 1958). The Frosterly Marble band, near the top of the limestone, is a biostrome composed mainly of the coral Dibunophyllum bipartitum and is limited to the Alston Block. The limestone naturally breaks along bedding planes into 'posts', from one metre to a few centimetres thick (Fairburn, 1978). The upper part of the limestone is shaley (the Tumbler Beds), but may be locally absent. The post below two other shale horizons are known as the High, Middle and Low flats, and have been preferentially replaced during mineralization.

2.3.2 Sandstone wash-outs

Thick sandstone wash-outs occur in the Coal Sills and the Grit Sills. They are best developed to the north of the orefield (Smith, 1974), where they form deltaic patterns, branching southwards (Fig 2.3). In places a wash-out may cut through the whole of the underlying cyclothem. The sandstone filled wash-out channels were important in the control of vein oreshoots.

2.4 Weardale Granite

Geophysical surveys over the Alston Block in the 1950's detected the presence of several negative gravity anomalies. These were interpretated to be due to the effect of a low density body beneath the Carboniferous sediments. This body was speculated to be an acid igneous intrusion (Bott and Masson-Smith, 1953 and 1957). Thermally metamorphosed Lower Palaeozoic slates in the Teesdale inlier provided indirect evidence for a buried intrusion.

A boring at Rookhope (NY935429) in 1961 penetrated granite at a depth of 390m (Dunham et al, 1965). However, the borehole showed that the Carboniferous sediments

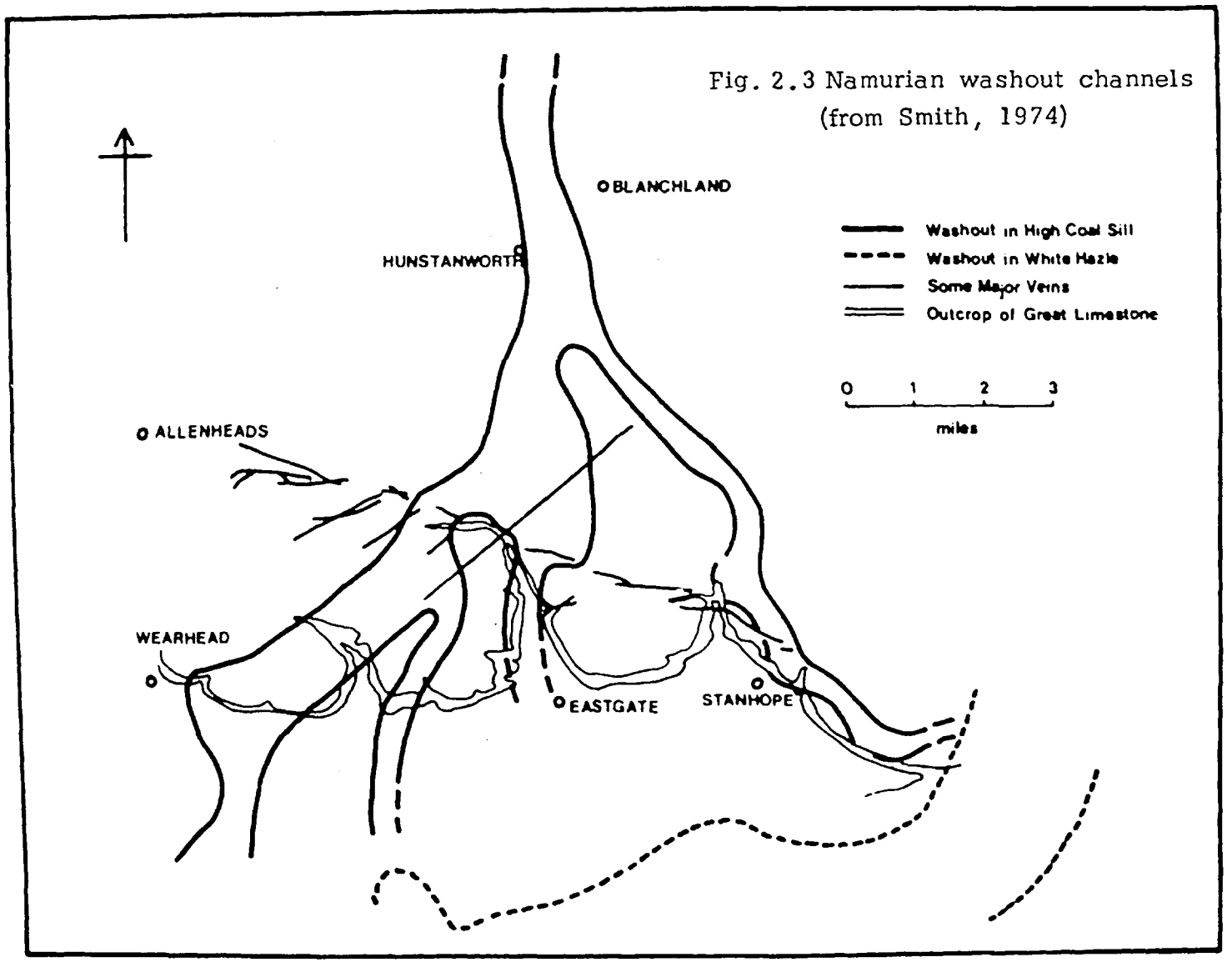


Fig. 2.3 Namurian washout channels (from Smith, 1974)

unconformably overlaid a weathered cap of granite and the granite was therefore pre-Carboniferous. Two radiometric dates on the granites give ages of 410 $\pm$ 10 My and 390 $\pm$ 8 My (Holland, 1980). The gravity lows described by Bott and Masson-Smith (1957) at Rookhope, Tynehead (NY7738), Scordale (NY7825), Cornsay (NZ1544) and Burnopfield (NZ1857) are interpreted to overlie cupolas in the Weardale Granite. Holland and Lambert (1970) note the chemical and isotopic similarities between the Weardale and the Lake District granites. Bott (1974) gives geophysical evidence for a link between these two granites in the form of a ridge beneath the Vale of Eden.

2.5 Whin Sill and related dykes

The Whin Sill is recorded in the earliest geological accounts of this region (Forster, 1809). The name is derived from two lead mining terms Whin, meaning a hard strata and Sill, meaning a persistent bed within the stratigraphic sequence. When the igneous nature of the rock became apparent, it was first suggested to have formed as a contemporary lava; a view held by many geologists until the late 1870's (Phillips, 1836 and Bewick, 1869). The intrusive nature of the sill was conclusively proved by Topley and Lebour (1877).

The whin is present throughout the area of the

northern Pennine orefield, but it is mainly exposed along the margins of the Alston Block and outcrops in the valley of the River Tees. Minor outcrops occur along the line of the Great Sulphur Vein (NY700385 and NY760372), and at Copt Hill (NY850408). Several mine workings and boreholes have penetrated the Whin Sill within the orefield and in the Durham coalfield to the east. To the north of the Alston Block, the sill crops out in an arcuate trend from the Roman Wall at NY600610 to the coast at Dunstanburgh (NU259222), and then turns northwards offshore to re-appear at Bamburgh at NU185350 (Randall, 1980). In this northern area several sills are often present vertically above each other (Carruthers et al, 1927). On the Alston Block only one sill is generally present; except at Greenfoot Quarry, Weardale (NY970385) and in the Rookhope borehole, where the Little Whin Sill has been proved about 120m above the main sill.

A cogenetic suite of dykes are associated with the intrusion of the Whin Sill (Fig 2.4), and occur in four main groups (Holmes and Harwood, 1928). The dykes occur both above and below the stratigraphic horizon of the Whin Sill to the north of the Alston Block. Within the orefield, whin dykes are rare: a dyke is intrude along a section of the Closehouse-Lunedale Fault, near Closehouse Mine (Hill and Dunham, 1968), but this is probably a westerly extension of the Hett dyke system. Other minor dykes occur within the orefield at Low Gill near Hartside Mine (NY642429), along the Stublick fault zone (NY900600)

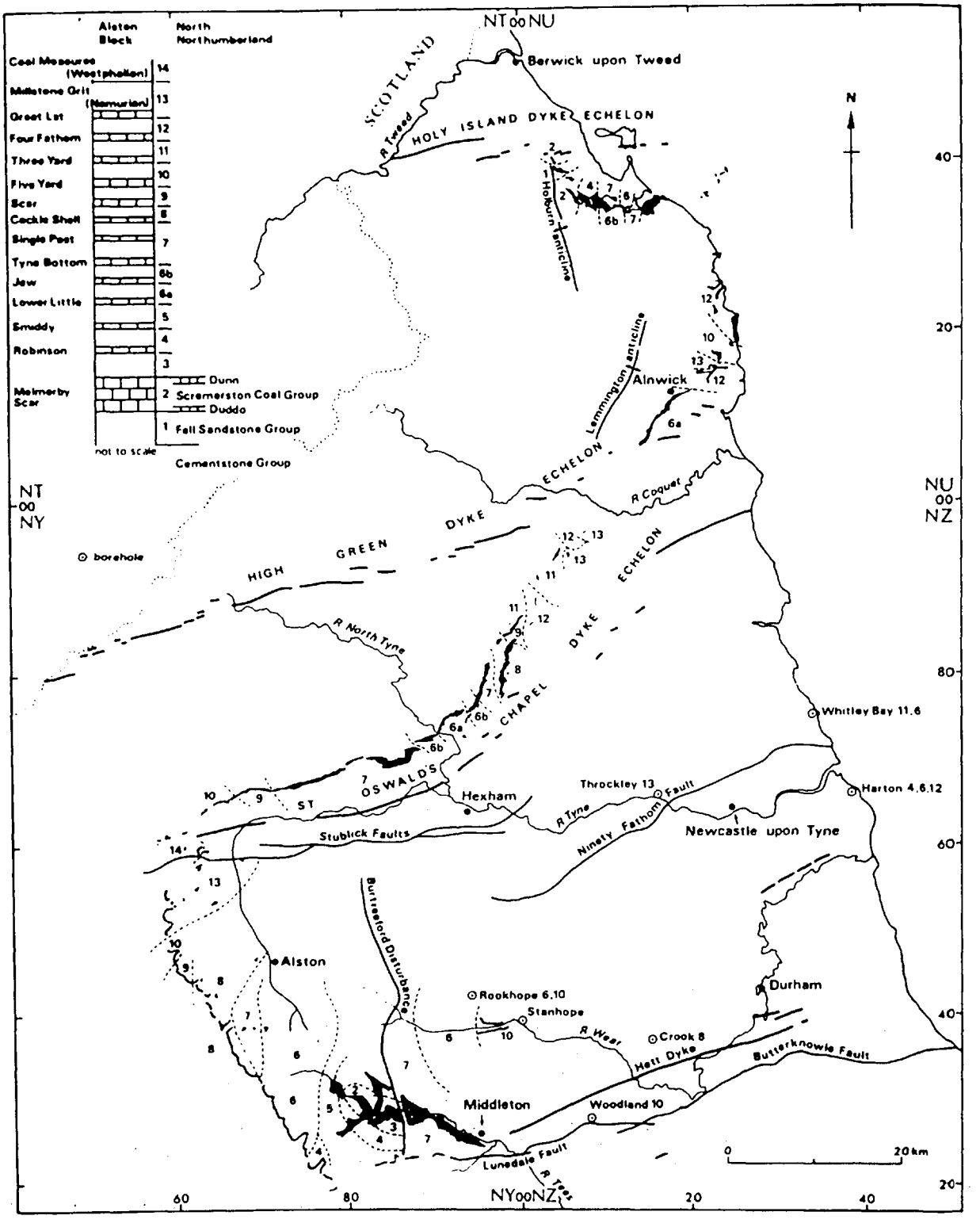


Fig. 2.4 Location of Whin dykes and horizon of the Whin Sill (from Randall, 1980)

and near Bradon (NZ180420).

2.5.1 Metamorphism adjacent to the whin

The rocks above and below the sill have been metamorphosed upto 30m away from the contact. Limestones are commonly re-crystallized and sandstones hardened. Shales show the most visible effects of metamorphism, and many have been converted into spotted hornfels. The bedding in some of the shales has been completely obliterated, and the resulting creamy-white rock is known locally as 'whetstone' (Dunham, 1948). Coals show marked effects of heating; natural coke has often formed where the coals are in contact with the whin (Edwards and Tomlinson, 1958). Trotter (1954) and Creaney (1977 and 1980), have described changes in coal rank and petrology over the Alston Block, which can be attributed to heating by the Whin Sill.

2.5.2 Thickness and horizon of the Whin Sill

The Whin Sill varies in thickness throughout northern England. The greatest known thickness is in the Gin Shaft at Burtree Pasture Mine (NY860417); here the sill is 73m thick (Dunham, 1948). The sill appears to thin away from the line of the Burtreeford disturbance; it is 57m thick

in the Roddymoor borehole, and only 38m thick in the Throckley borehole (NZ160676).

The sill is not intruded at the same stratigraphic horizon throughout the region, but transgresses abruptly to lower or higher levels. Dunham (1948) showed that the Whin Sill is at the lowest stratigraphic horizon in the neighbourhood of the Burtreeford disturbance in Teesdale, where it is intruded below the Melmerby Scar Limestone (Fig 2.4). Away from the Burtreeford disturbance, the sill generally transgresses upto higher stratigraphic levels. One of these transgressions has been observed in Blackdene Mine (NY880397), where the sill jumps suddenly along a vertical plane to a higher horizon (Greenwood and Smith, 1977). Some transgressions may be associated with faulting (Dunham, 1948).

2.5.3 Source and intrusion of the whin magma

The mechanism of intrusion of the Whin Sill and dykes, and the stress regime at this time is dealt with more fully in section 8.1; only the work of previous researchers is given here. The Whin Sill intrudes the Coal Measures, but not Permian rocks, and is affected by mineralization. Fragments of the whin have been discovered in the Upper Brockram (Holmes and Harwood, 1928; Dunham, 1932). The sill appears to have been emplaced during the

time of the unconformity between the Upper Carboniferous and the Permian (Randall, 1980). Potassium-Argon dating by Fitch and Miller (1967) indicate an age of 295 My.

The origin of the whin magma has been discussed by Russell and Smith (1979), who speculate that it was the product of rifting in the North Sea basin. They suggest that the rifting was accompanied by partial melting of the upper asthenoshere to form an alkali-basalt magma, which spread eastwards and rose as diapirs beneath the northern Pennines.

2.6 Tertiary dykes

The WNW-ESE striking Tertiary dykes in northern England are part of the dyke-swarm radiating from the Tertiary igneous centre of Mull. The most northerly dyke passes along a line between Hawick (NT505154) and Acklington. Around Morpeth and Blyth, there is a belt of several small dykes. The Cleveland Dyke crops out in the southern part of the northern Pennine orefield, and is exposed at several localities from Tynehead, through Teesdale to the Cleveland Hills.

2.7 Mineral deposits

In the Middle Ages, mining in the northern Pennine orefield was limited to surface workings, and small underground bell pits. Much of the lead produced during this period furbished the building of the great abbeys and monasteries (Wallace, 1890).

A rapid expansion of the lead mining industry occurred in the eighteenth century under the leadership of two main companies. In Weardale and Allendale, the family concern of the Beaumonts worked extensively; until handing over their Weardale leases to the Weardale Lead Company in 1884, and the Allendale leases to the same company in 1924. On Alston Moor, the London Lead Company started mining in the 1730's and continued until 1882. The Alston Moor leases passed to the Vieille Montagne Company, who concentrated on the production of zinc. Since 1949 there has been little production of lead or zinc ore. Some metallic sulphides have been derived as a by-product of fluorspar and barytes mining, which still continues today.

Two types of orebodies occur in the northern Pennine orefield; vein-fracture infillings and flats. Flats are stratiform mineralization which occur adjacent to vein-fractures, mainly in the limestones.

2.7.1 Vein textures

The veins typically exhibit a banded texture, parallel to the vein walls. According to Dunham (1948), the bands normally consist of pure, or nearly pure minerals, with crystal faces developed on the side of the band nearest the centre of the vein. Bands of gangue material are normally continuous, but sulphide bands may consist of a broken chain of lenses. Many of the bands show evidence of shearing between them, whilst others may include brecciated fragments of earlier bands. These features are suggestive of repetitive mineralization and movement along the veins.

Inclusions of wall rocks are commonly present in the veins. These fragments are often sharp edged, with adjacent fragments showing matching outlines. They are probably the result of brecciation of the wall rocks by the method of hydraulic fracturing as described by Phillips (1972).

2.7.2 Flats

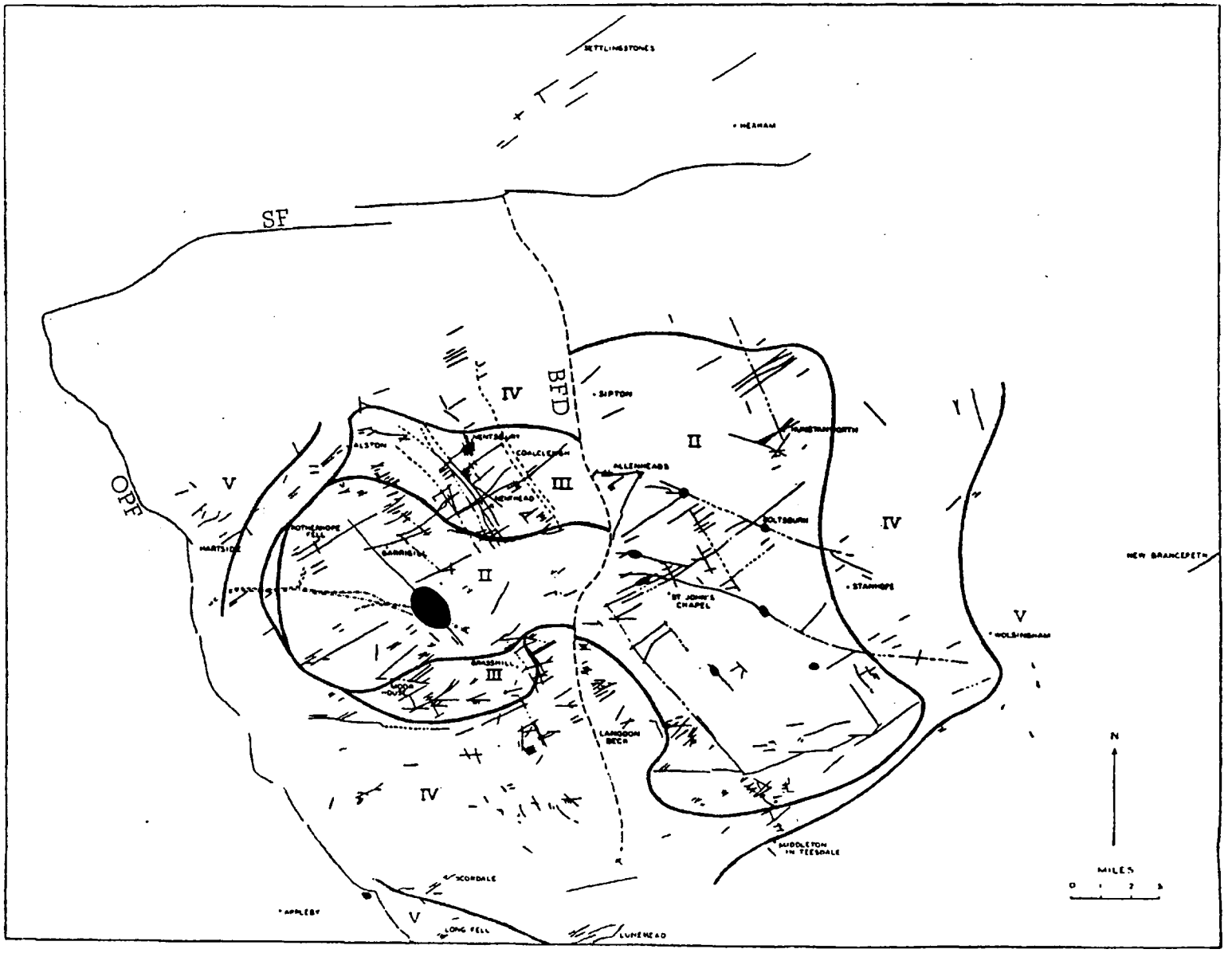
Economic flat mineralization is confined to the limestones in the orefield; principally the Great

Limestone. Dunham (1948), noted that (i) flats are found only in association with veins accompanied by numerous diverging or sub-parallel leaders, or in the neighbourhood of vein intersections; (ii) some flats were formed in places where vein oreshoots were restricted. Galena and sphalerite, with quartz-ankerite gangue, are the main minerals present in the flats of the Great Limestone. Flats in the Tynebottom Limestone at Tynebottom Mine (NY738419) contain nickel and cobalt sulphides (Vaughan and Ixer, 1980).

Flats in the Great Limestone are generally confined to three beds or posts, the High, Middle and Low flats. Dunham (1948), noted no microscopic differences between the limestones at the flat horizons and the surrounding rock. He did observe that thin shale bands overlie each flat. It seems unlikely, however, that a 5-10cm shale band would be thick enough to pond the ascending hydrothermal fluids into forming flats. Smith (1974), drew attention to the fact that flats in the Great Limestone at Boltsburn Mine (NY938429) only occur where a thick shale overlies the Great Limestone. Where sandstone occurs above the Great Limestone, there are no flats.

2.7.3 Zonation of primary minerals

A zonation of primary minerals in the orefield was

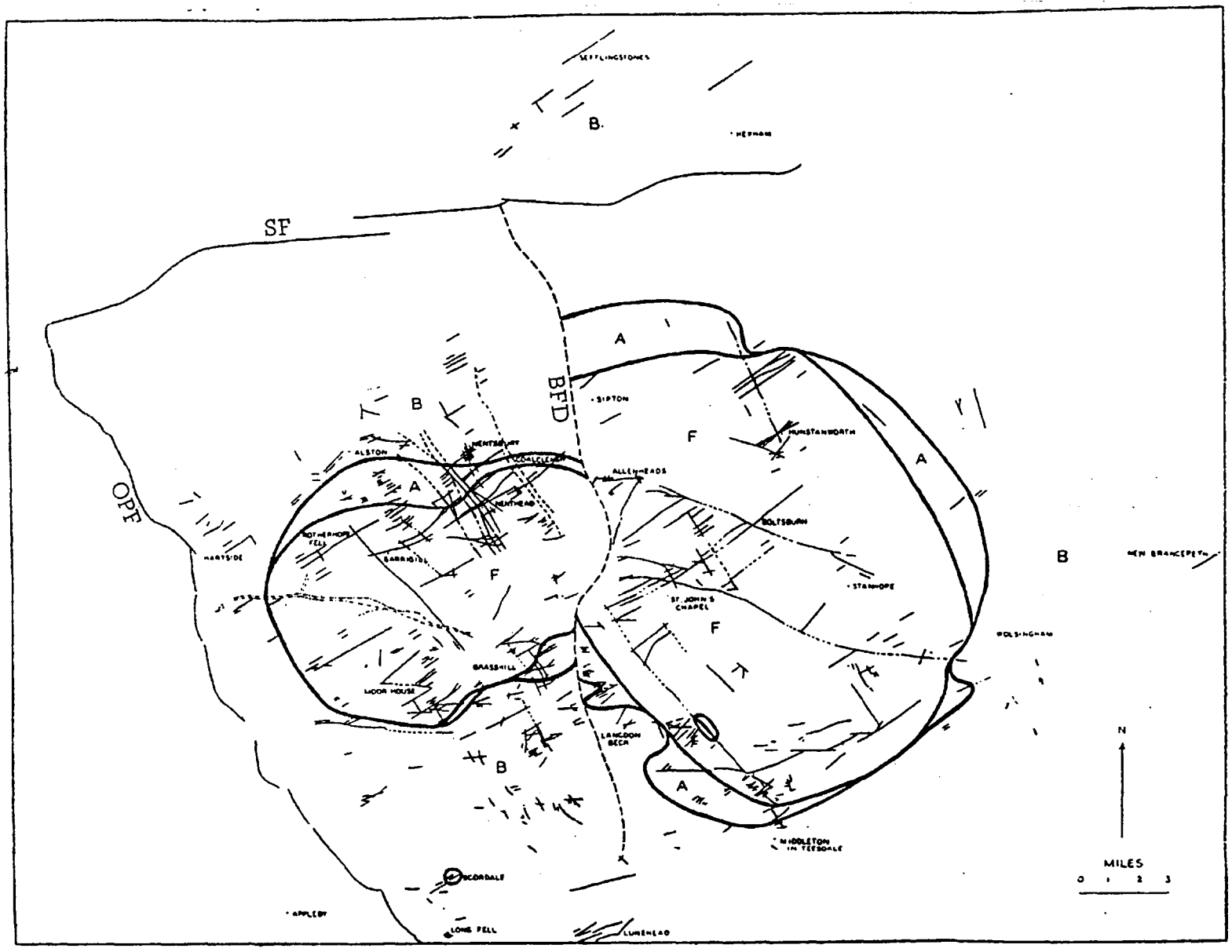


O.P.F. = Outer Pennine fault-system.
S.F. = Stublick fault-system.
B.F.D. = Burtreeford monocline.

Zone I. (Solid black.) Chalcopyrite, with subordinate galena and sphalerite.
" II. Galena with subordinate sphalerite.
" III. Galena-sphalerite.
" IV. Galena.
" V. Sulphides absent.

Pennine type veins, thin black lines.
Great Sulphur Vein type veins, dotted lines.
Zonal boundaries, heavy black lines.

Fig. 2.5 Sulphide mineral zones (from Dunham, 1934)



O.P.F. = Outer Pennine fault-system.
S.F. = Stublick fault-system.
B.F.D. = Burtreeford monocline.

Pennine type Veins, thin black lines.
Great Sulphur Vein type veins, dotted lines.
Zonal boundaries, heavy black lines.

Zone F = Fluorspar.
" A = Fluorspar and barytes, or neither mineral.
" B = Barium minerals.

Fig.2.6 Gangue mineral zones (from Dunham, 1934)

hinted at by Forster (1809) and Smith (1923). Dunham (1934) recorded five main concentric zones of sulphide mineralization (Fig 2.5), and two main zones of gangue mineralization (Fig 2.6). There may be a third inner zone of quartz gangue mineralization centred on the eastern end of the Great Sulphur Vein (roughly corresponding to the sulphide zone 1 in this area). This quartz gangue zone may also be represented by the early phase silicification seen at depth in other quarter-point veins.

The mineral zonation appears to be centred above cupolas of the underlying Weardale Granite (Bott, 1967). Although the granite is older than the overlying sediments, Solomon et al (1971), have suggested that fractures in the granite cupolas provided channel ways for uprising hydrothermal fluids.

2.7.4 Geochemistry and ore genesis

Fluid inclusion studies have shown that the ore-forming solutions were saline brines, with freezing-point equivalents of 21-23wt% NaCl (Sawkins, 1966, and Smith, 1974). Pressure corrected homogenization temperatures for primary fluid inclusions range from 124^{o}C to 219^{o}C. Trace element studies, together with fluid inclusion data have been used to locate feeder channels for fluorite mineralization (Phillips and Smith, 1974, and

Smith, 1974).

Sulphur isotope studies have shown that $d^{34}S$ ranges from $+15.0^{o}/_{oo}$ to $-5.9^{o}/_{oo}$, with a general decrease from the centre of the fluorite zone outwards (Solomon, et al, 1971). This range of $d^{34}S$ values is not characteristic of magmatic sulphur. A model for the genesis of the northern Pennine orefield has been suggested by Solomon et al (1971), in which circulation cells of chloride brines leached metallic ions from the Lower Palaeozoic sediments and/or the Weardale Granite. These brines were warmed by the residual heat from the granite, and rose along structural channels within the granite. On reaching the Carboniferous sediments the metal rich chloride brines mixed with connate Carboniferous sulphate brines, and the ore minerals were precipitated.

2.7.5 Wall rock alteration

The earliest effect of the mineralizing solutions upon the limestone wall rocks was the conversion of the limestone into an ankerite-rock, with variable amounts of chalybite and chalcedony. Dunham (1948) notes that ankeritized limestones are generally unfavourable to replacement by later phases of sulphide minerals. Replacement was often accompanied by a volume decrease resulting in the collapse and brecciation of the replaced

limestones. Replacement deposits of fluorite are generally small and uneconomic.

Alteration of the dark quartz-dolerite of the whin, adjacent to the veins, has resulted in the rock turning nearly white in colour (the White Whin). Metasomatism of sandstones adjacent to veins is rare in the area, a more common occurrence is the recrystallization of quartz in sandstone wall rocks. The silicification of shales at depth along the quarter-point veins and the eastern part of the Great Sulphur Vein can be regarded as an early stage of wall rock alteration.

CHAPTER 3 INTRODUCTION TO STRUCTURES OF THE NORTHERN PENNINE OREFIELD

3.1 Faulting

3.1.1 Boundary Faults

The northern, western and southern margins of the Alston Block are bound by major fault structures, now downthrowing away from the block (Fig 3.1). The Stublick Fault forms the northern margin of the Alston Block, and across this fault the Lower Carboniferous succession thickens from 450m on the block to 2,450m in the Northumberland Trough (Bott, 1967). It appears to have acted as a hinge line during Carboniferous sedimentation (Dunham, 1948). The sediments across the Ninety Fathom Fault in the Northumberland Coalfield also appear to thicken to the north, based on geophysical evidence (Bott, 1961). The evidence suggests that the Ninety Fathom Fault is the eastern continuation of the belt of Carboniferous thickening associated with the Stublick Fault. The Stublick-Ninety Fathom fault line thus separates the shallow basement of the Alston Block from the deeper basement of the Northumberland Trough (Bott, 1967).

The Swindale Beck-Lunedale faults comprise the

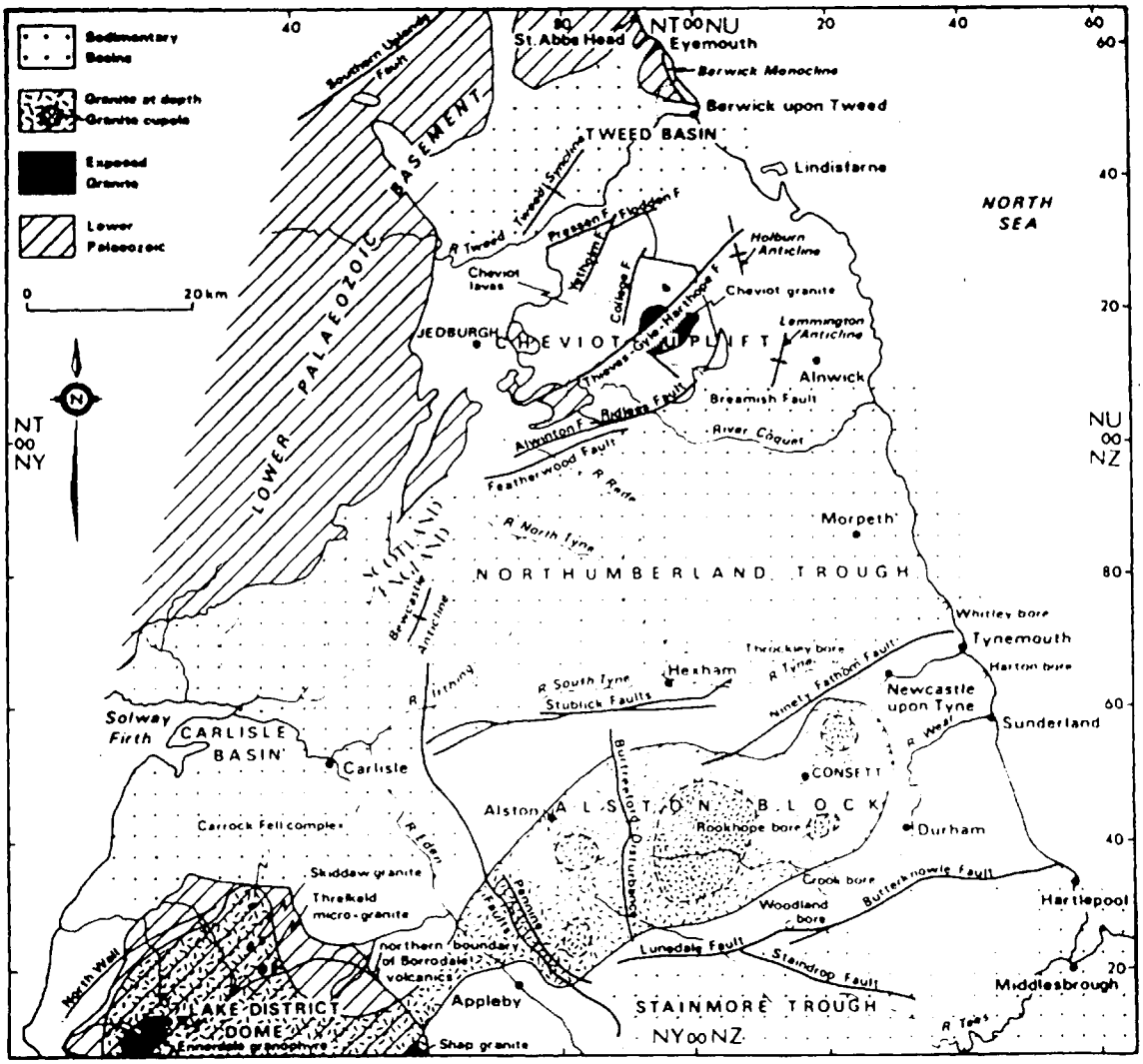


Fig. 3.1 Uplifted and basinal areas during the Carboniferous, and the major structures of northern England (from Johnson, 1980)

southern boundary to the Alston Block. To the south of this fault line is the Stainmore Trough, which divides the Alston and Askrigg blocks. Sections of the Lunedale Fault, near Closehouse Mine (NY842227) are intruded by the whin dykes. Bott (1961) calculates that there is a thickening of 3,050m in the Carboniferous sediments southwards across the fault line, which also acted as a contemporary hinge line during Carboniferous sedimentation. The southern margin of the Alston Block extends eastwards along the en-echelon ENE Sharnberry-Butterknowle fault.

The Alston Block appears to have been depressed along its northern and southern margins prior to the intrusion of the Whin Sill. There is a downward change in the horizon of the Whin northwards across the Stublick Fault, indicating that the down-throw along the fault was to the south at the time of the intrusion (Dunham, 1948). On the northern (block) side of the Lunedale Fault at Closehouse Mine, the strata dip steeply northwards. This suggested to Dunham (1948) that the original downthrow on the fault was to the north; an alternative explanation is that the dip of the strata is due to a north facing monocline.

The western margin of the Alston Block is defined by the Pennine Fault system. Shotton (1935) recognized three groups of faults in this system: (i) the NNW Inner Pennine Fault, downthrowing to the east; (ii) ENE thrust faults; (iii) The NNW Outer Pennine Fault, downthrowing several

thousand feet to the west into the Vale of Eden. Dunham (1948) assigned the first two groups to the Hercynian and the later to the Tertiary. A geophysical interpretation across the Vale of Eden led Bott (1974) to suggest that the region between Penrith and Appleby was underlain by a granite ridge linking the Lake District and Weardale granites. The northern section of the Pennine Fault system did not constitute an active hinge line during Carboniferous sedimentation; typical Carboniferous block facies sediments occur beneath the Vale of Eden (Mitchell et al, 1978).

Bott further proposed that the Hercynian movements produced a faulted monocline (Fig 3.2). This interpretation reconciled the downthrow of the Alston Block along the Inner Pennine Fault, with the occurrence of pebbles of Whin Sill in the Permian Upper Brockram of the Vale of Eden. The upturn of the beds on the Alston Block towards the Pennine faults suggests that an overfold or anticline formed at this time, rather than a true monocline: Arthurton and Wadge (1981) have independently drawn a similar conclusion. The present western downthrow along the Outer Pennine Fault is ascribed to the Tertiary by Bott.

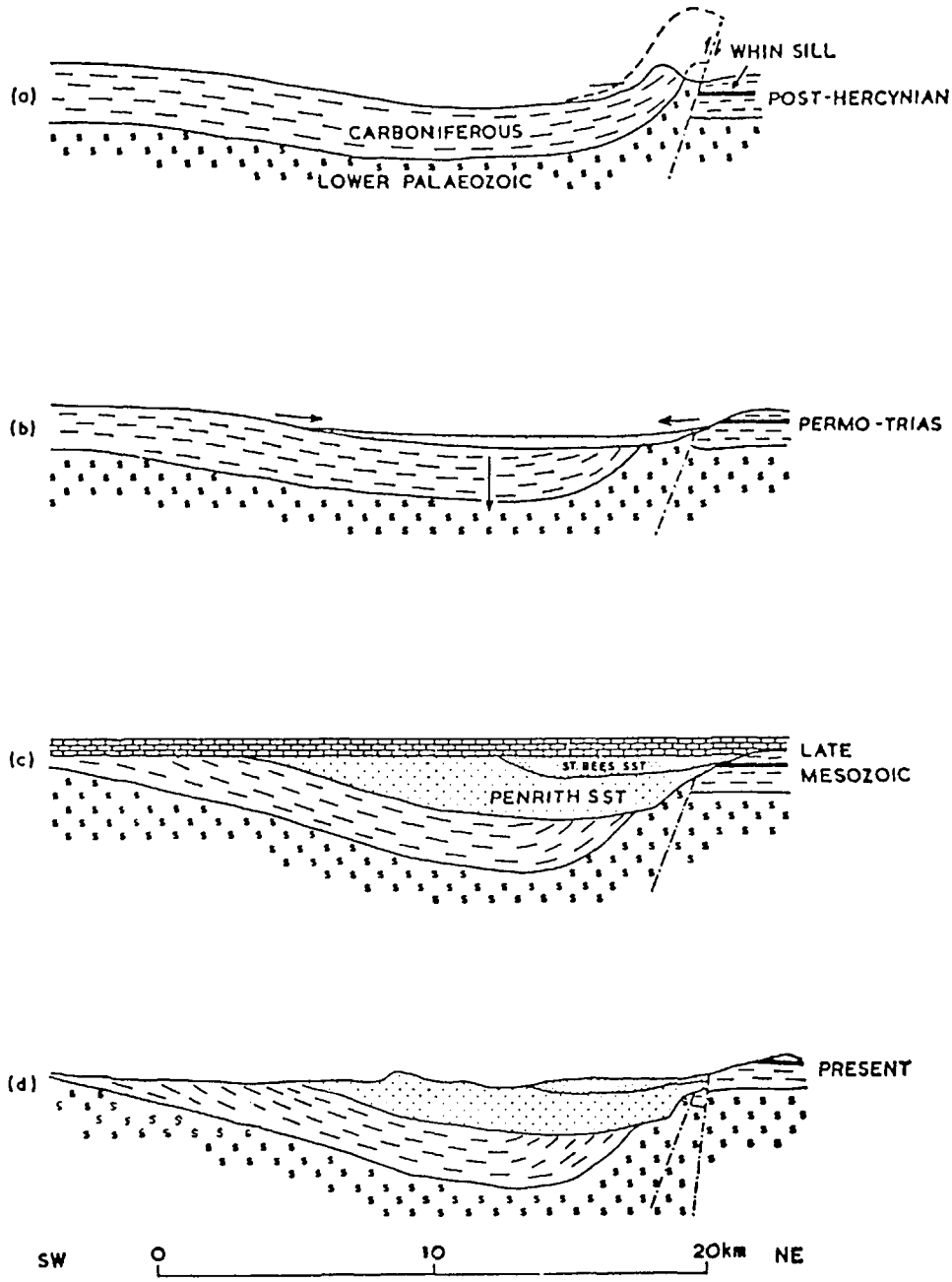


Fig. 3.2 Structural evolution of the Pennine faults (from Bott, 1978)

3.1.2 NW faults of the orefield

Within the orefield there are several major NW striking faults, the majority of which downthrow to the NE. Most of the NW faults carry little or no mineralization. The Teesdale fault is the most important member of this group of faults. It extends from the Stublick Fault in the north to the Lunedale Fault in the south. The downthrow on the fault is greatest in Teesdale; about 100m to the NE (Dunham, 1948). To the north and south of Teesdale the displacement decreases (Fig.3.6)

East of the Teesdale Fault is a series of NW to NNW cross veins on Alston Moor, the principal of which are Carrs and Wellgill cross veins. Another belt of NW faults run along the West Allen Valley, of which the most important are the Coalcleugh East and West cross veins, which form a fault trough depressed 27m to 40m. Further east the only NW faults of any importance are the Flushiemere Great and Western Hope Old veins, downthrowing to the SW and NE respectively.

3.2 Folding

Tight folding of the Carboniferous rocks in northern England are restricted to the basinal sediments of the

Stainmore and Northumberland troughs. On the Alston Block, the Carboniferous sediments at outcrop generally appear to be unfolded. However, folds may be seen in the developments of the larger mines, and may be inferred when comparing the dips of the beds betweem adjacent outcrops. An abnormally large monoclinal fold is associated with the Great Sulphur Vein (plate 1). On a larger scale the sediments have been warped into a broad and gentle dome; - the Teesdale Dome.

3.2.1 Teesdale Dome

The broad structure of the Teesdale Dome has been outlined by Dunham (1948), by means of contours on the base of the Great Limestone; a method previously employed in less detail by Hickling (1931). The dome is asymmetric, truncated by the Pennine faults (Fig 3.3). The highest areas of the dome occur around Cross Fell (NY687343) where the key horizon reaches 3000ft (913m) above ordnance datum. In the Durham coalfield the Carboniferous sediments tilt gently eastwards at about 2^{o}. This tilt to the east is probably related to the uplift along the Pennine faults. Removing this eastward tilt it is possible to deduce the structure of the Teesdale Dome as it was originally formed. On a scale east-west section across the Teesdale Dome (Fig 3.4a) the dome structure is virtually imperceptible. The structure becomes clearer with a 3.5 times vertical exaggerated scale (Fig 3.4b), and the sharp

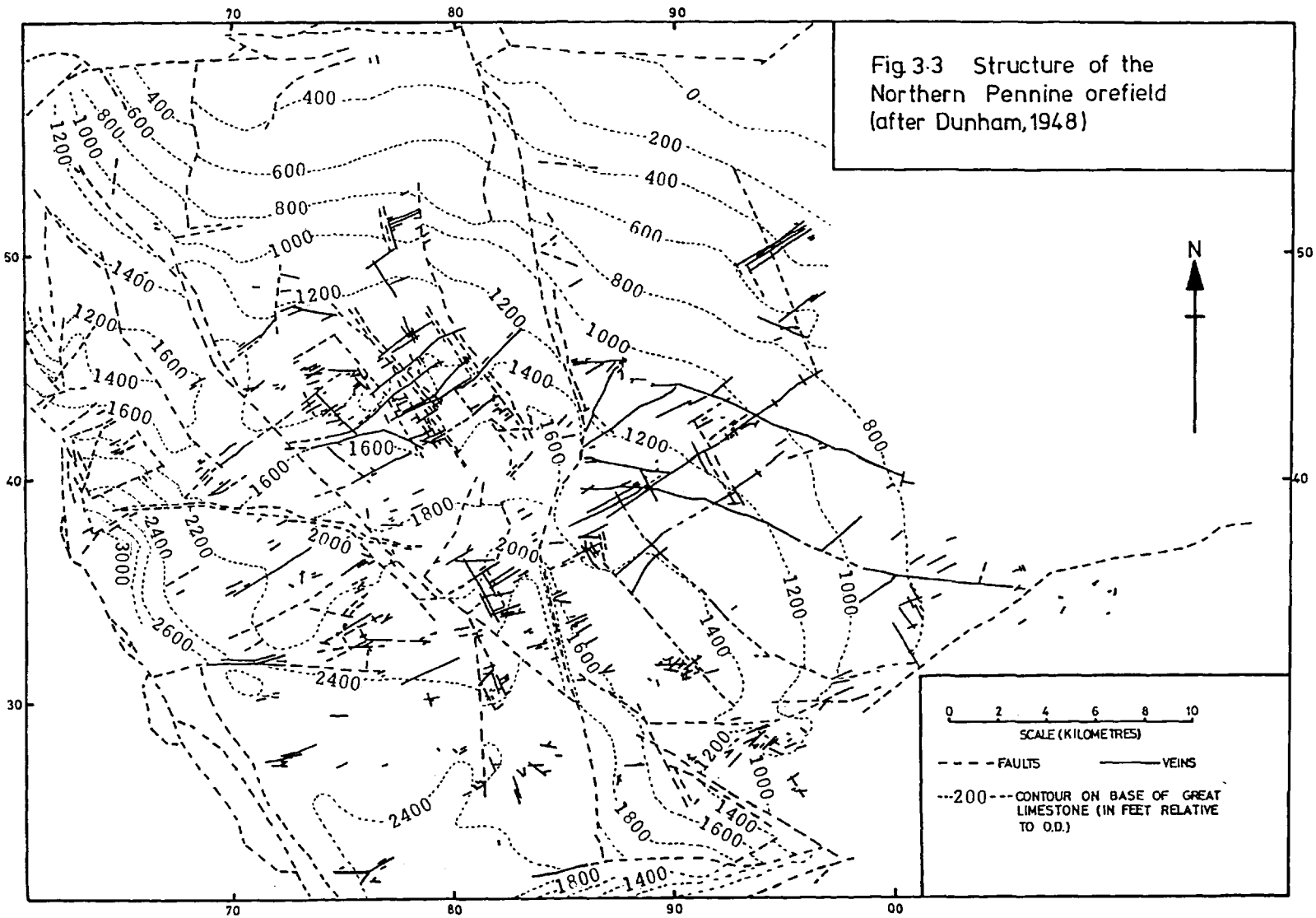


Fig. 3·3 Structure of the Northern Pennine orefield (after Dunham, 1948)

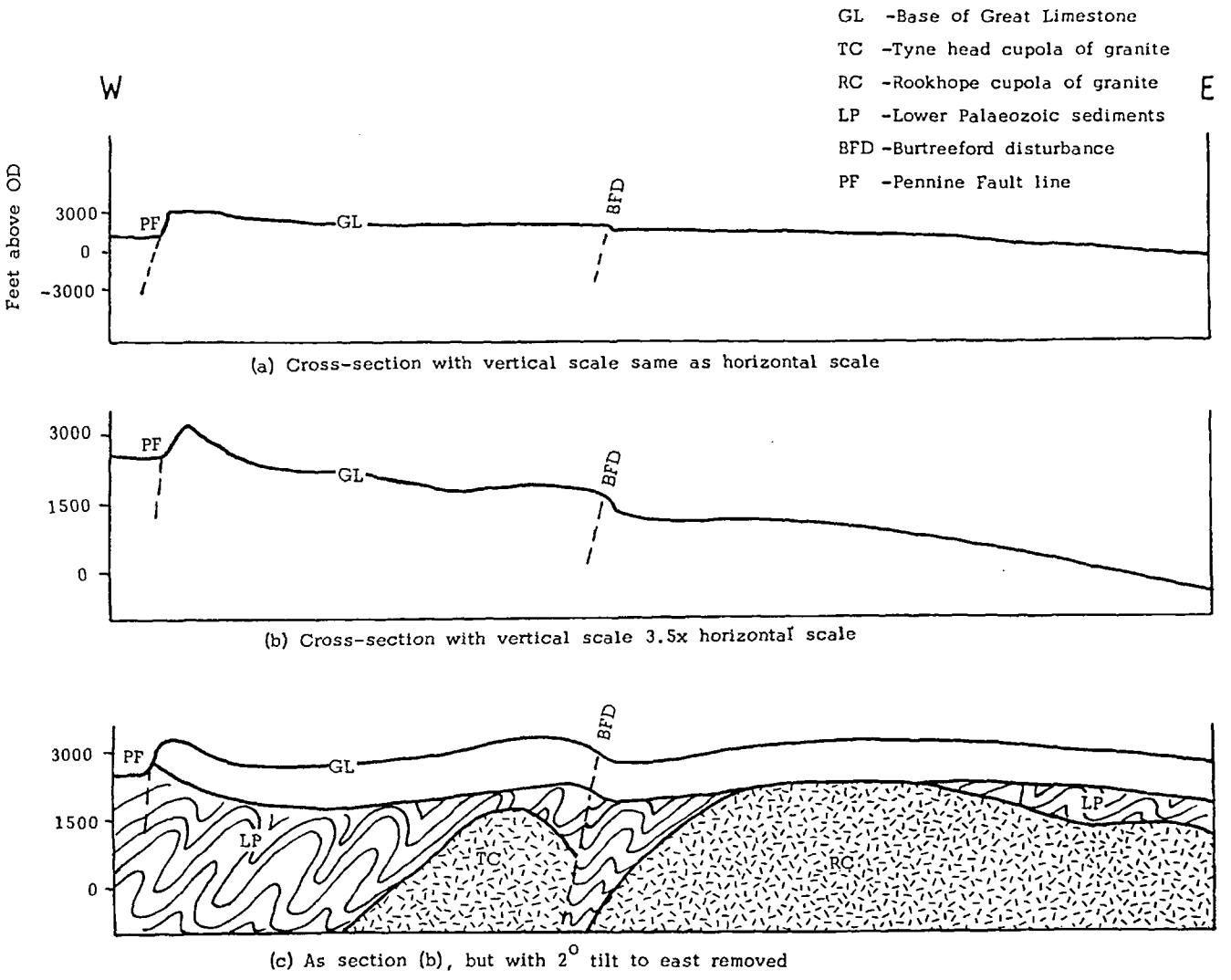


Fig.3.4 East cross-section of the Teesdale Dome, constructed from plan of contours on base of Great Limestone (Fig.5.3)

upward tilting of the beds towards the Pennine faults becomes apparent. Bott (1974), in proposing a model for the structural history of the Pennine faults, believes that the Outer Pennine Fault moved by reverse dip-slip in post-Hercynian times. The dip of the beds eastwards away from the Outer Pennine Fault is due to folding which accompanied the faulting.

Removing the general eastward tilt of the Carboniferous sediments on the Alston Block (Fig 3.4c), two 'highs' are noticable; around Burnhope Moor (NY785375) and in the vicinity of Eastgate (NY957387). Both these localities lie close to the cupolas of the underlying Weardale Granite, which suggests that the formation of the Teesdale Dome was controlled by the granite. The dome may have formed during a period of uplift caused by isostatic rise of the granitic basement, after consolidation of the sediments, but prior to the intrusion of the Whin Sill. The Whin Sill within individual stratigraphical horizons shows some radial doming, but not as much as the sediments. The sill cuts across sediments that were already domed, although some warping must have occurred after its intrusion (Jones et al, 1980).

3.2.2 Burtreeford disturbance

The most prominent fold structure in the orefield is

the NNW to NNE trending Burtreeford disturbance, which divides the orefield into two approximately equal parts. The disturbance takes the form of an east facing monocline with a vertical displacement of 150m. Near the head of Weardale at Ireshopeburn (NY850408) the monocline is overturned and may locally be a high angle thrust. To the north of Elpha Green (NY840363) the disturbance downthrows to the west, but Dunham (1948) suggests that this displacement is due to a later fault which followed the line of the monocline. The disturbance follows the line dividing the Rookhope and Tynehead cupolas of the Weardale Granite. The curving of the disturbance suggests that it is deflected around protrusions in the granitic basement (Jones et al, 1980).

The formation of the disturbance pre-dates or was contemporaneous with the intrusion of the Whin Sill. In Teesdale the Whin Sill transgresses to higher stratigraphical horizons eastwards across the disturbance, suggesting that a monocline had already formed by the time of the intrusion. At Copt Hill (NY840363) the Sill forms a phacolith in the neighbourhood of the Burtreeford disturbance (Wager, 1929). Dunham (1948), interprets the disturbance as a compressional feature, related to the same stresses which produced thrusting in the Cross Fell Inlier and NNW monoclines elsewhere in the orefield. There is no evidence to dispute this interpretation, and folding could easily have occurred on the Alston Block at an early stage if the sediments still contained a relatively large

amount of pure fluid. However, the Burtreeford disturbance is clearly a major structural feature, extending into the underlying granite. If the granite is a homogeneous body then it is difficult to envisage the large strains associated with formation of a structure of this size in a solid granite mass, with the relatively small scale of deformation elsewhere. If the Burtreeford disturbance is simply a fault caused by compression in a previously unfractured granite then one would expect other similar features to be present randomly throughout the granite: this is not the case.

An alternative hypothesis is that the Burtreeford disturbance marks the junction between two separate intrusions of granite; the Weardale Granite to the east and the Tynehead Granite to the west. There was no relative movement between the two granites during Carboniferous sedimentation. The ENE compression responsible for the smaller NNW striking monoclines in the orefield may have triggered failure along the junction between the two granites, and uplift of the western granite, relative to the eastern granite, occurred. Draping of the Carboniferous cover rocks over the step created at the junction, resulted in the formation of the Burtreeford disturbance.

3.2.3 Minor folding

Minor folding is often present parallel to the vein-fractures in all directions, again in the form of monoclines. One such fold accompanies the ENE St Peter's Vein in East Allendale, and the fold is shown on the Weardale Lead Company's section of St Peter's Mine (Fig 3.5). The fold is a SE facing monocline; it occurs in the hanging wall of the vein below the Great Limestone, and in the footwall above. Dunham (1933) considered that the vein-fracture formed by extension and post-dated the fold, which was formed by compression. It will be shown later that the vein-fractures did not generally form under tension, but by shear failure. Thus, it is not necessary to invoke a period of compression and then tension to explain the co-existance of fold-fault structures. If, the vein-fracture formed at a certain depth where the stress ratio was large enough to cause failure, then drape structures would form in the overlying sediments as monoclines. A reduction in the strength of the rocks by drape folding would allow the upward propagation of the fault through the monocline. The resultant faulted monocline would take on the appearance of reverse (anomalous) drag, which has been termed the 'bur' of the vein by Leithart (1838). Anomalous drag of this type can extend for several metres either side of the vein-fracture (plate 2). Normal drag in contrast, where developed, rarely extends for more than a metre from the vein.

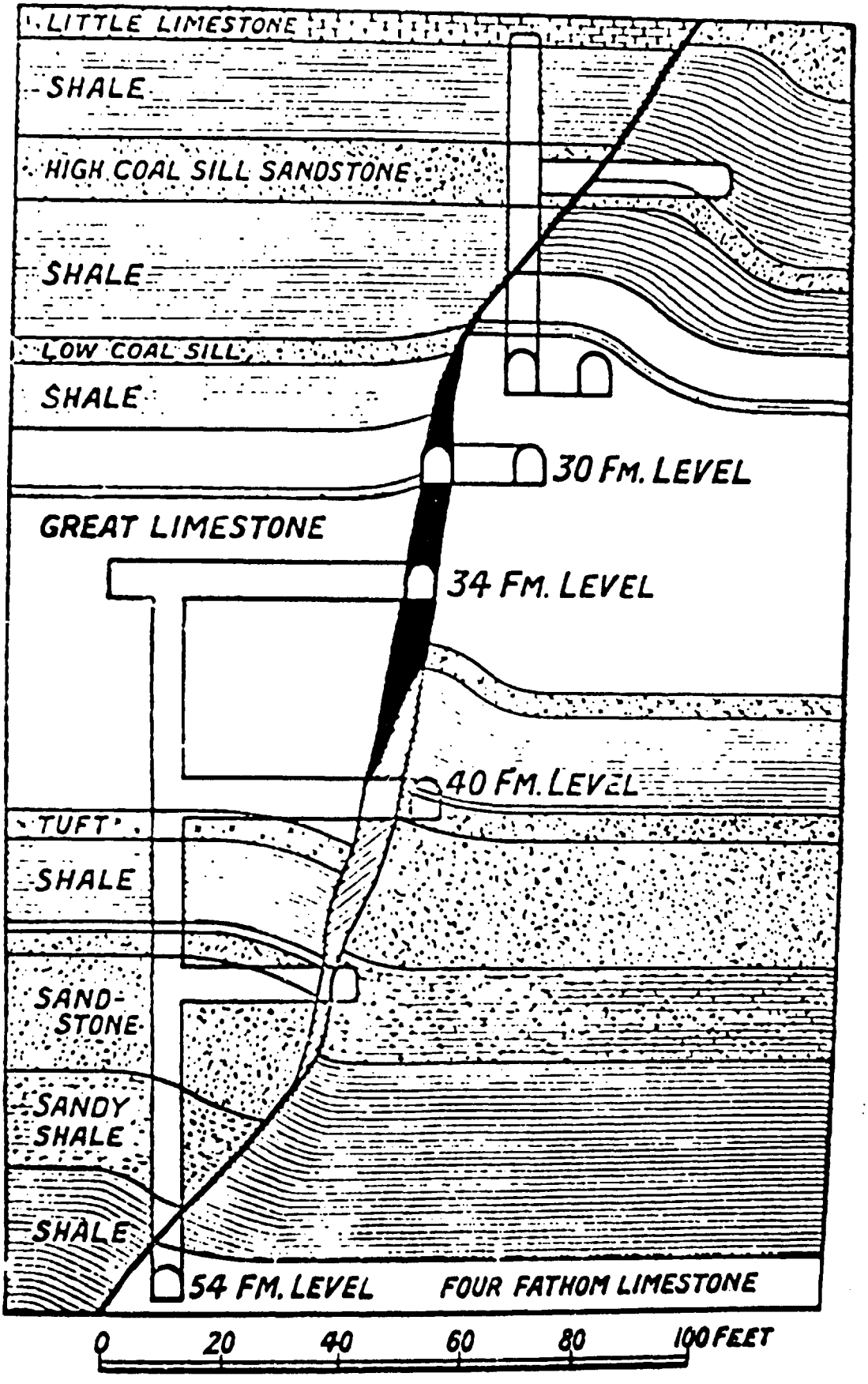


Fig.3.5 Fold adjacent to St.Peter's Vein (from Dunham, 1937)



Plate 1 Fold on north side of the Great Sulphur Vein, near Tynehead

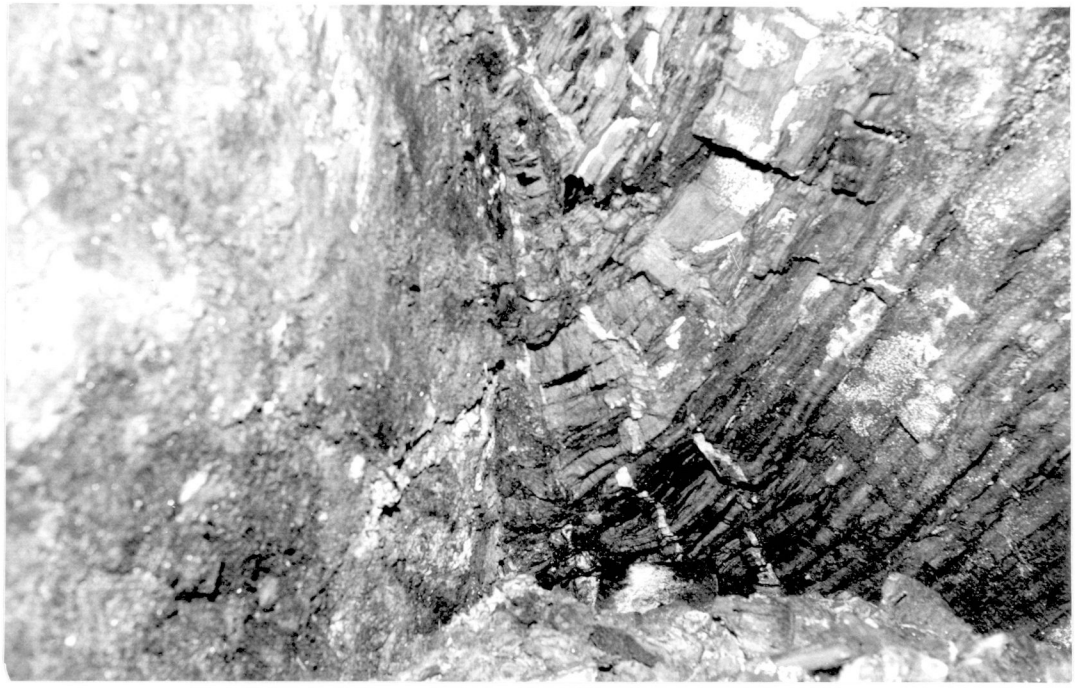


Plate 2 Drag fold, Smallcleugh Vein, Nenthead

3.3 Vein-fractures

The veins in the northern Pennine orefield can generally be classified into one of three groups: ENE 'productive' veins; NNW 'cross' veins; east-west to ESE 'quarter-point' veins (Fig 3.6).

3.3.1 ENE veins

The ENE veins were formerly an important source of lead ore. Individual ENE veins may be traced for several kilometres, although they are not continuously mineralized. Displacements on the productive veins are rarely more than a few metres. Dunham (1948) notes that the larger faults are poorly mineralized; they were most probably choked at the time of mineralization by gouge from dragged-in shales.

In hard beds, such as limestones and sandstones, the hade of the vein is small, but in softer beds, such as shales, the hade increases and the opening across the vein fissure decreases (Forster, 1809). This feature suggests that the vein fissures are the result of dip-slip normal

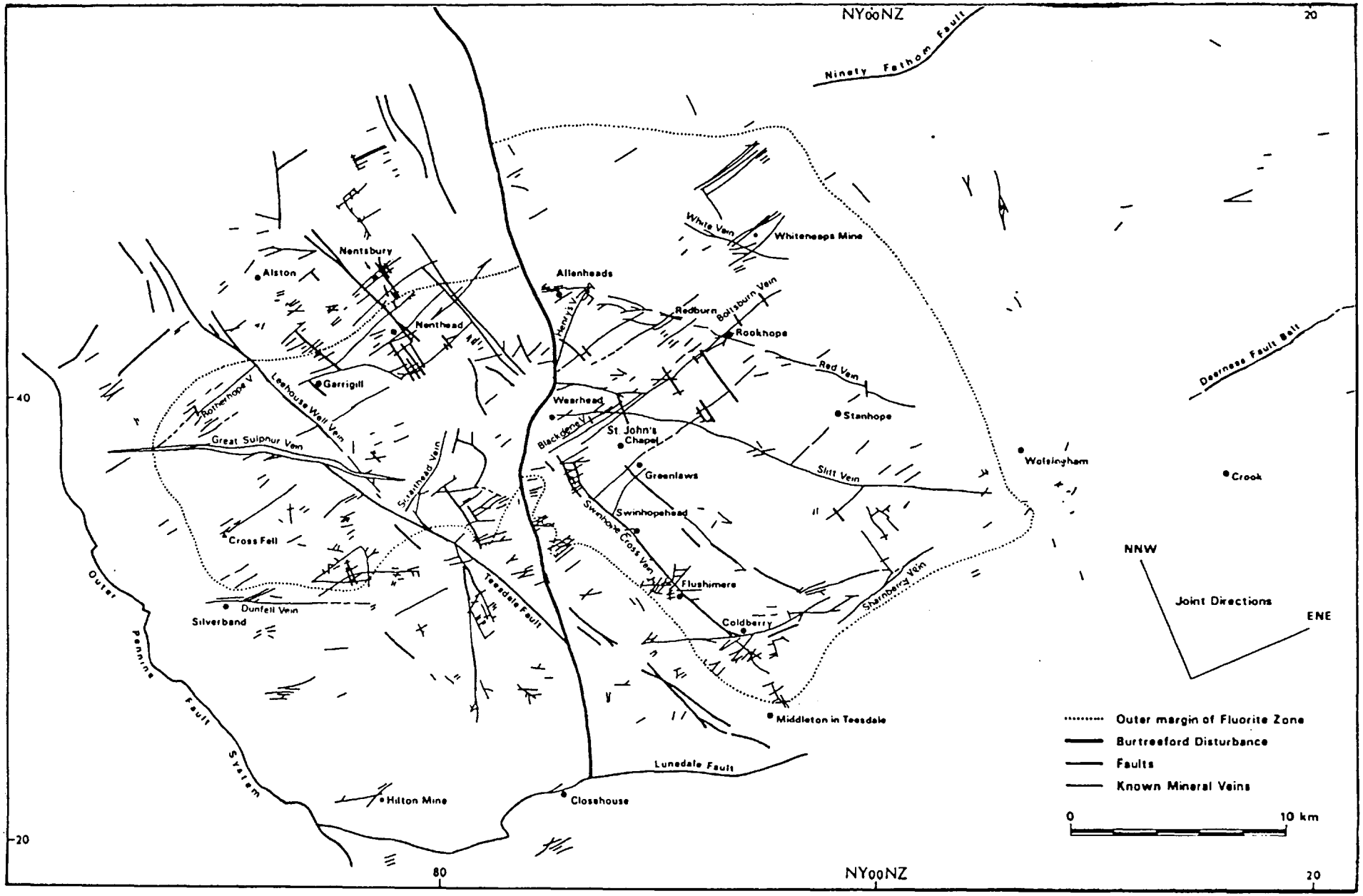


Fig. 3.6 Veins of the northern Pennine orefield (from Smith, 1980)

faulting, and thus openings in the vein are confined to the steeper parts of the fissure, within competent horizons (Leithart, 1838). This is clearly the case in many of the ENE veins, where oreshoots are confined to the competent horizons, but may extend for hundreds of metres laterally to form 'ribbon' oreshoots (Fig 3.7).

Locally, vertical continuity of the oreshoots may be increased by sandstone filled wash-out channels and metamorphosed shales adjacent to the Whin Sill (Greenwood and Smith, 1977).

3.3.2 Cross (NNW) veins

The NNW cross veins are the least known and most poorly mineralized of the three vein sets. The throw on the NNW veins is generally much greater, although displacements seem to be confined to a few large fractures, with many parallel subsidiary fissures having little or no displacement. These subsidiary fissures are seldom mineralized, but appear in many cases to terminate the oreshoots of the productive and quarter-point veins (Dunham, 1948). The offset relationships between the productive and cross veins is highly variable, and it would appear that they developed contemporaneously (Wallace, 1861).

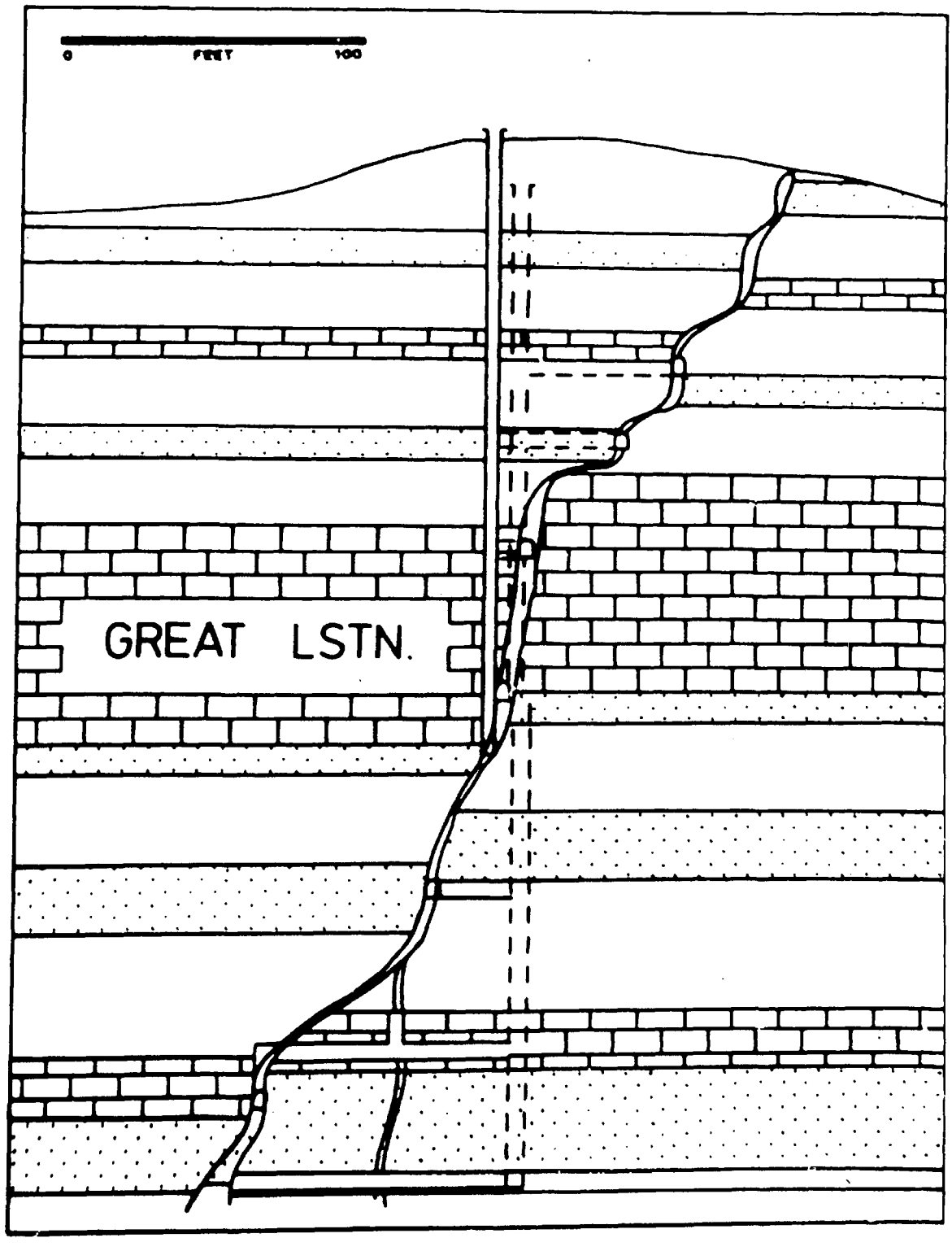


Fig.3.7 Ribbon oreshoots in Wolfceugh Mine
(from Smith, 1923)

3.3.3 Quarter-point (ESE) veins

The quarter-point veins are more complex than the productive veins. Lateral branching is particulary well marked in these veins, but the refractive effect of normal faulting is less evident. The oreshoots show greater vertical continuity, but less horizontal extent than those of the productive veins. Dunham et al (1965), noted that oreshoots in the Red Vein of Rookhope were confined to east-west sections of the vein, and suggested that this strike control was due to sinistral strike-slip movement along the vein.

The oreshoots are often thickened by structural overlap, due to the juxtaposition of orebodies by strike-slip movement. In other cases, the two halves of an oreshoot have been offset by strike-slip movement. These movements appear to have been pre-, syn-, and post-mineralization. Greenwood and Smith (1977) cite the sinistral displacement by 27m of a transgression in the Whin Sill by the Slitt Vein at Blackdene Mine as an example of pre-mineralization strike-slip movement (Fig 3.8). A similar movement on the same vein has been deduced at the Heights Mine (Scott, 1956).

The vertical continuity of oreshoots is again locally

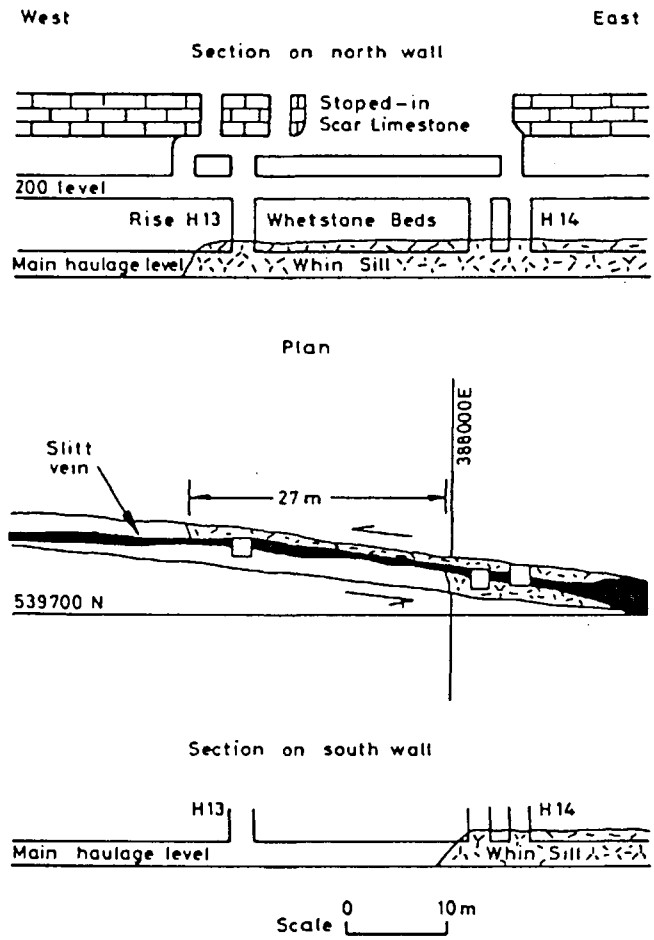


Fig.3.8 Sinistral displacement on the Slitt Vein in Blackdene Mine (from Greenwood and and Smith, 1977)

enhanced by the presence of sandstone filled wash-out channels and metamorphosed shales (Lyon and Scott, 1957). In addition, however, quarter-point oreshoots may show a greater vertical continuity due to the presence of early quartz-Cu-Fe sulphide mineralization around feeder channels at vein intersections (Greenwood and Smith, 1977). Shales which were silicified by this early phase mineralization behaved as competent beds. The early phase silicification also occurs in the fluorite bearing ENE veins close to their intersection with the quarter-point veins, suggesting a common feeder channel to both veins.

3.4 Joints

Joints are the most persistent and noticeable minor structures in the orefield. Dunham (1933), noted two dominant joint sets; 020° to 025° and 060° to 070°. The joints rarely vary more than a few degrees from the vertical; in contrast to the vein-fractures which may dip as much as 45°. Although joints strike parallel to the veins (Moseley and Ahmed,1967), and are mineralized adjacent to them, the two types of fractures have originated under different circumstances (Dunham, 1948).

Dunham stated that joints were absent in the Whin Sill. Subsequently, Spears (1961) showed that two types of joints could be identified in the Whin Sill of Teesdale.

The first type consists of curved and irregular fractures, which Spears considered to have formed during cooling of the intrusion. The second type is composed of two or more sets of later fractures, which strike in similar directions to joints in the surrounding sediments; although the former are more variable in direction and dip. Many of the joints in the Whin Sill at High Force (NY880284) show hackle marked faces, suggesting that these joints were formed by tensile failure.

CHAPTER 4 WRENCH FAULT TECTONICS

Many of the Hercynian vein and fault structures in the Carboniferous of northern England were generated by strike-slip faulting. It is thus relevant to outline briefly some of the structures associated with this type of faulting.

4.1 Faulting in cover rocks due to basement tectonics

The term 'cover rocks' is generally applied to undeformed or gently deformed rocks, unconformably overlying an older, deformed, rigid basement. The generation of structures in these cover rocks can often be directly related to movement along large fractures in the basement. If the basement and cover rocks have similar competency, then fractures in the basement may simply be propogated upwards into the cover rocks. However, as is more usual, if the cover rocks are less competent than the basement, then the structures in the cover would differ from those of the basement.

4.1.1 Vertical movement along basement faults

With slight vertical displacements of basement

blocks, Horsfield (1977) has shown experimentally that monoclines, and then fault grabens develop in the overlying cover. These effects are produced by both normal and reverse faulting in the basement.

4.1.2 Strike-slip movement along basement faults

Strike-slip movement in the basement occurs when both s_1 and s_3 are horizontal. The resultant cover rock structures are varied, and often complex, folds and faults.

(a) Extension fractures

The simplest failures produced in cover rocks above basement wrenches are extension fractures, initially orientated at 45^{o} to the strike of the basement fault, and often parallel to the minimum principal stress direction (Fig 4.1). In clay model experiments, Cloos (1955) has shown that extension fractures only developed when the clay was water saturated. Wilcox et al (1973), have also performed clay model experiments in which they have shown that extension fractures only develop in the initial stages of deformation. With increasing deformation, the extension fractures are destroyed and replaced by riedel shears.

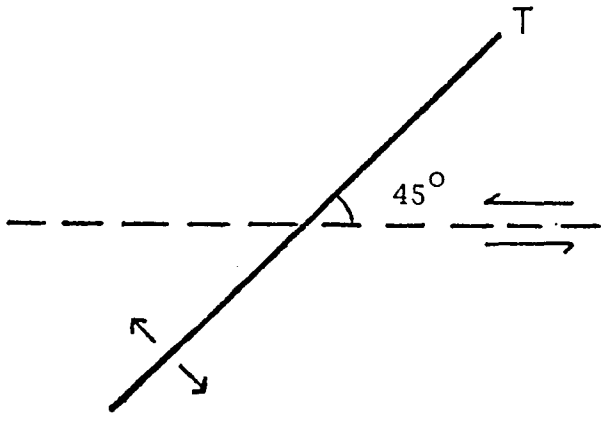
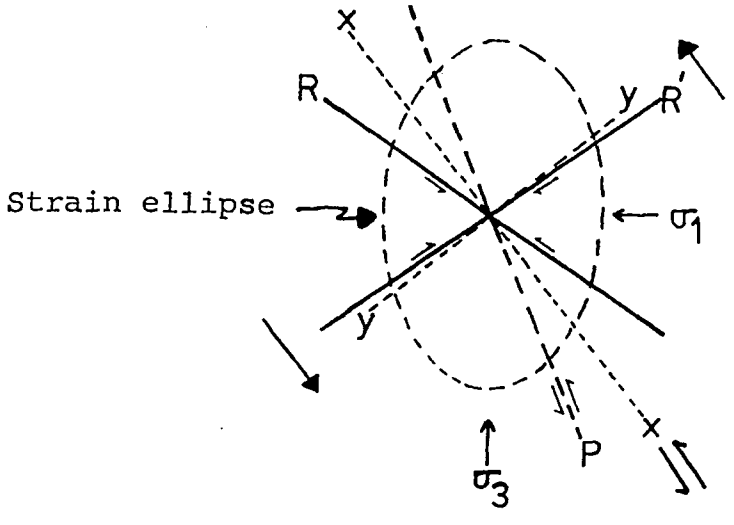


Fig. 4.1 Development of tension gash (T) above a wrench fault



x-x Main basement wrench fault

y-y Normal to basement wrench fault

R Synthetic Riedel shear

R' Antithetic (conjugate) Riedel shear

P P-shear

Fig. 4.2 Orientation of riedel shears above a sinistral wrench fault

(b) Riedel shears

It is frequently found that shear faults develop in cover rocks above basement wrenches, in a similar direction to extension fractures, but are orientated at 12 to 17 degrees from the strike of the basement wrench (Riedel, 1929). These faults have been termed 'riedel shears' by Tchalenko and Ambraseys (1970). Riedel shears show the same direction of movement as the underlying wrench fault.

Associated with the riedel shears are two other fault sets (Tchalenko and Ambraseys, 1970). Firstly, 'conjugate riedel shears', which develop at 73 to 78 degrees to the basement in the same quadrant as the riedel shears. Secondly, with high deformation along the basement wrench, a weaker set of 'P shears' develop in the cover rocks. The angular orientation of these P shears to the basement wrench is the same as the riedel shears (12 to 17 degrees); but the P shears are in the adjacent quadrant to the riedel shears (Fig 4.2). The sense of movement on the P shears is the same as the basement wrench, but the movement on the conjugate riedel shears is in the opposite direction.

(c) Synthetic and antithetic faults

The riedel and conjugate riedel shears are termed synthetic and antithetic faults (Fig 4.2) respectively by Wilcox et al (1973). They have observed that with increasing displacement along the basement wrench, a synthetic riedel shear may curve into the trend of the underlying wrench fault. At other locations a new fracture forms nearly parallel to the main wrench. As this process continues a main strike-slip fault emerges in the cover rocks which is a series of interconnected earlier fractures. Antithetic faults often inherit some of the tensional component of deformation (especially when extension fractures are absent). In this case the antithetic faults become near normal faults, with little lateral displacement.

4.2 Convergent and divergent wrenching

Opposed basement blocks which do not move parallel to the basement wrench either converge or diverge. Locally, both convergence and divergence may develop along a wrench fault. Convergent wrenching enhances the compressive structures in the cover, especially folds and conjugate strike-slip faults. Strong convergence can cause reverse faulting and thrusting. The formation of extensional structures, mainly normal faults, is associated with

divergent wrenching.

4.3 Rotation of cover rock structures by basement wrenching

4.3.1 Rotation of pre-wrench structures

Distortions and rotations of pre-existing structures, particularly joint systems, are common features in cover rocks overlying major wrench faults (Moore, 1977). A dextral basement wrench would produce a clockwise (+ve) rotation of pre-existing structures. A sinistral basement wrench would produce an anticlockwise (-ve) rotation (Fig 4.3).

4.3.2 Rotation of contemporary faults

Continuing deformation, after conjugate synthetic and antithetic faults have developed, causes the acute angle between the two faults to enlarge. The antithetic shears are rotated away from the main fault; synthetic shears are unaffected by continuing movement along the main fault.

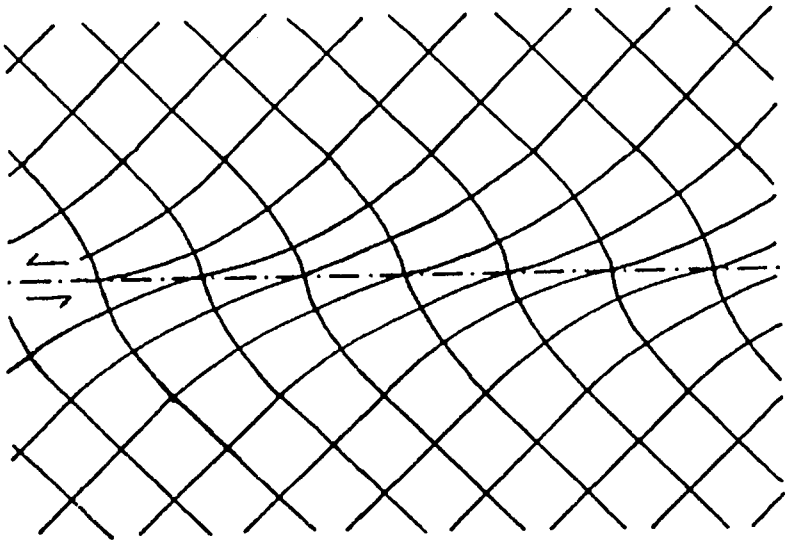


Fig.4.3 Rotation of a joint system above a wrench fault (from Carter and Moore, 1978)

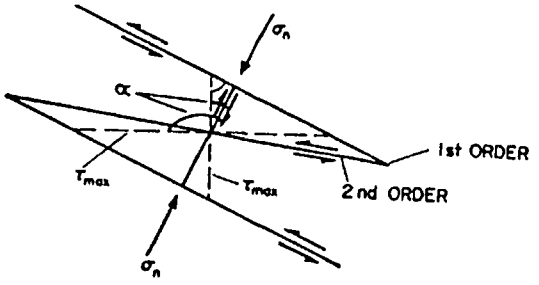


Fig.4.4 Planes of maximum shearing stress and planes of second-order shear failure between two parallel wrench faults (after McKinstry, 1953)

4.4 Second-order faulting

Many strike-slip faults have subsidiary faults branching off them at angles of about 30 degrees. These subsidiary faults (termed 'second-order faults' by McKinstry, 1953), form on either side of the wrench fault, but do not cut across it. They show the same sense of movement as the main fault (Fig 4.4), and thus cannot be interpreted as a complementary set. McKinstry (1953) has interpretated these second-order shears to be the result of local re-orientations of the stress field due to differential movement along the main fault plane.

Moody and Hill (1956) extended the idea of second-order faulting to incorporate the development of third and higher order faults, and associated folds adjacent to a strike-slip fault (Fig 4.5a). Chinnery (1966b) has criticized both McKinstry, and Moody and Hill, maintaining that their arguments are mechanically unsound, and that stress concentrations sufficient to cause faulting can only build up at the ends of major faults. However,fault patterns similar to those predicted by Moody and Hill (1956) have been observed in many parts of the world. Price (1968) has proposed an alternative explanation, in which sudden movement along a pre-existing strike-slip fault generates a shock wave. This shock wave results in the momentary re-orientation of the primary stress field and the formation of second-order faults.

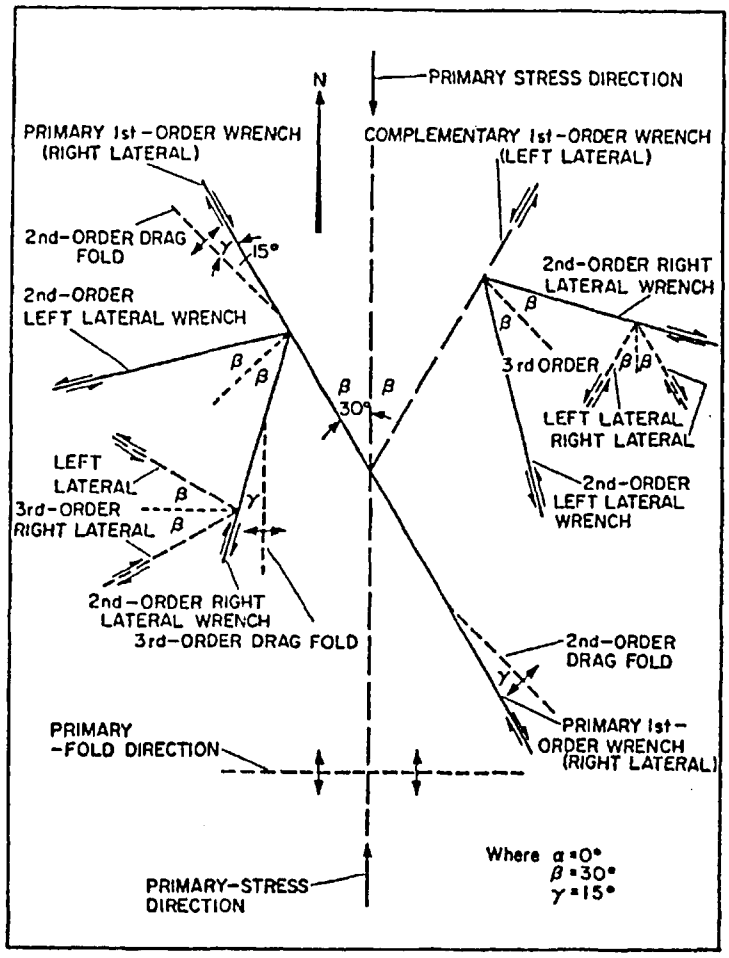


Fig.4.5a First-, second- and third-order faults and folds resulting from north-south primary compression (after Moody and Hill, 1956)

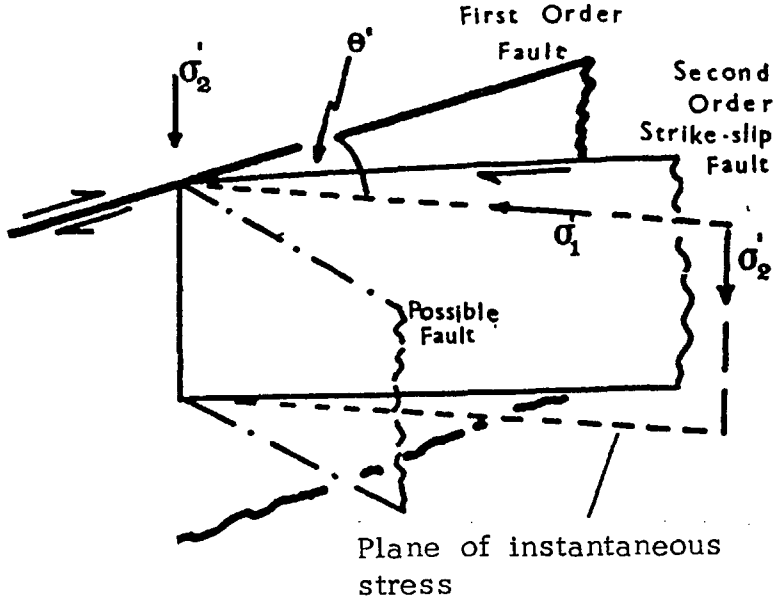


Fig.4.5b Formation of second-order faults by momentary re-orientation of the greatest principal stress due to shock wave (from Price, 1968)

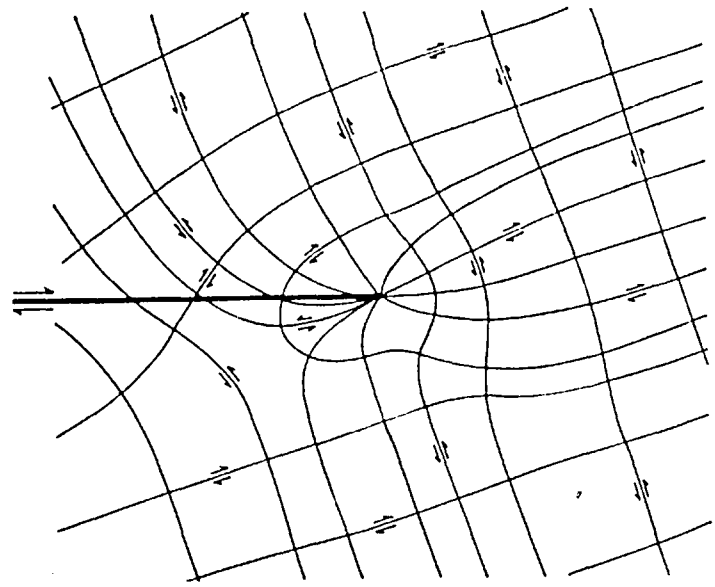
Price has proposed two possible orientations of second-order faults, depending upon the angle (F) between the maximum principal stress direction (s_1) and the strike of the main fault plane. He proposed that second-order faults would develop at 45-3F/2 degrees and 135-F/2 degrees to the maximum principal stress direction. Thus, if F = 30 degrees, as is usually the case, then second-order faults develop at 0 degrees and 120 degrees to the maximum principal stress direction, or at 30 degrees and 90 degrees to the main fault (Fig 4.5b). However, the latter second-order fault direction rarely develops due to its high angle with the maximum principal stress direction. Price (1968) gives four criteria for the development of second-order faults:

(1) rock is weak;
(2) pore-water pressure is high;
(3) the least effective principal stress is low;
(4) the angle which the direction of maximum principal stress makes with the first-order fault is relatively high (F = 40 to 50 degrees).

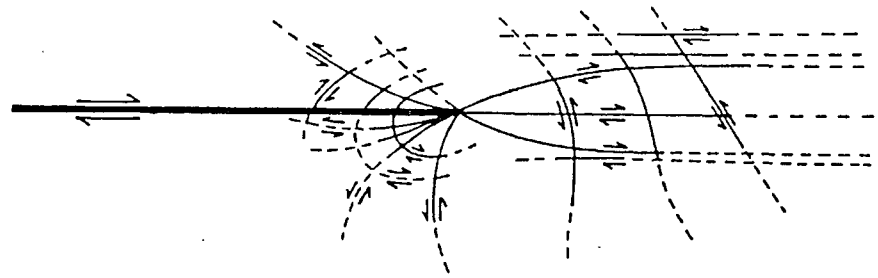
4.5 Secondary faulting

Chinnery (1966a) has considered the build up of stresses at fault termini. Previously, Chinnery (1961 and 1963) used the theory of 'elastic dislocations' to calculate the stress changes which accompany strike-slip faulting. Subsequently (1966a), he showed that the calculated changes in the stress components during faulting could be added to the initial stress components, to obtain the stress distribution after the movement had ceased. The pattern obtained by Chinnery showed that the initial shear stress is reduced over most of the length of the fault, except at the ends, where there are strong concentrations. Chinnery suggested that secondary faulting was likely in two situations. Firstly, where the maximum shear stress after faulting was equal to, or exceeded, the maximum shear stress before faulting, and secondly, in areas of extension. In the regions of compression, the secondary faults were assumed to form at 30 degrees to the principal axis of compression. In regions of extension, secondary faults were expected to develop parallel to the planes of maximum shear stress.

In proposing his model for secondary faulting, Chinnery (1966a) considered two possible primary stress fields. Firstly, where the direction of maximum principal stress is inclined at 45 degrees to the main fault. This he termed 'pure shear', and the resulting secondary fault



(a) Maximum shear stress trajectories



(b) Orientation of secondary faults

Fig. 4.6 Stresses at end of a wrench fault under uniaxial compression and orientation of resulting secondary faults (from Chinnery, 1966a)

patterns were symmetrical about the axis of the main fault. In the second case, Chinnery considered the situation of 'uniaxial compression' where the angle between maximum principal stress direction and the strike of the main fault was 30 degrees. In this case, the secondary fault pattern was asymmetric about the axis of the main fault. Only the uniaxial compressive model is shown in Figure 4.6.

CHAPTER 5 FRACTURE TRACE ANALYSIS

The fracture trace analysis described here is concerned with the spatial distribution and variations of fractures at all scales over the Alston Block and surrounding area.

5.1 Trend surface analysis

The local variations in vein strike have been investigated by Carter (1977) using trend surface analysis (TSA). Trend surface analysis is a computing technique which fits a mathematical equation to a set of data whose values are dependent on two other independent variables. In this case the equation expresses the strike of the veins in terms of the two geographic co-ordinates. The difference between the calculated vein strike (using the trend surface equation) and the actual vein directions are known as residuals. The trend surface describes the regional variations in vein directions and the residuals show the local variations in vein trend.

Carter in his analysis, divided the complete family of vein directions present in the northern Pennines into three sets: ENE, NNW and east-west. It is impossible to treat all veins together, as the resulting trend surface

would give a mean direction, that would not represent any of the sets. The data used by Carter were measured from the published 1:50,000 geological maps using 2.5km by 2.5km grid squares. Carter used a computer program published by Fox (1967). During the present research Carter's original data were re-run through a more efficient program (Davis, 1973), using the strike of each vein, rather than the average strike direction in each 2.5km grid cell.

5.1.1 Results of TSA

The results of the trend surface analysis described by Carter and Moore (1978) were presented as contour maps of vein density and residual density (from the third order trend surface) for each vein set (Fig 5.1). The residuals show linear zones of positive and negative values. The zones of positive residuals represent areas where the vein directions are apparently rotated clockwise relative to the predicted (regional) direction. The zones of negative residuals represent areas of anticlockwise rotation. Similar results to those described by Carter were obtained during the present analysis, and thus, attention was focussed on the interpretation the linear zones of residuals (lineaments).

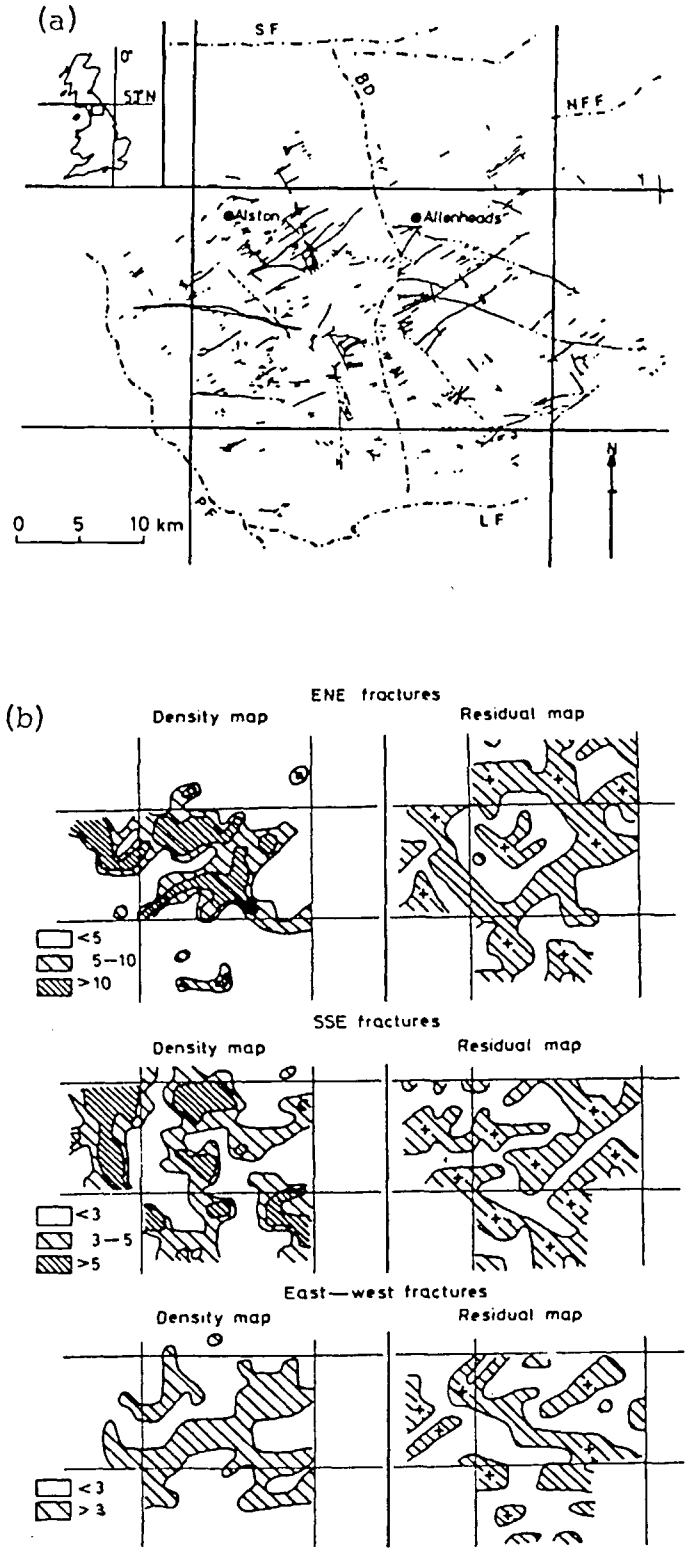


Fig. 5.1 (a) Region covered by trend surface analysis (b) Density and residual maps (from Carter and Moore, 1978)

5.1.2 Interpretation of TSA residuals

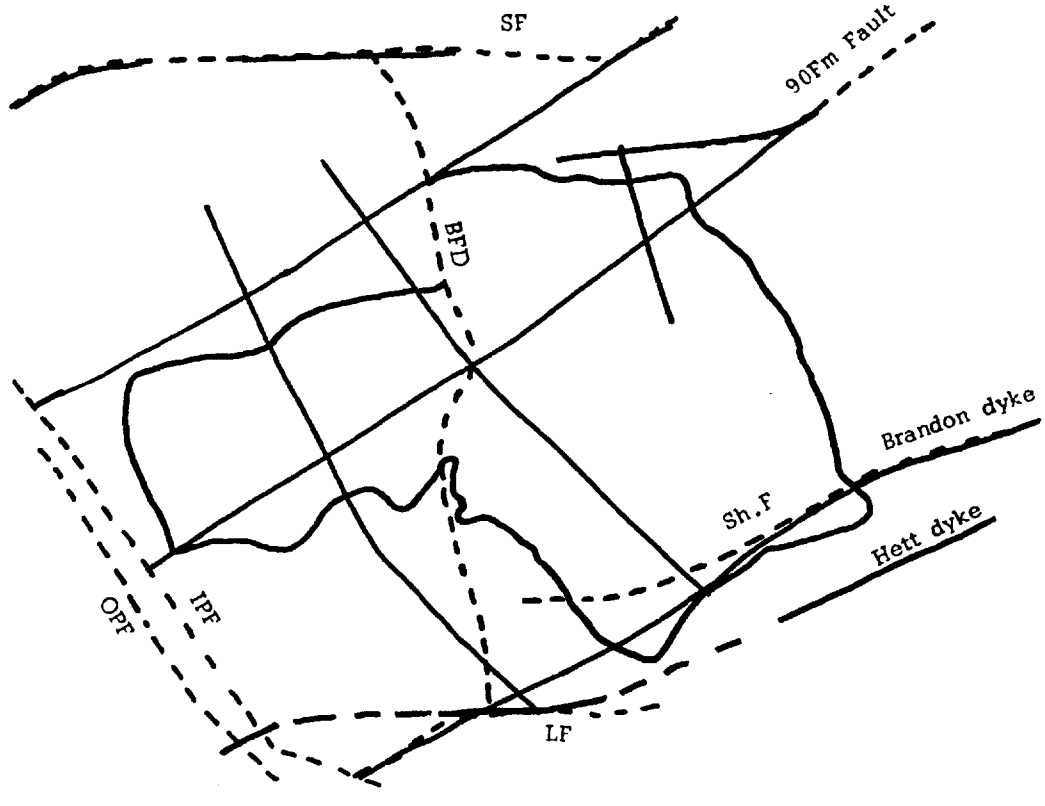
Carter and Moore (1978) have suggested that the apparent rotations of the vein trace, as shown by the TSA residuals maps, are the result of movement along basement wrench faults. A dextral wrench fault in the basement would produce a clockwise rotation of structures in the cover rocks. This rotation would be exhibited by a line of positive residuals above the wrench. Similarly, a sinistral wrench fault in the basement would produce a line of negative residuals.

The residuals for each vein set show two linear orientations, each consisting of alternate bands of positive and negative residuals. These bands strike NW and ENE. If the supposed basement wrenches were active under the same stress field, then in one direction, movement along the basement wrench would have been dextral, and in the other sinistral. It is emphasized that the lineaments have not been proved to be the result of movement along basement wrenches, as it is impossible to observe large areas of the basement beneath the Carboniferous cover of the Alston Block. It is also difficult to assign the proposed dextral and sinistral basement wrenches to either the NW or ENE lineaments. Movement along the basement faults could either be contemporary with the vein fracture formation, or post-date the veins entirely.

The NW lineaments parallel many major NW fractures of northern England, particulary the Craven and Pennine boundary faults. In the Lake district NW wrench faults were formed during the Caledonian orogeny (Firman, 1957). Major ENE faults are rare in the Lake District but they may be difficult to recognize, as this direction parallels the main Caledonian cleavage. In the Cheviots ENE to NE crush zones cut through the Devonian granite and surrounding lavas. These faults are believed to have moved dextrally (Carruthers et al, 1932). In the Durham coalfield and in north Northumbria, the whin dykes strike ENE. A whin dyke follows the 90fm Fault; this fault was active during Lower Carboniferous times, and shows evidence of dextral strike-slip movement (Robson, 1980). Dextral movement along the 90fm Fault would result from east-west compression. If the proposed basement wrenches were active at the same time that strike-slip movement occurred along the 90fm Fault, then the ENE positive residuals would be the result of dextral wrench faults in this direction. The NW negative residuals would result from NW sinistral basement wrenches.

It is not possible to precisely fix the position of the proposed basement wrenches, as the zones of positive and negative residuals are upto 4km wide. However, one possible interpretation is shown in Figure 5.2. It is apparent from this diagram that many of the basement wrenches coincide with known major structural features of

Fig.5.2 Lineaments and major structures of the Alston Block



------ Major faults

Outer margin of fluorite zone

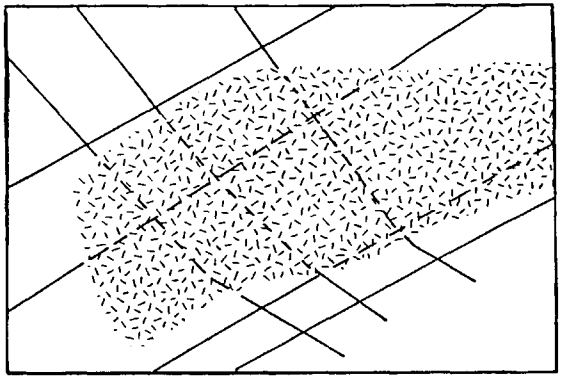
Whin dykes

Lineaments interpreted from trend surface analysis

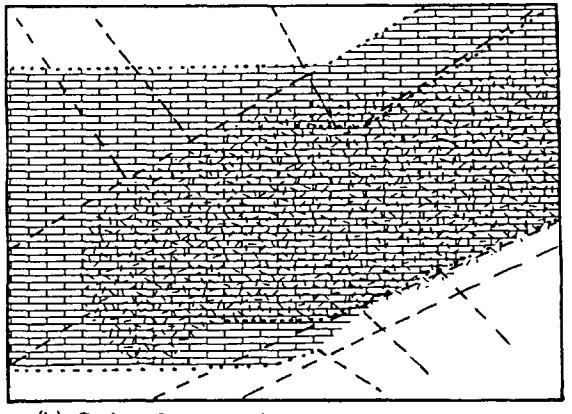
BFD	Burtreeford disturbance
IPF	Inner Pennine Fault
OPF	Outer Pennine Fault
LF	Lunedale Fault
SF	Stublick Fault
Sh.F	Sharnberry Fault

the area. Those in the NW direction coincide with the lines of major NW faults: the Pennine faults, the Teesdale fault, and the Coalcleugh-Flushiemere fault zone. The ENE faults coincide with the ENE whin dykes of the Durham coalfield, including that intruded along part of the 90fm Fault. On the Alston Block, the whin dykes and their associated features curve markedly onto east-west trends, however, the inferred basement wrenches continue to follow the ENE strike extension from the coalfield. In the coalfield the whin dykes follow major pre-existing fractures, but it must be explained why these fractures did not control the dykes on the Alston Block.

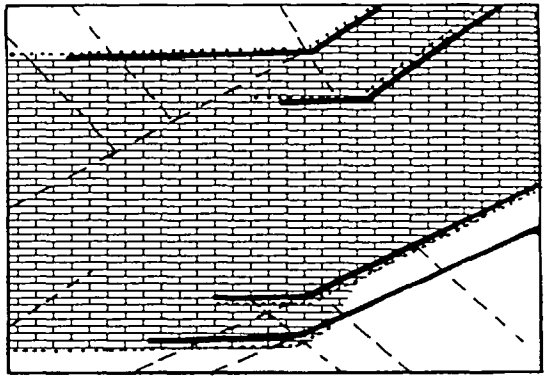
One explanation is that although NW and ENE basement fractures were originally present in the Lower Palaeozoics beneath the Alston Block, they were partly destroyed by the intrusion of the Weardale Granite. Only where thick Lower Palaeozoic rocks lie between the base of the Carboniferous and the granite, or the granite is absent, would these basement fractures be preserved. Thus, whin dykes would have followed the line of weakness provided by the ENE basement fractures only in Carboniferous basins; on the north and south margins of the block the east-west hinge lines provided easier lines of weakness for the whin magma, than the basement fractures. During a period of post-whin movement new fractures were initiated along the strike extensions of the basement fractures from beneath the basins. The possible sequence of events is shown in Figure 5.3. The granite could not have been fractured



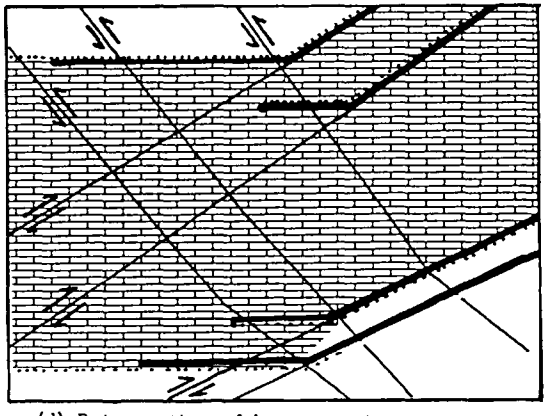
(a) Partial destruction of basement faults by the intrusion of the Weardale Granite



(b) Carboniferous sedimentation controlled by basement faults and granite



(c) Whin dykes controlled by basement faults and margin of Alston Block



(d) Rejuvenation of basement faults

Basement faults

Carboniferous hinge lines

Whin dykes

Granite

Block sediments

Fig.5·3 Evolution and effect of basement faults on the Alston Block

during Carboniferous times, if it was already broken, then it could be expected to have foundered into many small blocks and basins, as occurred in Derbyshire at that time.

In summary, the trend surface analysis has suggested the presence of major lines of structural weakness in the pre-Carboniferous basement of northern England. In the Carboniferous basinal areas these lines of weakness were active during the sedimentation, and the ENE set were intruded by the whin dykes. On the Alston Block, the intrusion of Weardale Granite destroyed these structures. However, in late Hercynian times, new fractures appear to have formed in the basement of the Alston Block. Movement along the fractures resulted in slight rotations of the veins in the overlying Carboniferous sediments.

5.2 Statistical analysis of vein and fault patterns

5.2.1 Method of analysis

The vein and fault patterns of the central part of the orefield were analysed by the computer program FRACAN (Fiche 1). Data for this analysis were in the form of digitized vein and fault traces (Fig 5.4) taken from the 1:50,000 geological sheet number 25 (Alston sheet). The

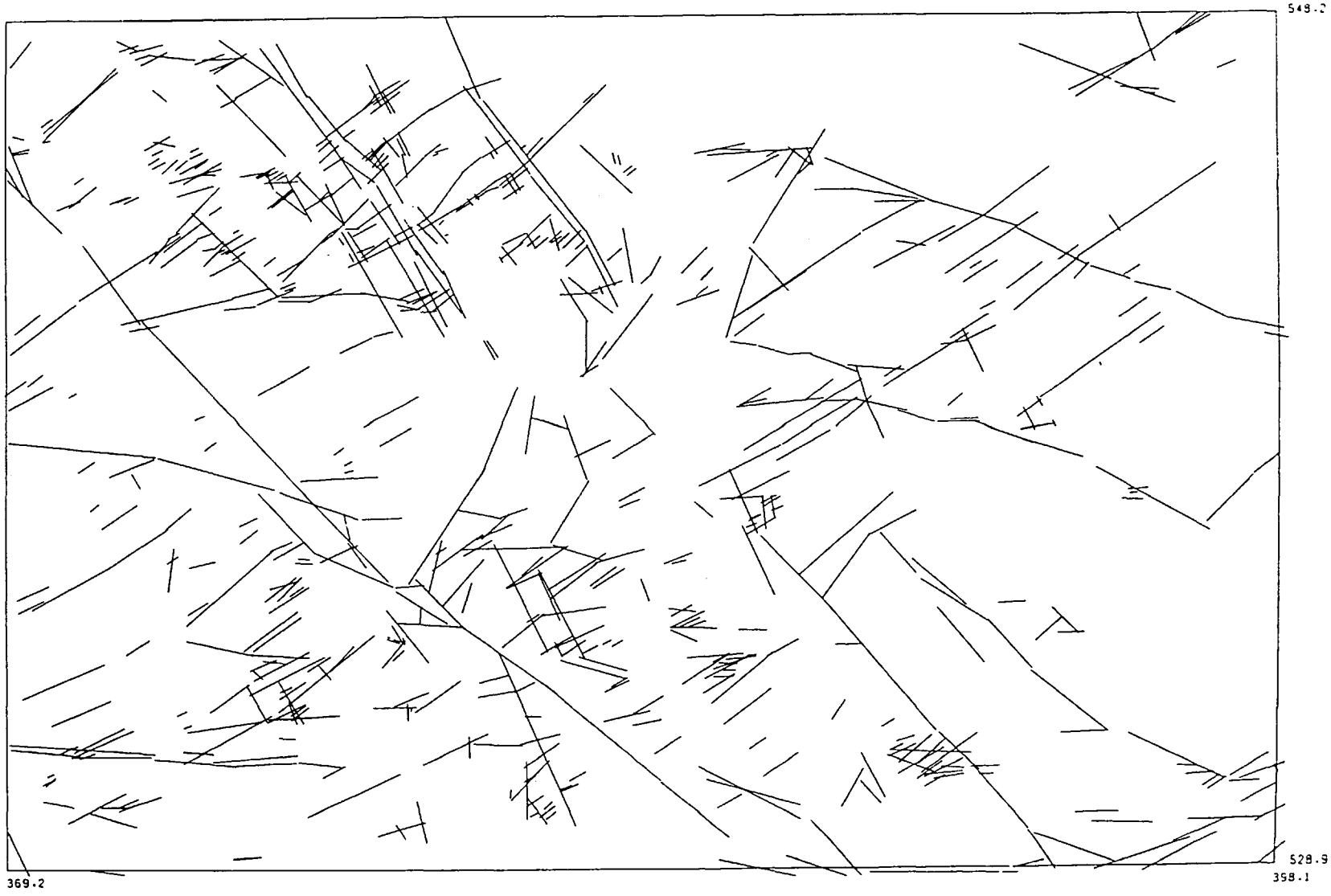


Fig.5.4 1:50,000 GEOLOGICAL MAP, ALSTON SHEET NO. 25
FRACTURE TYPE=ALL

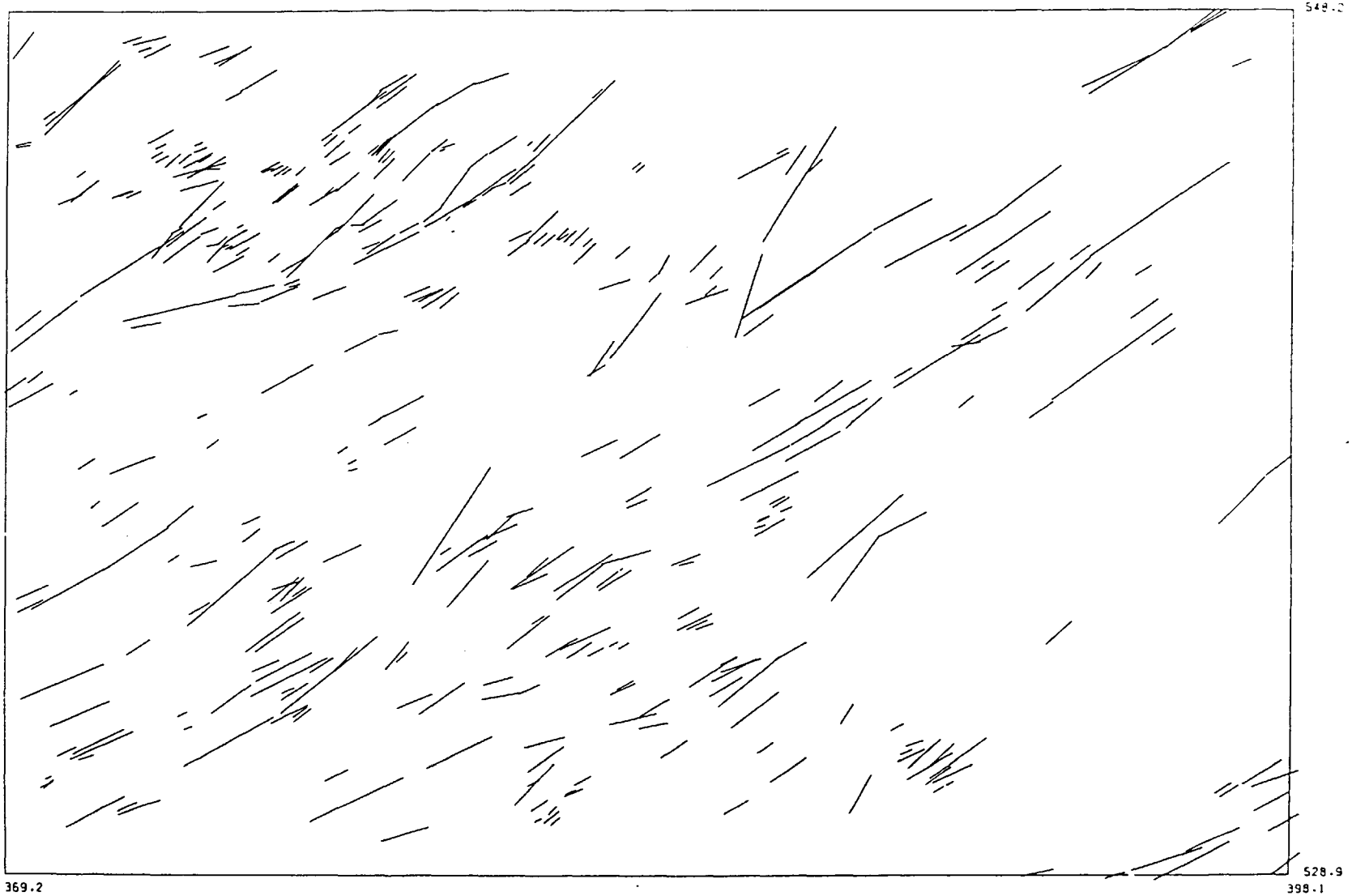


Fig.55 1:50,000 GEOLOGICAL MAP, ALSTON SHEET NO. 25
FRACTURE TYPE=1

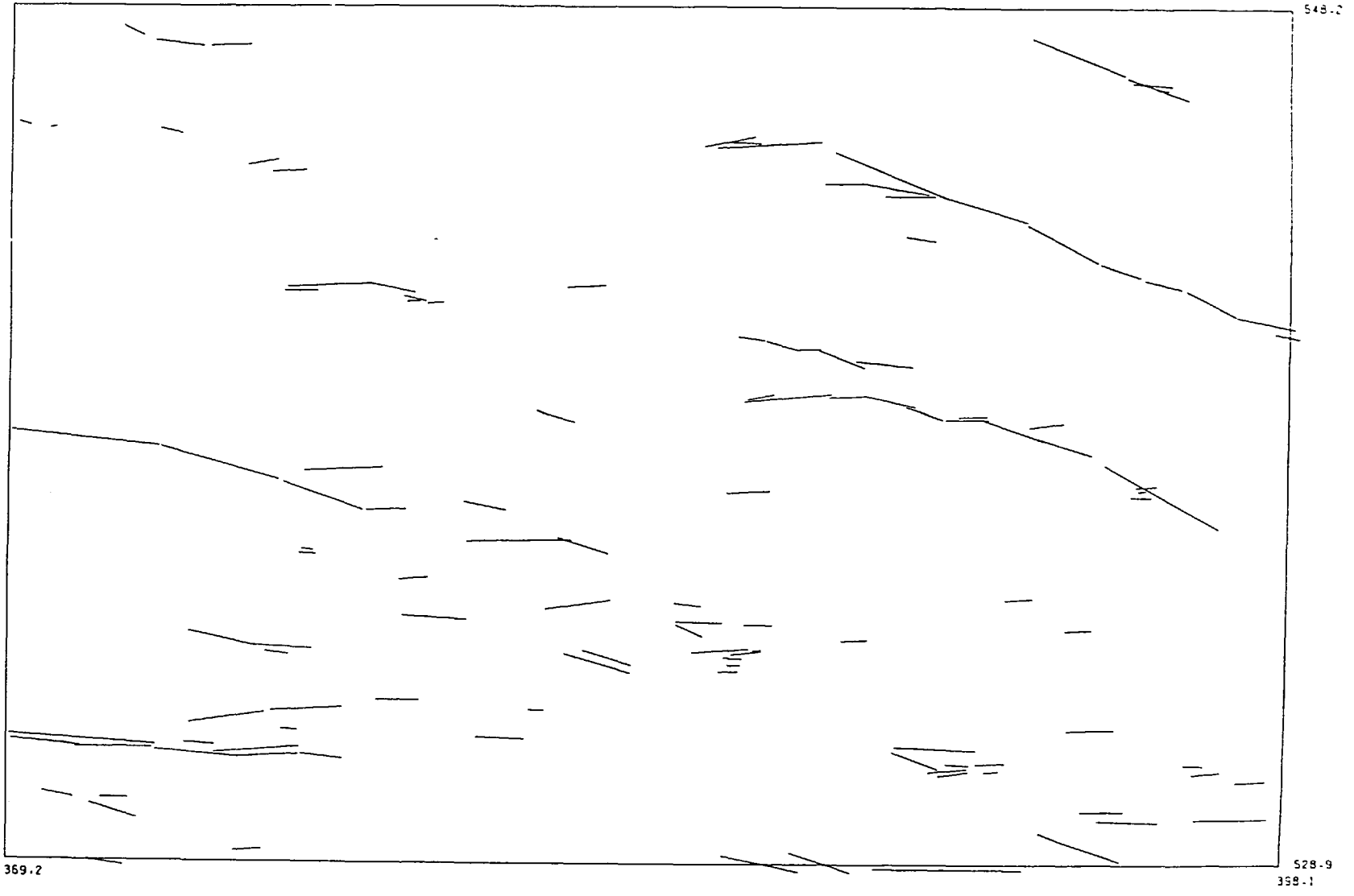


Fig.5.6 1:50,000 GEOLOGICAL MAP, ALSTON SHEET NO. 25
FRACTURE TYPE=2

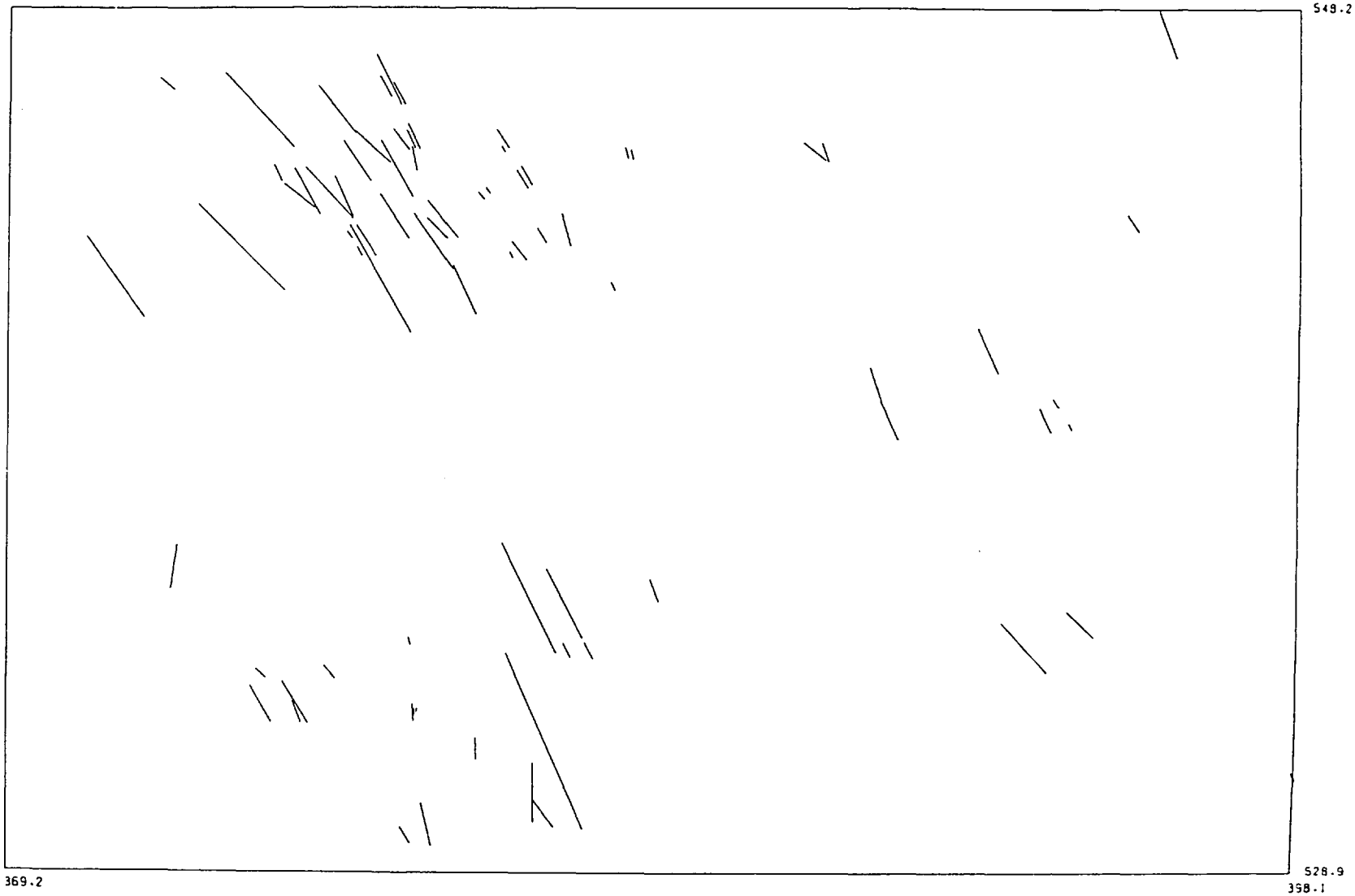


Fig.5.7 1:50,000 GEOLOGICAL MAP, ALSTON SHEET NO. 25
FRACTURE TYPE=3

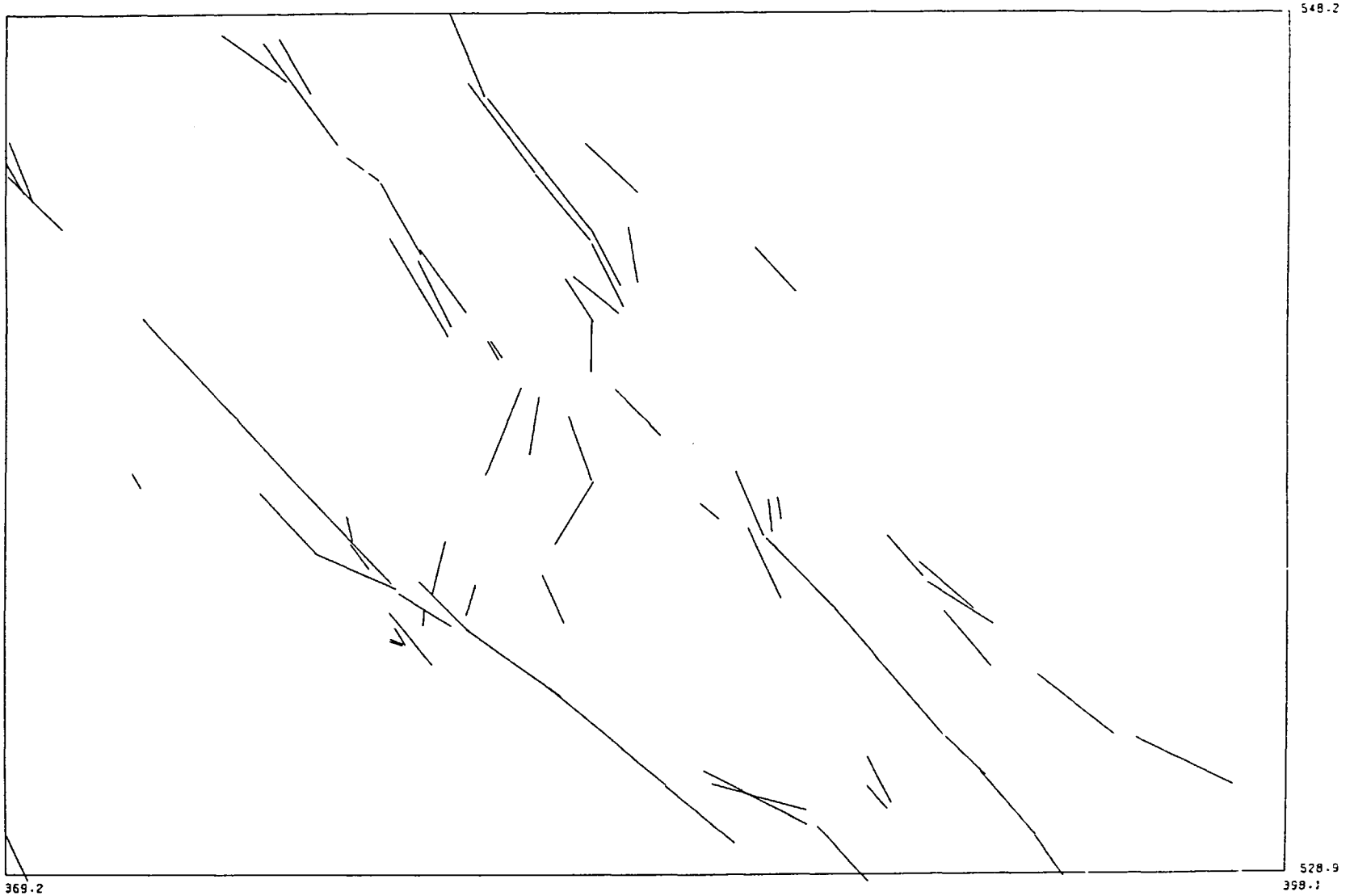


Fig.5.8 1:50,000 GEOLOGICAL MAP, ALSTON SHEET NO. 25
FRACTURE TYPE=4

fractures shown on the map were coded into four types; ENE veins (Fig 5.5); NNW veins (Fig 5.6); east-west veins (Fig 5.7); and faults (Fig 5.8). Statistical analysis was performed on each separate fracture type and the combined fracture set. The following statistics were calculated for the whole sheet, and for 4km by 4km grid cells (the map data were divided automatically by the computer program into grid cells):

(1) Frequency, length and average length rose diagrams
(2) Frequency and length densities per a 1km square
(3) Relative entropy
(4) Atypicality index

The directional (rose diagram) and density statistics are commonly used in fracture trace analysis (Norman, 1976). Calculation of relative entropy and the atypicality index are more unusual. The relative entropy expressed as a percentage, is a measure of the randomness of the strike directions of the fractures for the whole sheet or for each individual grid cell. A value of 100% indicates perfect randomness, a value of 0% indicates no randomness: all fractures would be parallel. The relative entropy is calculated using the following equation:

$$RE\% = \frac{-100*(\Sigma_{i=1,N} P^i(\log_2 P^i))}{\log_2 N}$$

Where; i=1,N are the class intervals used in the rose diagram (for 10^o classes, N=180/10=18)

P^i=Probability of a fracture falling into class i. This is equal to the relative frequency of fractures in class i divided by 100.

The atypicality index is a measure of the percentage of fractures whose strike differs from the average (or typical) directions. Figure 5.9 (from Pretorius and Partridge, 1974) shows a graph of the length of fractures versus their strike direction for an area in South Africa. The distribution shows two well defined peaks (B and D). Fractures having orientations close to these peaks can be regarded as being typical, similarly, fractures with orientations close to the frequency lows (A and C) can be classed as being atypical.

In the computer program FRACAN the angular intervals for atypical directions (u to v, w to x, and y to z in

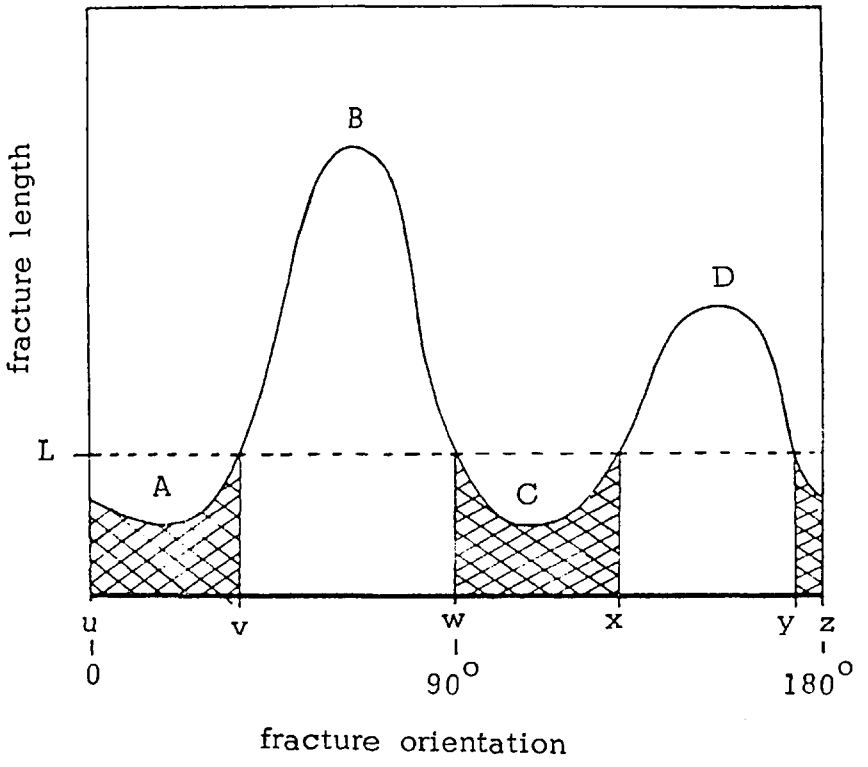
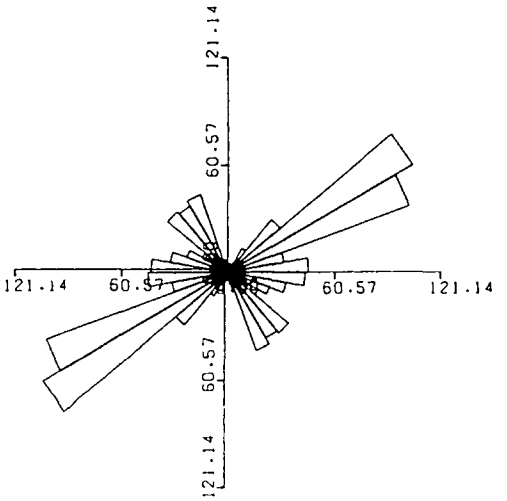


Fig. 5.9 Classification of atypical directions (from Pretorius and Partridge, 1974)

Figure 5.9) can be fixed for all fracture types, and the angular intervals are input into the program. Alternatively, the angular intervals can be automatically calculated by the computer; this is done by defining the percentage of fractures in the whole sheet to be classified as atypical. In Figure 5.9, the shaded area represents 20% of the total fracture lengths, using this value it is possible to find the cut-off frequency level (L). The angular atypicality intervals are found where L cuts the frequency curve. In this case 20% of the lineaments in the whole area strike atypically, and the atypicality index is 0.2. An atypicality index of 0 indicates that there are no fractures in atypical directions. An index of 1 indicates that all fractures are atypical. For smaller grid cells, the atypicality index is, of course, calculated only using those fractures in that cell.

5.2.2 Results and interpretation of fracture trace analysis

A complete listing of the output from FRACAN for the Alston geological sheet is given on Fiche 1. Figures 5.10 to 5.19 show length rose diagrams for each fracture type and the combined data set. These rose diagrams have been plotted for the whole sheet and each grid cell. Grid cells where rose diagrams are absent do not contain any fractures.



ROSE DIAGRAM OF WHOLE SHEET

Fig.5.10 1:50,000 GEOLOGICAL MAP, ALSTON SHEET NO. 25

FRACTURE TYPE=ALL FRACTURE LENGTH

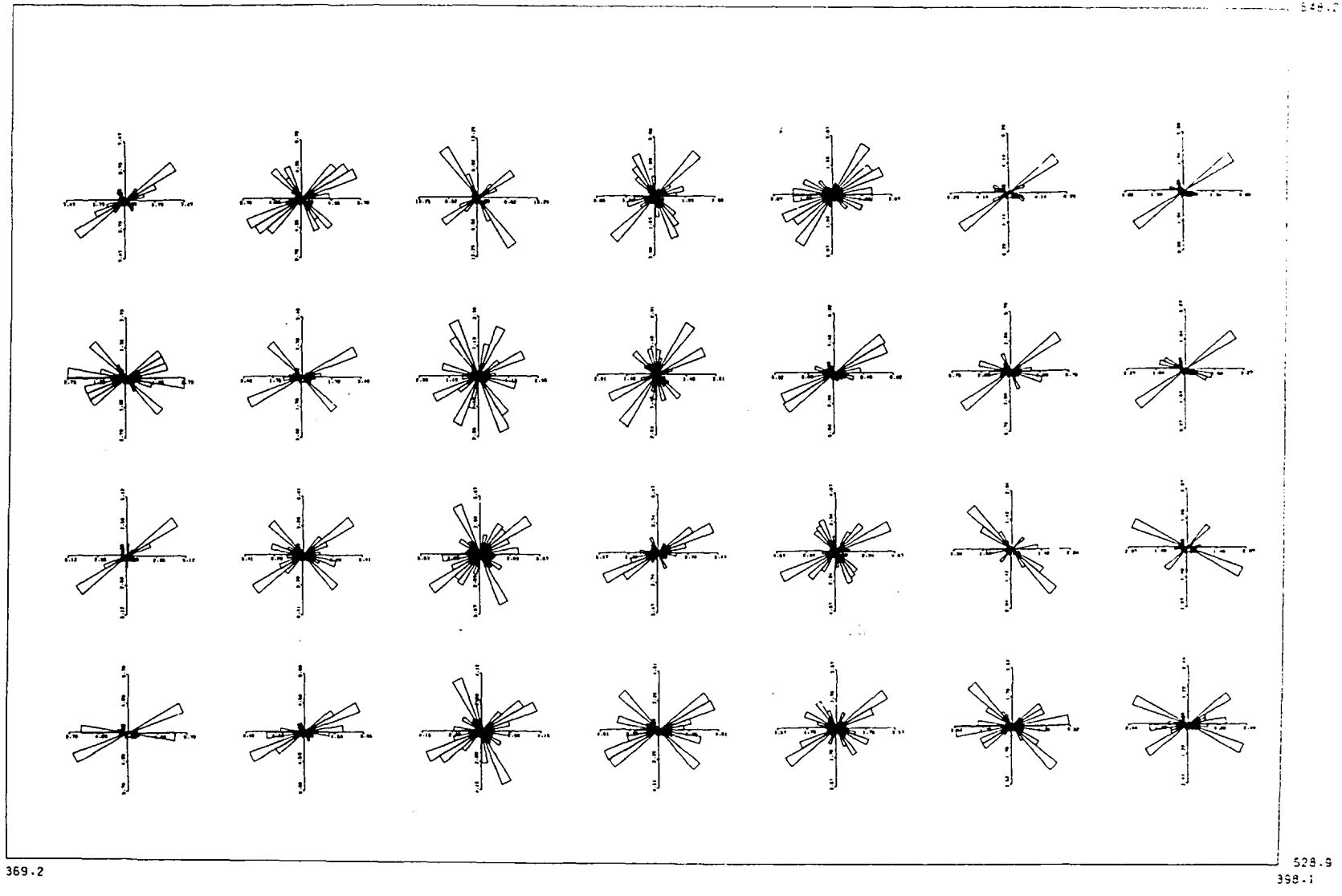
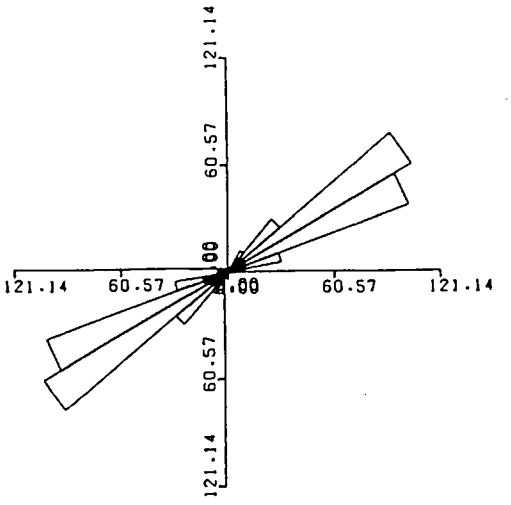


Fig.5.11 1:50,000 GEOLOGICAL MAP, ALSTON SHEET NO. 25
FRACTURE TYPE=ALL FRACTURE LENGTH



ROSE DIAGRAM OF WHOLE SHEET

Fig.5.12 1:50,000 GEOLOGICAL MAP, ALSTON SHEET NO. 25

FRACTURE TYPE=1 FRACTURE LENGTH

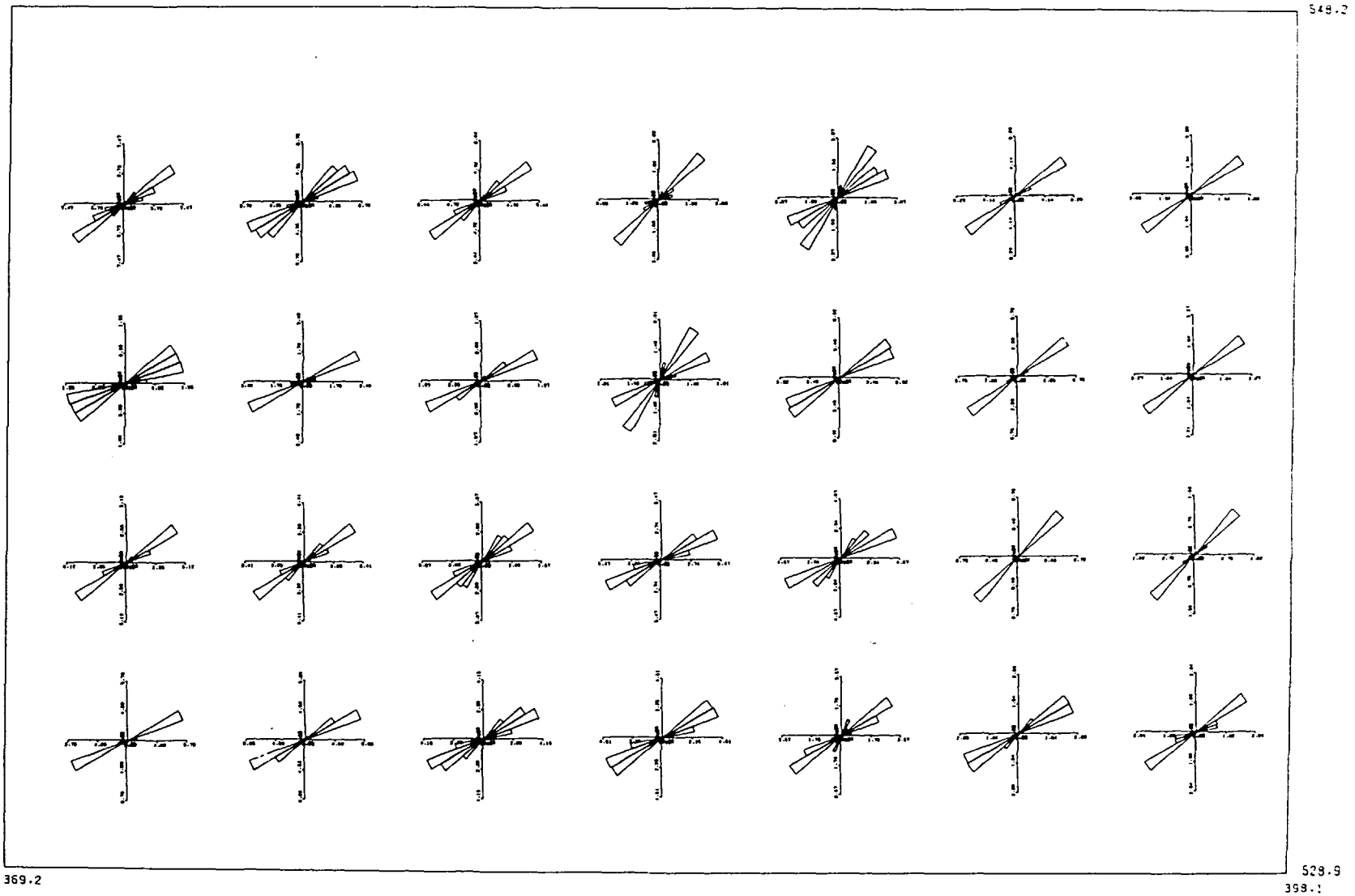
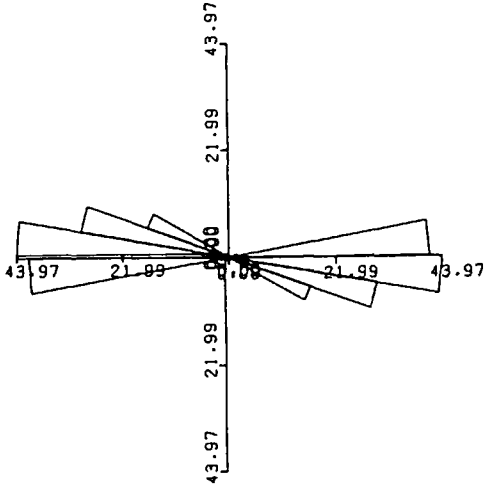


Fig.5.13 1:50,000 GEOLOGICAL MAP, ALSTON SHEET NO. 25
FRACTURE TYPE=1 FRACTURE LENGTH



ROSE DIAGRAM OF WHOLE SHEET

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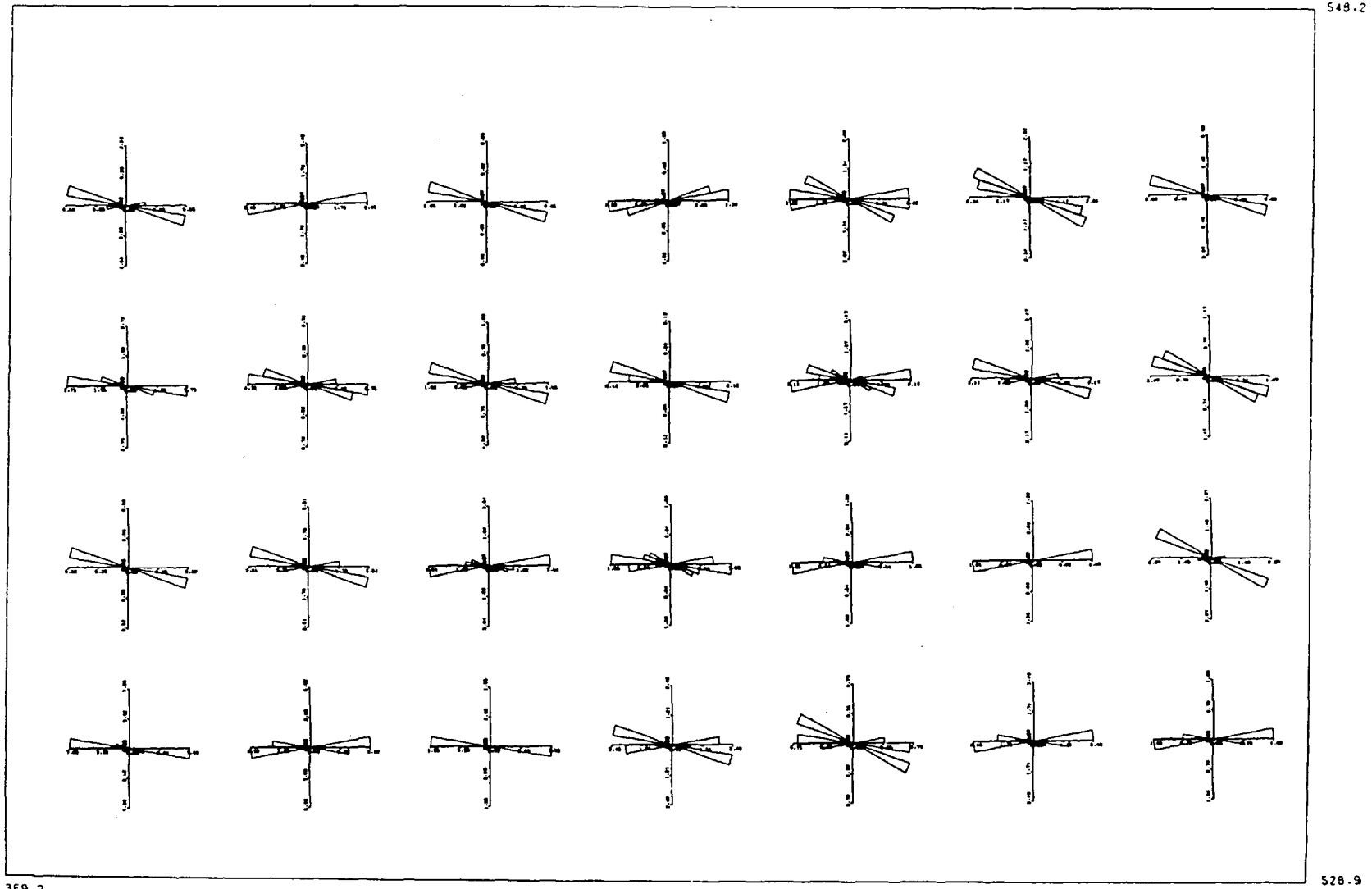
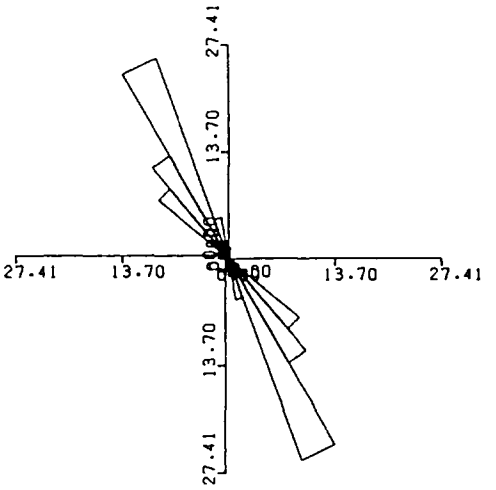


Fig.5.15 1:50,000 GEOLOGICAL MAP, ALSTON SHEET NO. 25
FRACTURE TYPE=2 FRACTURE LENGTH



ROSE DIAGRAM OF WHOLE SHEET

Fig.5.16 1:50,000 GEOLOGICAL MAP, ALSTON SHEET NO. 25
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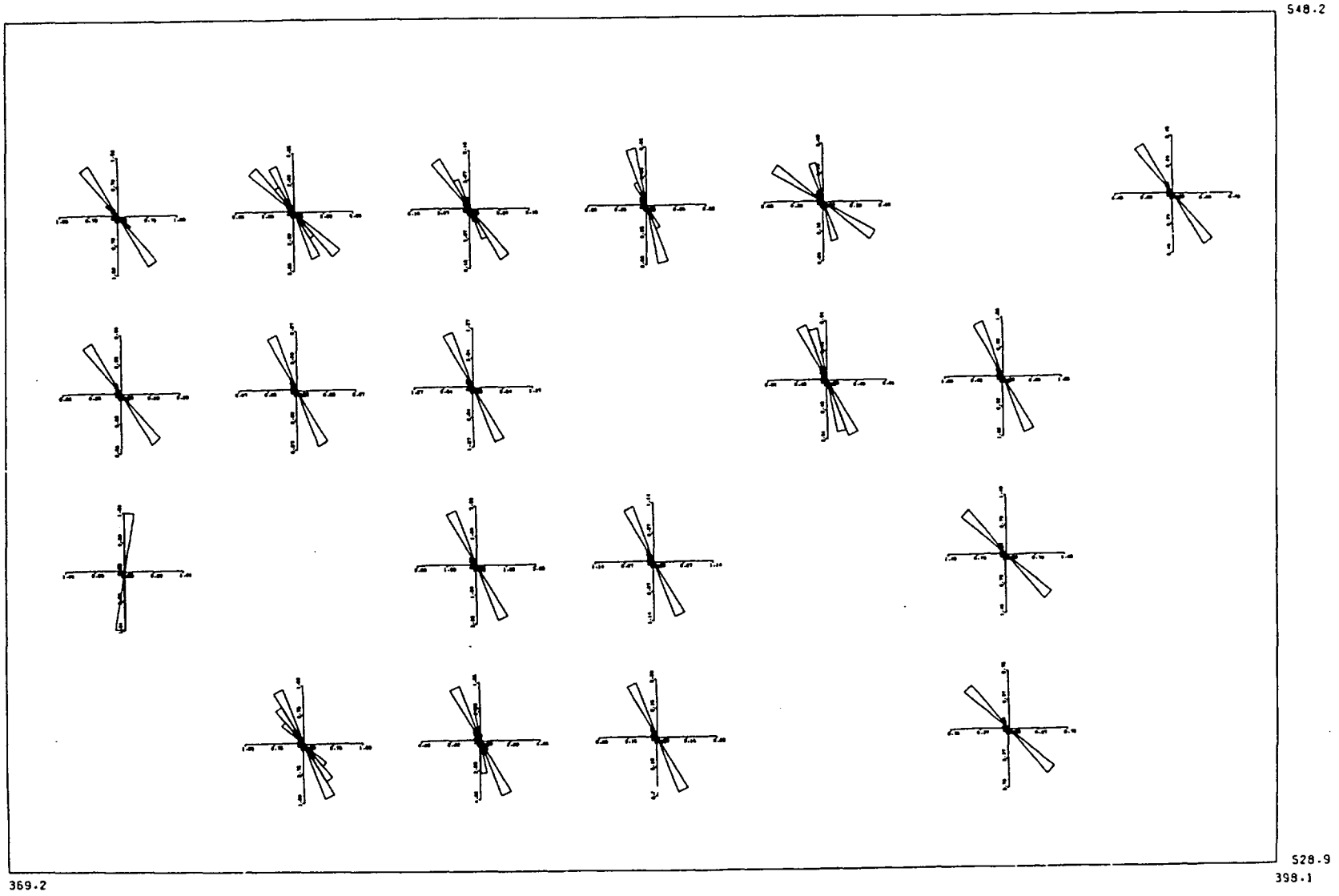
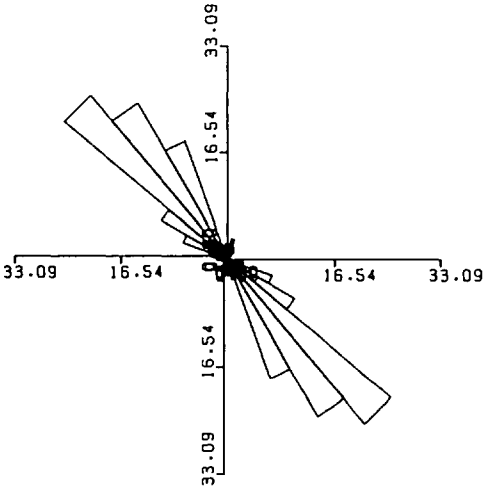


Fig.5.17 1:50,000 GEOLOGICAL MAP, ALSTON SHEET NO. 25
FRACTURE TYPE=3 FRACTURE LENGTH



ROSE DIAGRAM OF WHOLE SHEET

Fig.5.18 1:50,000 GEOLOGICAL MAP, ALSTON SHEET NO. 25
FRACTURE TYPE=4 FRACTURE LENGTH

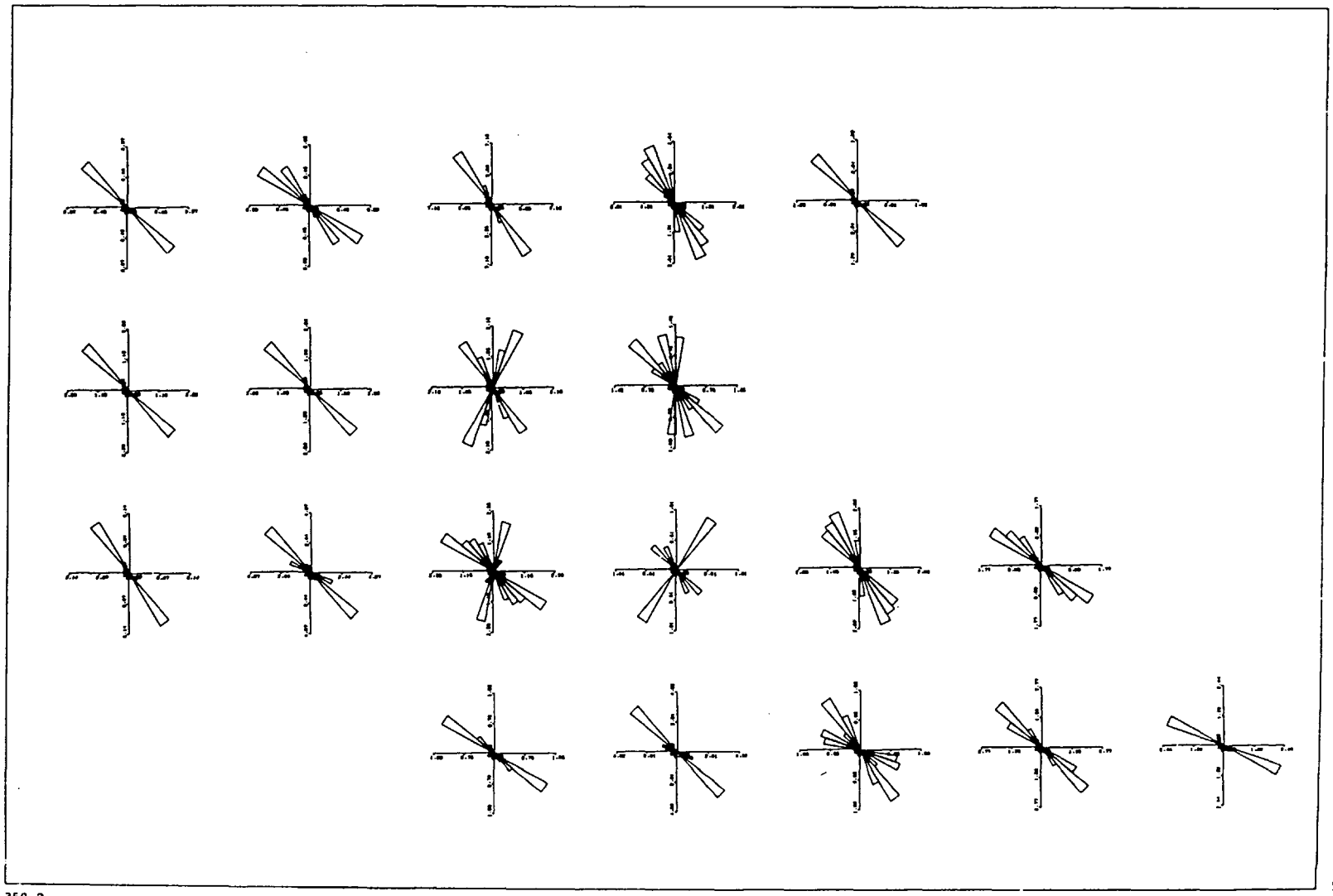
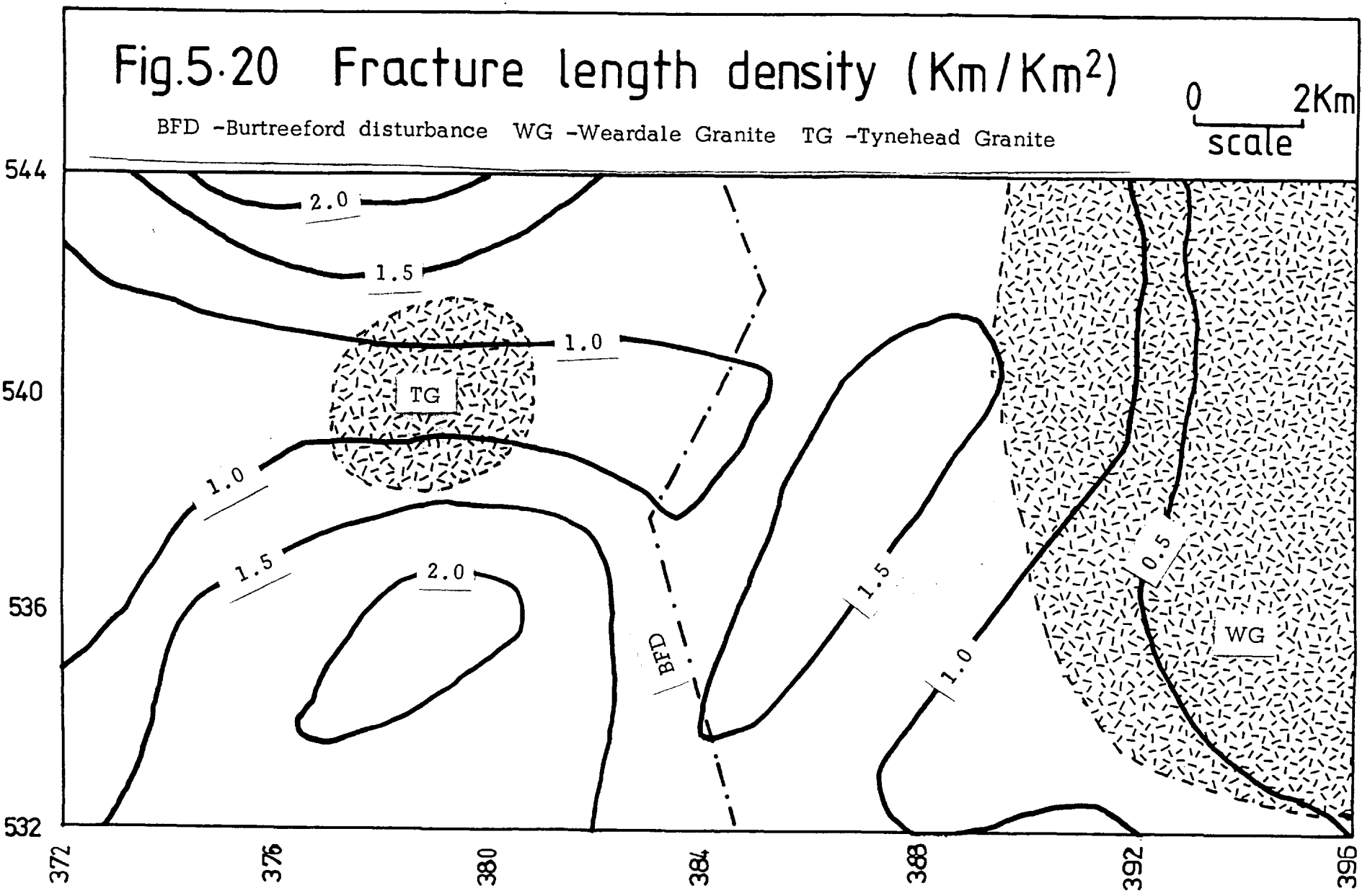
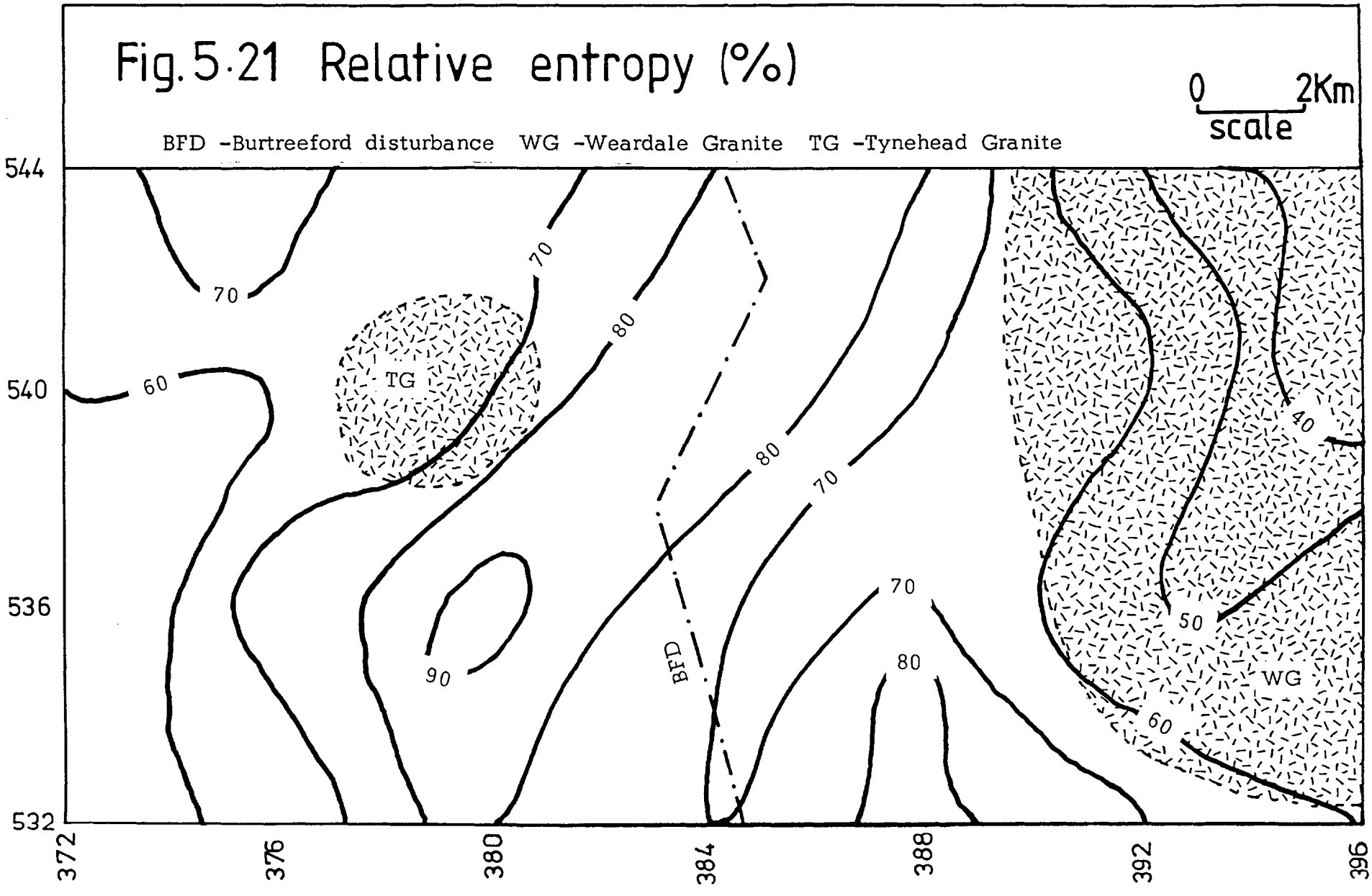


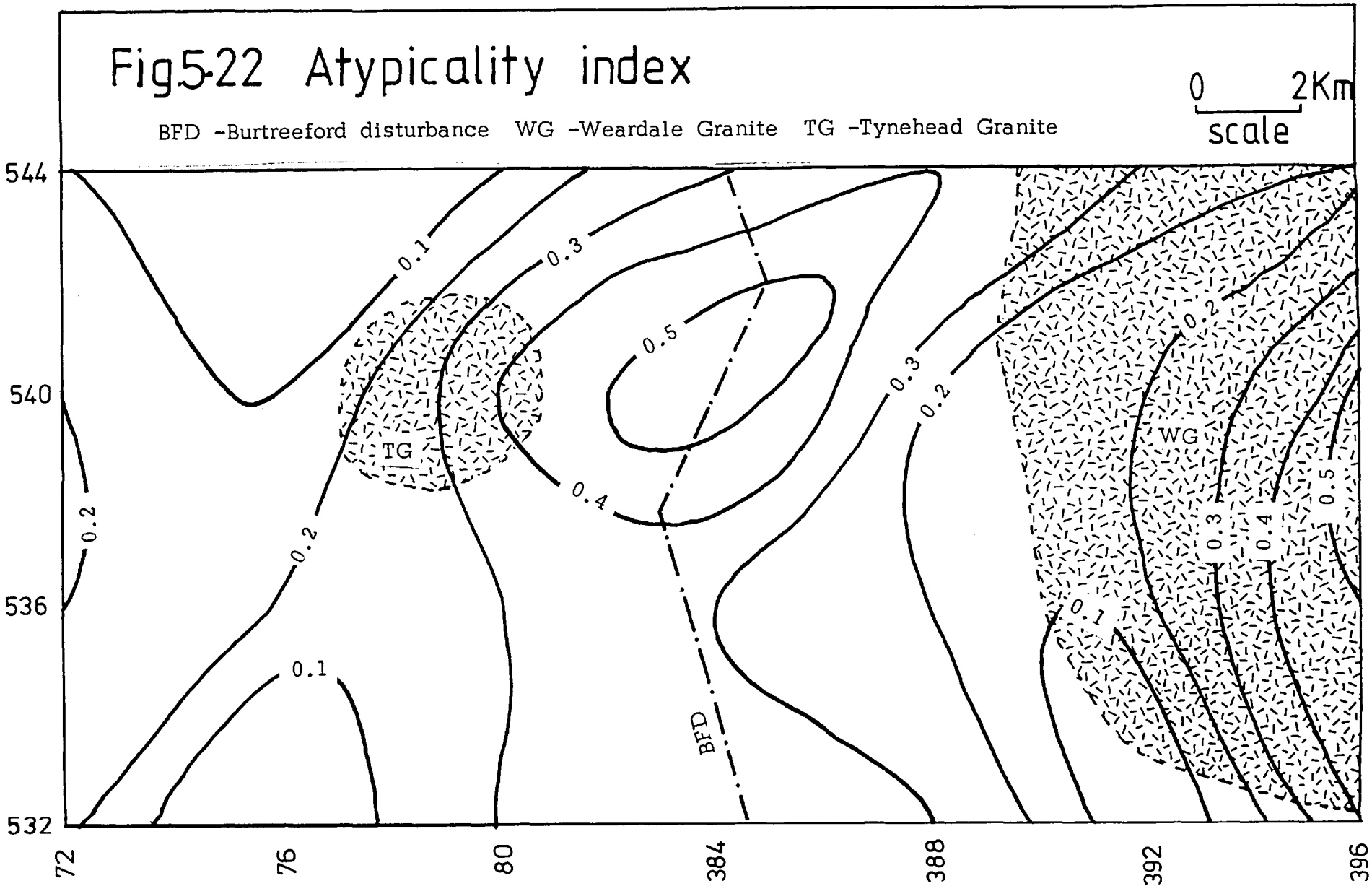
Fig.5.19 1:50,000 GEOLOGICAL MAP, ALSTON SHEET NO. 25
FRACTURE TYPE=4 FRACTURE LENGTH

The rose diagram for all fracture types on the whole sheet (Fig 5.10) shows the dominance of the ENE vein set. These veins, striking between 40^{o} and 60^{o}, account for 36% of the total vein lengths. The NNW vein direction shows an ill defined peak around 335 degrees. Veins in the east-west direction are present in a similar proportion to the NNW veins, about 20% of the total vein lengths. The ENE veins are dominant over most of the orefield (Fig 5.11), except in grid cell number 13 (the grid cells are numbered in rows from the bottom left corner). Few veins occur in grid cell number 13, the main fracture is the NNW striking Westernhope Old Vein. The spatial distribution of the ENE, east-west and NNW vein directions (Figs 5.13, 5.15 and 5.17) have already been treated under the discussion of trend surface analysis.

The values of length density relative entropy and atypicality index have been contoured (Figs 5.20, 5.21 and 5.22). The length densities expressed in kilometres of fractures per a km^2, show two regions of lows (Fig 5.20), centred on grid cells 16 and 21 (equivalent to national grid co-ordinates NY760400 and NY960400 respectively. The relative entropy around grid cells 16 and 21 (Fig 5.21) are less than 60%. These grid cells coincide with the approximate cupolas of the underlying Weardale Granite at Tynehead and Weardale. The analysis suggests that veins over the granite cupolas are present in fewer numbers than


Fig.5·20 Fracture length density (Km/Km²)
BFD -Burtreeford disturbance WG -Weardale Granite TG -Tynehead Granite
0 2Km
scale
544
540
536
532
372
376
380
384
388
392
396
2.0
1.5
1.0
TG
1.0
1.5
2.0
BFD
1.5
1.0
0.5
WG


Fig. 5·21 Relative entropy (%)
BFD -Burtreeford disturbance WG -Weardale Granite TG -Tynehead Granite
0 2Km
scale
544
540
536
532
372
376
380
384
388
392
396
70
60
80
70
90
80
70
70
80
40
50
60
TG
WG
BFD


Fig5-22 Atypicality index
BFD -Burtreeford disturbance WG -Weardale Granite TG -Tynehead Granite
0 2Km
scale
544
540
536
532
372
376
380
384
388
392
396
0.1
0.2
0.3
0.4
0.5
TG
WG
BFD

in the surrounding sediments, and that these veins show a moderately strong prefered orientation over the cupolas. This latter result is unexpected; typically the fractures above a granite cupola show radial fracture patterns due to up-doming of the sediments (Norman,1976).

The granite in the northen Pennines pre-dates the Carboniferous sediments, and its intrusion could not therefore have up-domed the Carboniferous sediments. Doming of the sediments could only occur by uplift of the granite basement. The association of low fracture length density and relative entropy with the granite cupolas may be explained by the rigidity provided by the underlying granite. Where the Carboniferous sediments were underlain by Lower Palaeozoic rocks, fracturing would have taken place more easily, to give higher vein length densities. The more random distribution of fractures in areas away from the granite cupolas may partly be explained by failure along pre-existing fractures in the Lower Palaeozoic rocks, which are present in many orientations.

Atypicality analysis shows little correlation with the granite cupolas, nor with the vein length density and relative entropy maps. However, a high atypicality index of 0.6 in grid cell 18 (NY840400) is centred on a segment of the Burtreeford disturbance, where the disturbance is running on an abnormal NNE trend. The increase in atypicality index at this point can be explained by the

generation of local fractures, associated with the Burtreeford disturbance. The Burtreeford disturbance is a reverse fault along this NNE section, indicating that it was subject to high compressive stresses. The rose diagram for veins of type 1 in grid cell 18 shows a moderately strong development of NNE to NE veins, parallel to the disturbance. These fractures may have been generated as the reverse faulting of the disturbance, and would explain the high atypicality index.

5.3 Joints

Joints were measured in many of the quarries and exposures in the central part of the orefield, and underground at Blackdene Mine. The joints were analysed using the computer program ROSEPT to draw frequency and length rose diagrams. The distribution of the joints and joint patterns were studied on regional and local scales.

5.3.1 Regional joint patterns

Dunham (1933) in his analysis of joint trends in the orefield presented the results of his study of jointing in the Stanhope quarries (NY995397). He later stated that joint patterns similar to those seen in the Stanhope quarries persisted across the Alston Block (Dunham, 1948).

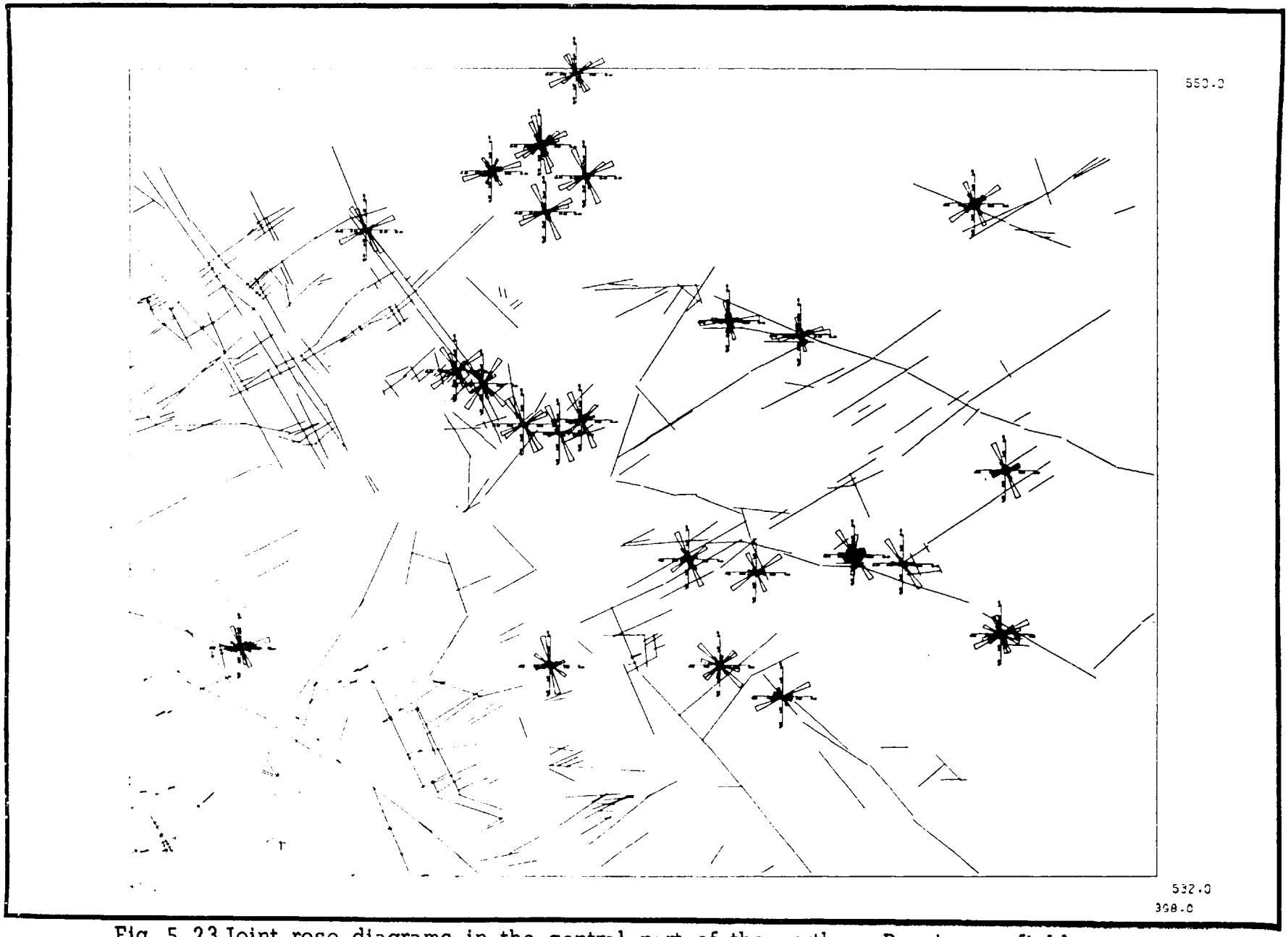


Fig. 5.23 Joint rose diagrams in the central part of the northern Pennine orefield

A detailed study of joint patterns in the central part of the orefield has shown that this is not the case. The strike of the two main joint sets average 070° and 165°. A less frequent set strikes between 085° and 105°. At most of the localities where joints were recorded, these three peak directions in the joint frequency are parallel to the nearby veins (Fig 5.23). The east-west joints are mainly developed adjacent to the quarter-point veins.

5.3.2 Joints in Teesdale

In the Cockleshell Limestone near Newbiggin in Teesdale (NY910273) joints are present in several directions. These joints can be relatively dated, based on offsetting relationships and mineral infillings (Fig 5.24). Five joint sets have been identified:

(1) 050° to 060°:- Dextral shear joints. Displace crinoid fragments 3mm, but other joints only offset 0.5mm. Calcite and siderite infilling.

(2) 080°:- Extension joints. May be deflected into the trend of the 050° set. Upto 3mm of fluorite infill.

(3) 115° to 125°:- Sinistral shear joints. Displace the extension joints of set 080° set by

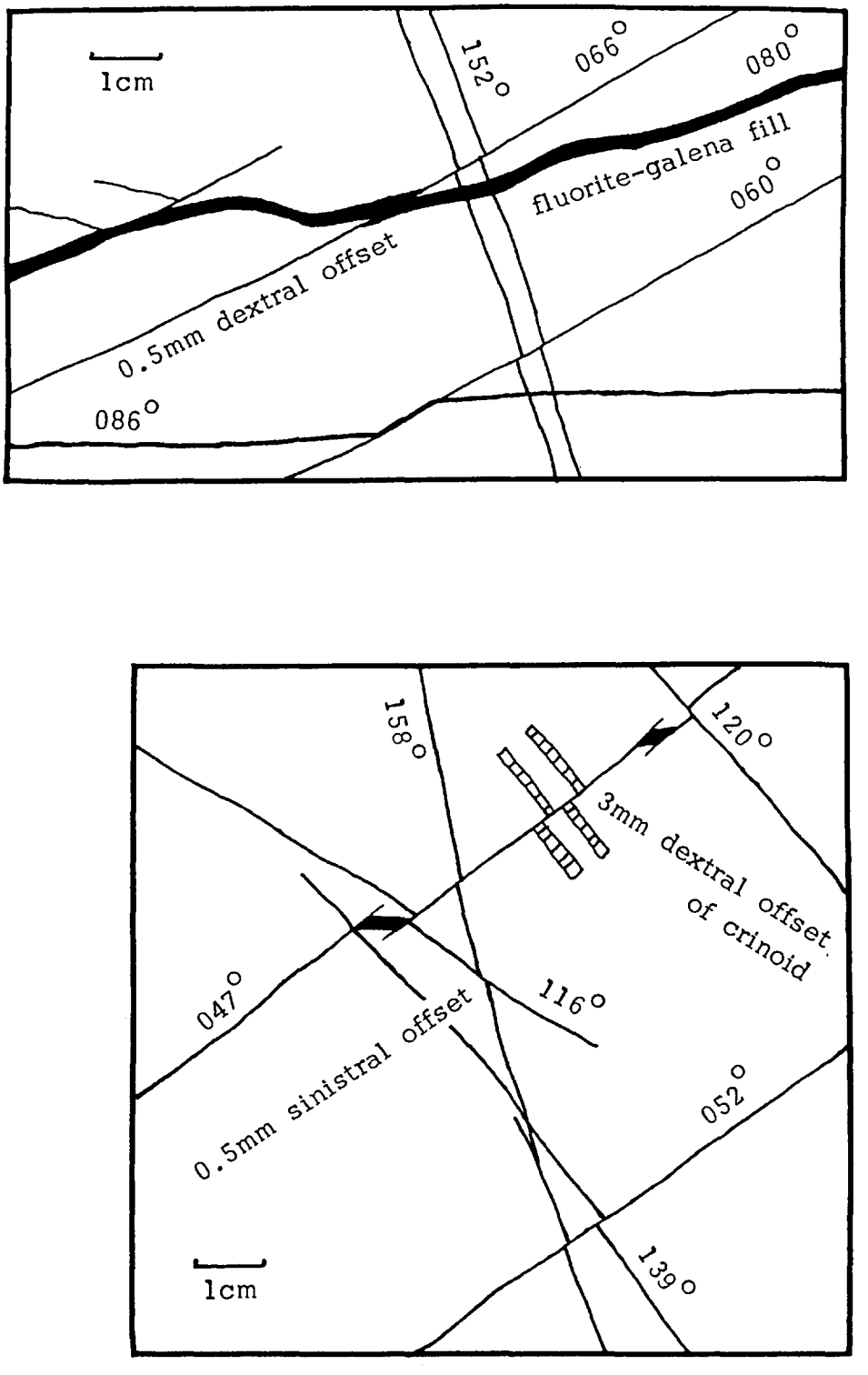


Fig. 5.24 Sketch of joints in the Cockleshell Limestone, Teesdale

0.5mm. Thin calcite and siderite infilling.

(4) 140°:- Rarely present. Possibly shear joints, although direction of movement is variable. Calcite infilling.

(5) 150° to 160°:- Extension joints. Generally barren or with a thin flim of calcite. Slightly displaced by shear joints of sets 1 and 3.

Calcite infilling in the joints does not necessarily mean that the joints pre-date the mineralization; the calcite could have been locally remobilized from the limestone by pressure solution. However, the fact that there is fluorite and siderite in some of the joints lends support to Dunham's (1933) assertion that some jointing did indeed precede mineralization.

5.3.3 Jointing history in Teesdale

Invoking Price's (1966) explanation for the formation of joints during post-compressional uplift, the following sequence of events seems plausible for the formation of joints in Teesdale:-

(1) During the early stages of deformation s_1 was directed towards the ENE, with s_2 vertical. Dextral and sinistral shear joints developed at 050° and 120° respectively (sets 1 and 3). Total horizontal displacement along these joints at this time was in the order of 2.5mm.

(2) The initiation of the shear joints caused a release of residual stresses in the ENE direction tending to reduce s_1 and increase s_3, and the vertical load due to gravity took on the role of the maximum principal stress. Uplift of the sediments caused the horizontal stresses to become tensile, and extension joints developed (sets 2 and 5). The extension joints of set 5 (150° to 160°) are most frequent. Price (1966) states that bc joints (perpendicular to the direction of the maximum stress during tectonic compresssion) are generally the most common joints in rocks that have been uplifted. The joints of set 5 are thus interpretated as bc joints, which would imply thatthe pre-joint direction of s_1 was towards the ENE-WSW.

(3) Following the uplift, and formation of the shear and extension joints, there was a period of renewed compression from the ENE resulting in the formation of the quarter-point veins in Weardale. Mineralization was concurrent with the compression, opening and filling the extension joints of set 2.

Some renewed shear movement occurred along the existing shear joints of sets 1 and 3, together with the deposition of thin films of siderite and/or fluorite along these joints.

5.3.4 Jointing in the Tyne-Tees tunnel

The Tyne-Tees tunnel, part of the Kielder water scheme, extends for 40km through the eastern part of the orefield to transfer water from the River Tyne to the rivers Wear and Tees (Fig 5.25). The two main tunnels (Derwent to Wear and Wear to Tees) were driven in four sections: (1) South Derwent portal (NZ041508), to Waskerley air shaft (NZ023445); (2) Waskerley air shaft to north Wear portal (NZ011377); (3) South Wear portal (NZ011371) to Sharnberry air shaft (NZ007308); (4) Sharnberry air shaft to Tees portal (NZ002225). The tunnels traverse strata of the upper Alston Group and lower Namurian, including the Little Whin Sill, Hett dyke and Cleveland dyke. Several major faults and mineral veins were also intersected. During the driving of the tunnels, geological logs were made by the consulting geologist, together with measurements of joints along 100m sections. The joints in tunnel sections 1 and 4 are shown in Figure 5.27. The strike direction of maxima in the joint frequency are shown in this diagram. The corresponding geology along these sections of the tunnel is shown in Figure 5.26.

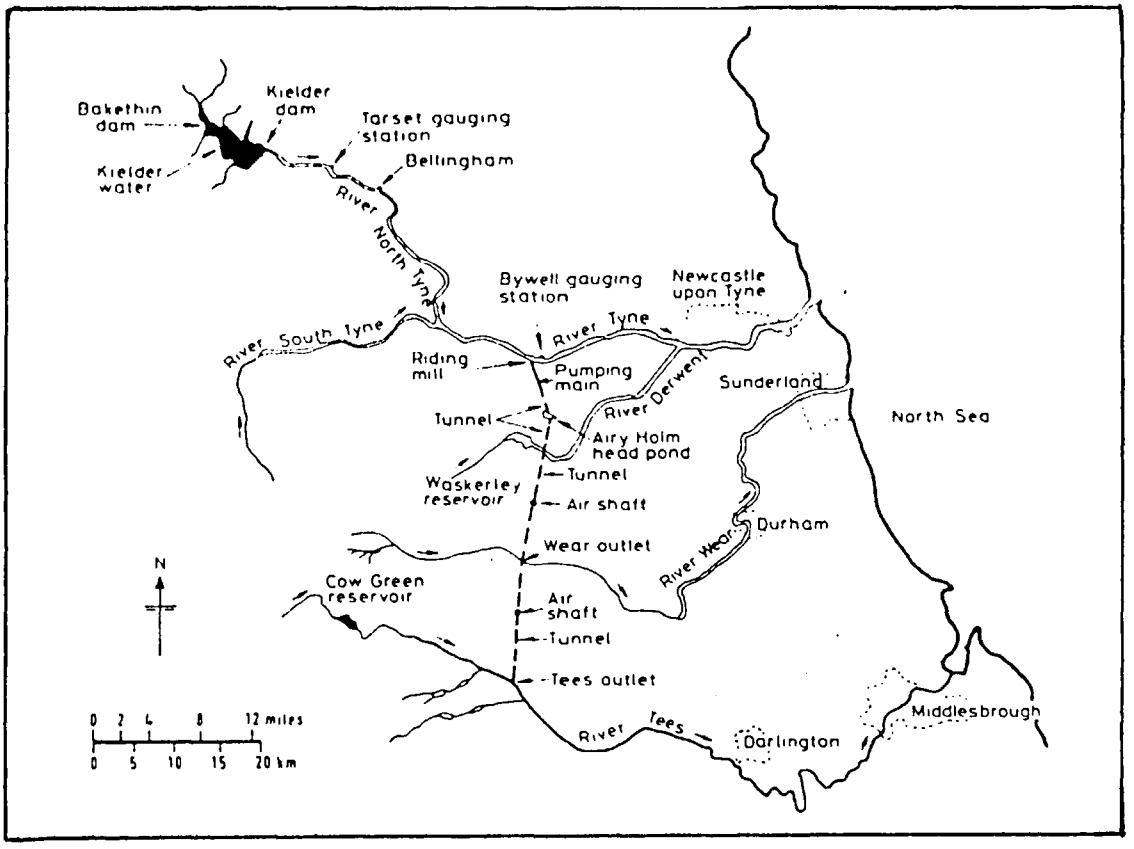


Fig.5.25 Plan of the Tyne-Tees Tunnel (from Berry, 1980)

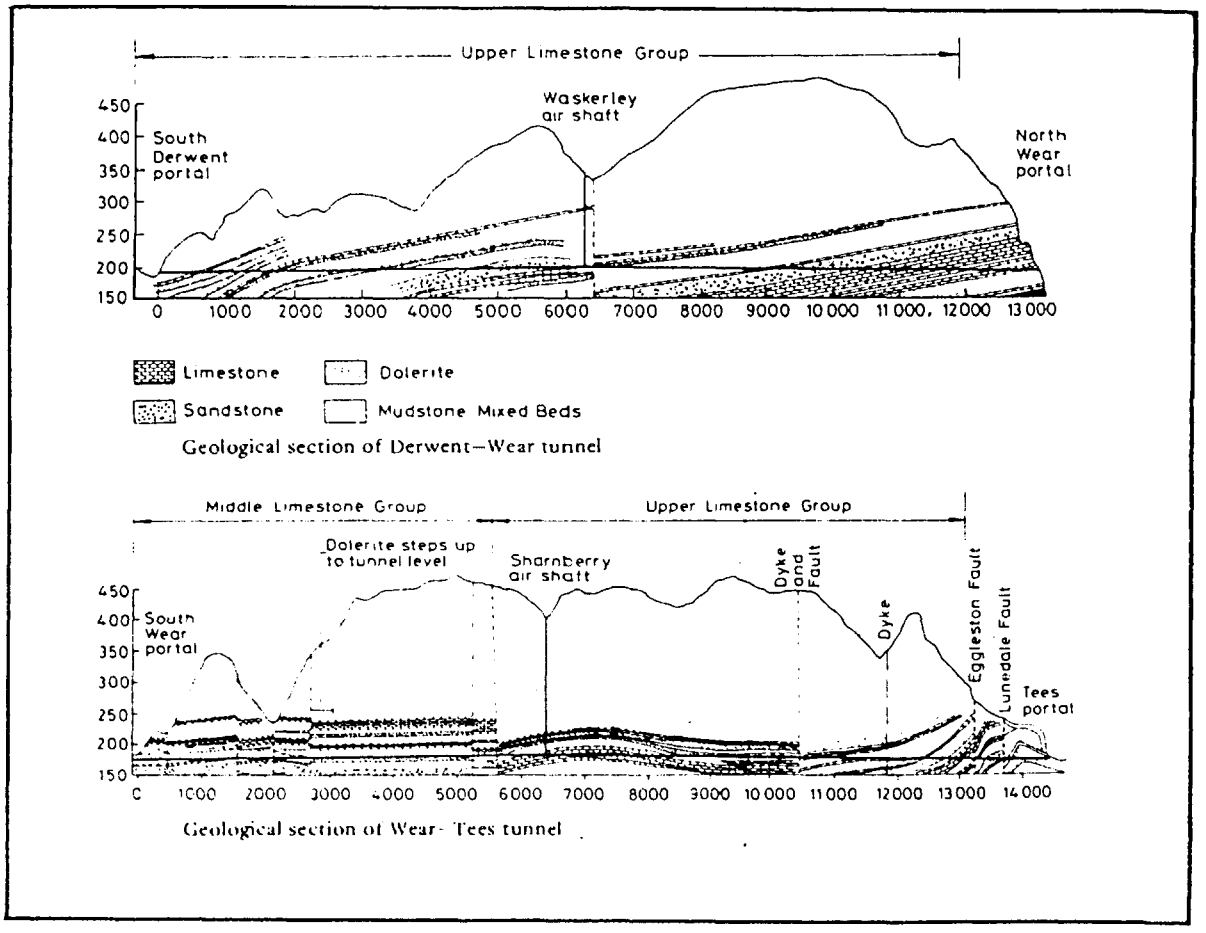


Fig. 5.26 Geological sections of the Tyne-Tees Tunnel (from Berry, 1980)

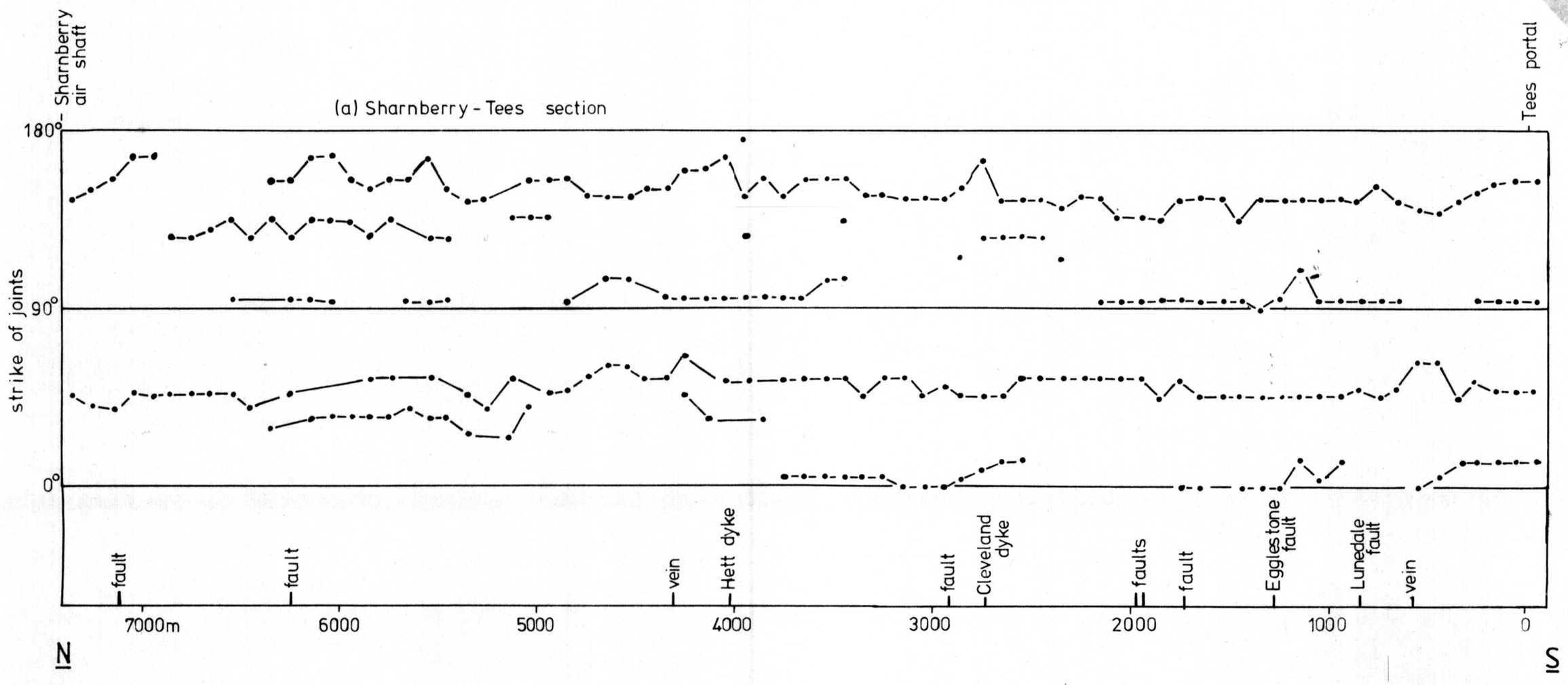
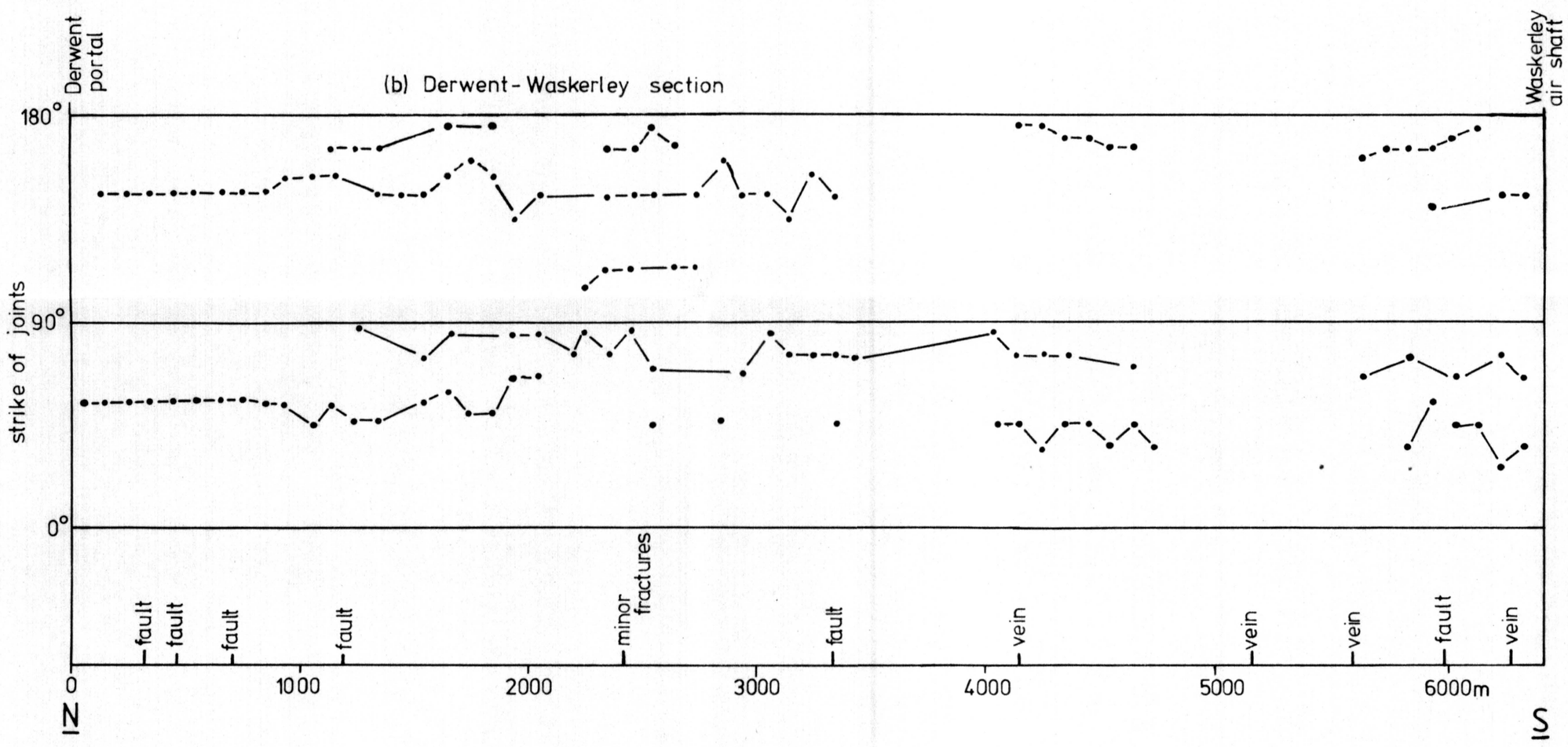


Fig.5.27 Joints in the Tyne-Tees Tunnel (published by permisson of the Northumbrian Water Authority)



Generally more than two joint sets are present along the tunnel, although the NE to ENE, and NNW sets are dominant. In tunnel section 1 these two joint sets have average directions of 075° and 165° respectively. Other joint sets have strike directions of 045°, 110° and 145°. The joints in each set show variations about these mean values, but the variations do not appear to coincide with any of the major structures encountered in the tunnel. It is impossible to fully assess the variations in joint frequency along the tunnel; only rose diagrams for the relative percentage of joints were supplied by the consulting geologist. However, notes accompanying the tunnel logs record an increase in jointing and fracturing towards major faults and veins. The orientation of the five joint sets are similar to those described in the Cockleshell Limestone in Teesdale, and a similar history to their formation is probable.

Joints along the Sharnberry air shaft-Tees section are grouped into six sets; 010°,030°, 050°, 095°, 130° and 150°. The joint sets are comparable to those along the first section of the tunnel, except the average strikes are all rotated anticlockwise by about 20°. The 010° set, or its equivalent are rarely developed in the Derwent-Waskerley section of the tunnel. Joints of this set may have been generated as shear joints, and are complementary to the 130° set. The differences in overall

strike of the joints along the two sections of the tunnel may be explained by either; (1) differences in the orientation of the stress field between the two sections; or (2) rotation of the joints along one section by basement wrench movement.

5.3.5 Local joint patterns adjacent to veins in Teesdale

Joints adjacent to mineral veins in the Whin Sill of Teesdale were studied to investigate changes in joint frequency and direction away from the veins. The Whin Sill at Wynch Bridge, Teesdale (NY903278) lies beneath the sandstone which occurs between the Scar and Single Post limestones. The upper junction between the sill and the sandstone is exposed 0.5km south-east of Wynch Bridge at NY908274. Both the sediments and the sill are cut by at least nine siderite-sphalerite veins, striking NE and ENE. The most westerly deposit has been opened up for 120m to the south-west and has proved fissure and replacement mineralization in the Single Post Limestone (Dunham, 1948).

Joints are present in the sediments and the whin. Joints in the Cockleshell Limestone, above the Whin Sill 1km south of Wynch Bridge, have already been described. In the whin, jointing is less regular than those in the surrounding sediments, and have to be distinguished from

columnar cooling joints. The columnar joints bound vertical polygonal prisms of whin, and are commonly coated with a thin film of chlorite and are calcite filled (Spears, 1961).

In the bed of the River Tees are several flat exposures of the whin, cut by barren or siderite filled veins. A particularly pronounced siderite vein was selected, and the joints were recorded along lines perpendicular to the vein by the following method:-

A tape measure was placed on the ground, stretching away from the vein. Photographs were then taken along the line of the tape, and each frame covers just over $0.5m^2$ on the ground. A compass was included in each frame in order to record its orientation. After printing, a box covering $0.5m^2$ of the ground was drawn on each photograph, and the joint traces within the box digitized. A computer program was used to calculate the joint strikes from the digitized data, and draw rose diagrams for each photograph. This method was chosen because;

(1) The photographs would provide a permanent record of the joints and veins and the joints could easily be remeasured without revisiting the locality.

(2) Joints were present at all scales in the outcrops, and the resolution of the photograph would set a lower limit to the size of joints included. If the joints were measured in the field, then it might not have been possible to consistently select joints above a certain size.

(3) A considerable amount of time was saved; digitizing the joints was much faster than measuring their orientations in the field.

Figure 5.28 shows the variations in total number of joints, total length of joints and peak joint directions along lines to the north and south of the reference vein. The total number and length of joints (per $0.5m^2$) show peaks adjacent to the main vein and other known veins 45m and 64.5m to the north, and 4m to the south. The increase in jointing adjacent to the veins may be explained by an increase in residual strain energy in the rocks near to the veins, after the vein fracture had formed. On uplift the residual strains will result in high residual stresses, which can only be released by an increased number of fractures (Price, 1966). There are several points along the measured lines, where moderately high values of joint numbers and lengths do not appear to coincide with any known veins. These are interpretated as veins where the stress was concentrated, but was not enough to cause faulting. Consequently large strains built

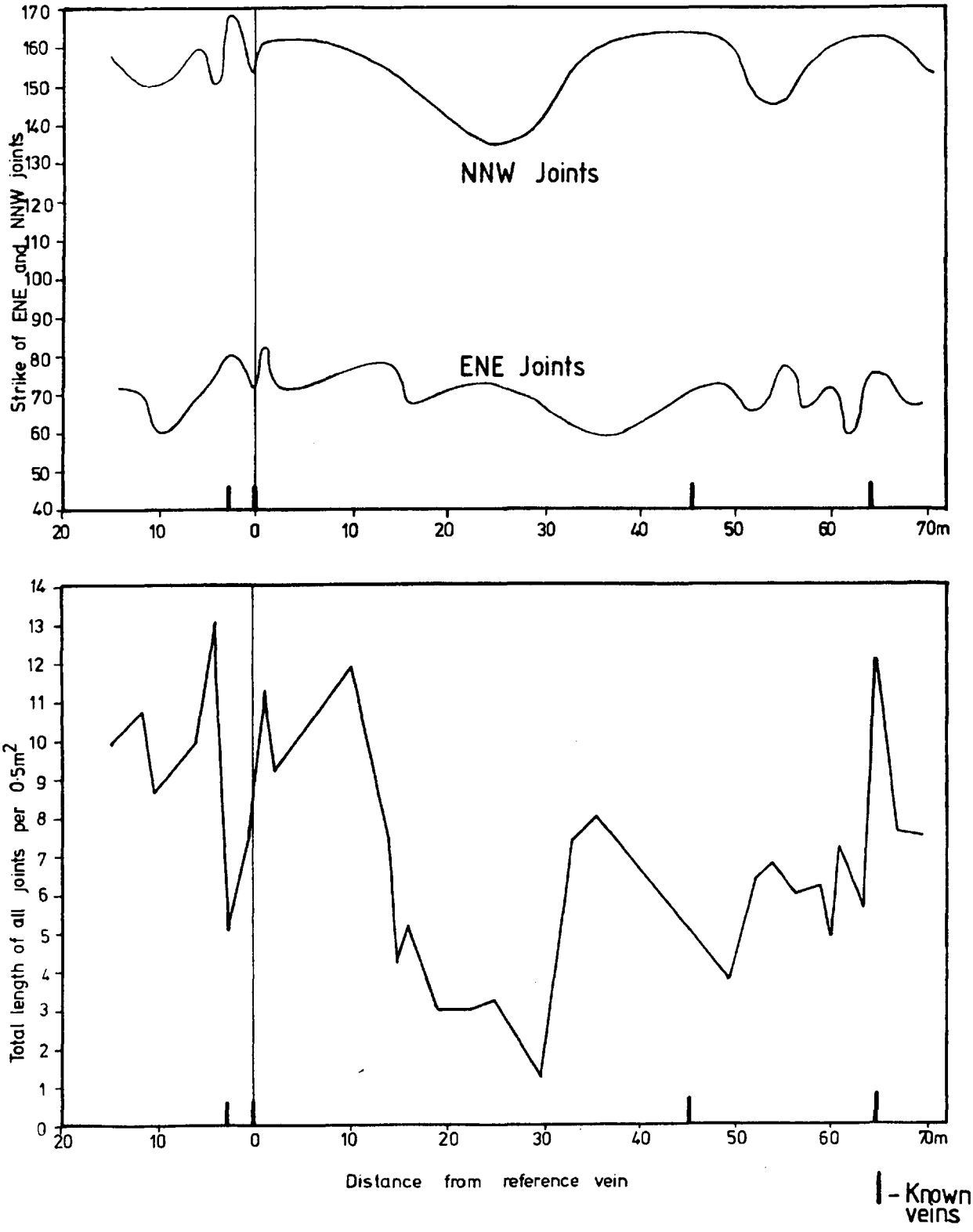


Fig.5·28 Joints in the Whin Sill near Wynch bridge

up in the rock, to be released by jointing.

The NNW joints also show high angles of strike near to the known veins. The strike of the NNW joints adjacent to the veins is 160°-165°, whilst between the veins their strike is upto 30° less. The apparent clockwise rotation of NNW joints adjacent to the veins suggests that dextral strike-slip movement has occurred along the veins. Where peaks in joint frequency and length do not coincide with known veins, there is no corresponding rotation of the NNW joints; supporting the idea that stress built up in the rocks, but the stress ratio was not large enough to cause faulting.

The strike of the ENE joints is more erratic than the NNW joints, and shows little correlation with the known veins. A third joint set is often present striking 050°, and the erratic nature of the ENE joints may partly arise from difficulties in distinquishing between the ENE and NE joint sets. In addition new fractures in the NE direction may have been generated by the movement along the veins.

5.3.6 Joints in Blackdene Mine

Over nine hundred minor fractures have been measured in Blackdene Mine, and a summary of their angular

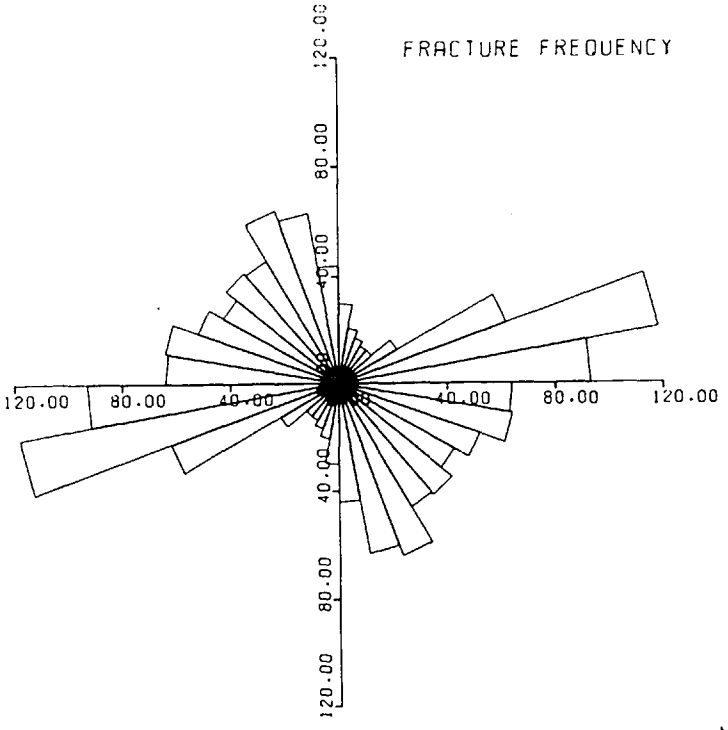


Fig.5.29 JOINTS IN BLACKDENE MINE N=927

distribution is shown in Figure 5.29. It cannot be certain that all the fractures measured in the mine are joints in the strictest sense; many may have been generated during the formation of the veins. Fractures associated with the vein formation may explain the large spread of values in the rose diagram. Nevertheless, the ENE joint direction can be discerned striking between 70° and 80°.

5.4 Conclusions from fracture trace analysis

The spatial distribution and orientation of fractures of all sizes have been controlled to some extent by structures on a larger scale than the fractures themselves: vein fractures are influenced by large, deep-seated, wrench faults and by variations in the composition of the basement; joints are partly controlled by local vein and fault patterns. The main results and interpretations of the fracture trace analysis are: -

(1) Trend surface analysis has indicated the presence of linear zones, or lineaments, across the orefield, within which the vein traces have been systematically rotated when compared with their mean directions. The rotation of veins within these linear zones is interpretated to be the result of strike-slip movement along basement faults, after the generation of the vein fractures. These inferred basement fractures are speculated to have formed in

pre-Carboniferous times. In the basinal areas the basement fractures were active in controlling Carboniferous sedimentation. On the Alston Block they appear to have been destroyed by the intrusion of the Weardale Granite, and were rejuvenated during the later stages of the Hercynian orogeny.

(2) Statistical analysis of vein directions and densities in the Central part of the orefield reveals that the vein fractures were partly controlled by the cupolas of the underlying granite. Curiously, the analysis suggests that veins in the strata over the granite cupolas are present in fewer numbers than in the surrounding sediments, and that these veins show a moderately strong preferred orientation. The fracture density may be explained by the rigidity of the granite inhibiting fracturing. The more random distribution of vein fractures in the Carboniferous strata underlain by Lower Palaeozoic rocks, may be due to the presence of many lines of weakness in the basement rocks.

(3) Five joint sets have been identified in the Cockleshell Limestone near Newbiggin, Teesdale. The relationships between the joint sets indicate three periods of joint formation: (a) shear jointing with s_1 orientated ENE; (b) extension jointing, producing persistant and regular fractures. Joints formed at this time are the most abundant; (c) a second generation of

shear joints formed under east-west compression and contemporary with mineralization. Similar joint patterns and jointing history have been identified in the Tyne-Tees Tunnel.

(4) In the Whin Sill in Teesdale, joints increase in frequency and are rotated adjacent to known mineral veins. The increase in joint frequency is the result of the build up of residual strains in the rocks adjacent to the vein fractures. Rotation of the joints were caused by strike-slip movement along the veins. Joints in the Tyne-Tees Tunnel are not apparently affected by the major structures seen in the tunnel. However, the sampling density of the joints in the tunnel may not have been close enough to resolve local changes in the joint patterns adjacent to the major structures.

CHAPTER 6 FLUORITE VEIN STRUCTURES

6.1 Fluorspar mining in the northern Pennine orefield

The decline of the lead mining industry in the late nineteenth century was partly offset by the growth in the exploitation of gangue minerals; particulary fluorspar. The term fluorspar is generally applied to the milled concentrate or ore, whilst the pure mineral is called fluorite.

The principal uses of fluorspar are as follows; in the manufacture of fluorine compounds, especially hydrofluoric acid; as a flux in metallurgical operations (mainly in the making of steel); and to a lesser extent in the ceramic industry.

There are two main market grades of fluorspar. 'Acid' grade fluorspar is required to be very fine (less than 100 mesh), and must contain a minimum of 97% fluorite and a maximum of 1% silica and 1% calcium carbonate. 'Metallurgical' grade fluorspar (met-spar) should range in size from 3 to 102mm; and finely ground floatation products must be briquetted. This grade must contain a minimum of 75-80% fluorite, and not more than 12% silica.

Today, most fluorspar is benificated using heavy-media separation and/or floatation. Washing and jigging were prevalent in the past and may still be used by small scale operators.

Serious fluorspar mining commenced in the northern Pennine orefield in 1882 at the Weardale Iron Company's Crawley Mine, and was expanded in the early twentieth century by its successor, the Weardale Lead Company. In 1959 there were five operators in the orefield with seven active mines producing 25,000t of ore per annum (Dunham, 1959). Today, only the British Steel Corporation (BSC) and Swiss Aluminium Mining UK Limited (SAMUK) are engaged in mining, producing in 1975 about 80,000t of concentrate (Greenwood and Smith, 1977). Two of the mines operating in 1959 are now considered worked out (Barbary and Stotsfieldburn), and in 1980 there were eight active mines (Fig 6.1): four operated by BSC (Allenheads, Blackdene, Groverake and Whiteheaps) and four by SAMUK (Burtree Pasture, Redburn, Stanhopeburn and Cambokeels).

Recently there was a deep recession in the fluorspar business, due to the decline of steel making and the availability of cheaper fluorspar from abroad. This resulted in the suspension of operations at Allenheads in August 1979, and at Blackdene, Burtree Pasture and Redburn in March 1981. Developments by SAMUK at Frazer's Hush, near Groverake, were also suspended.

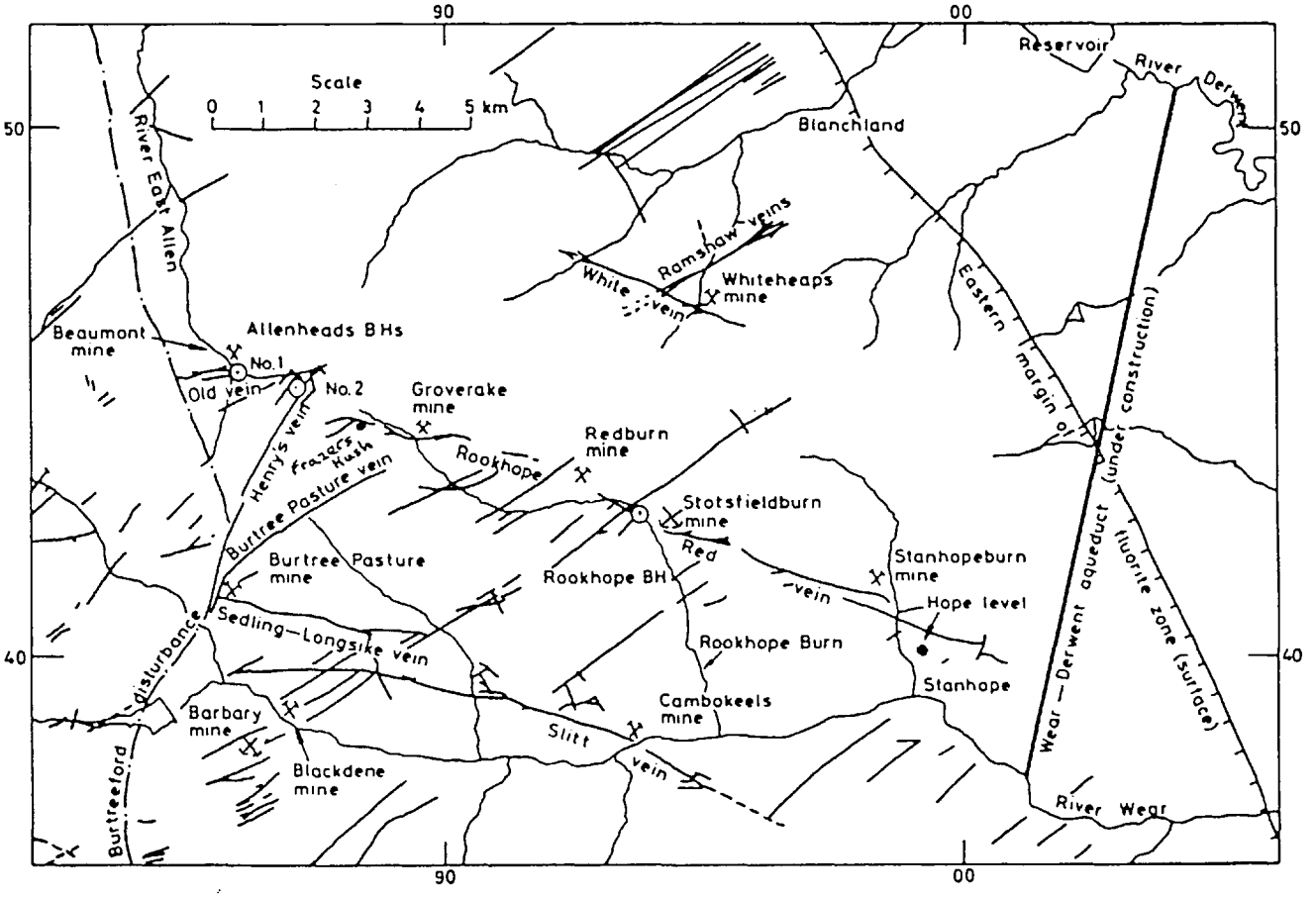


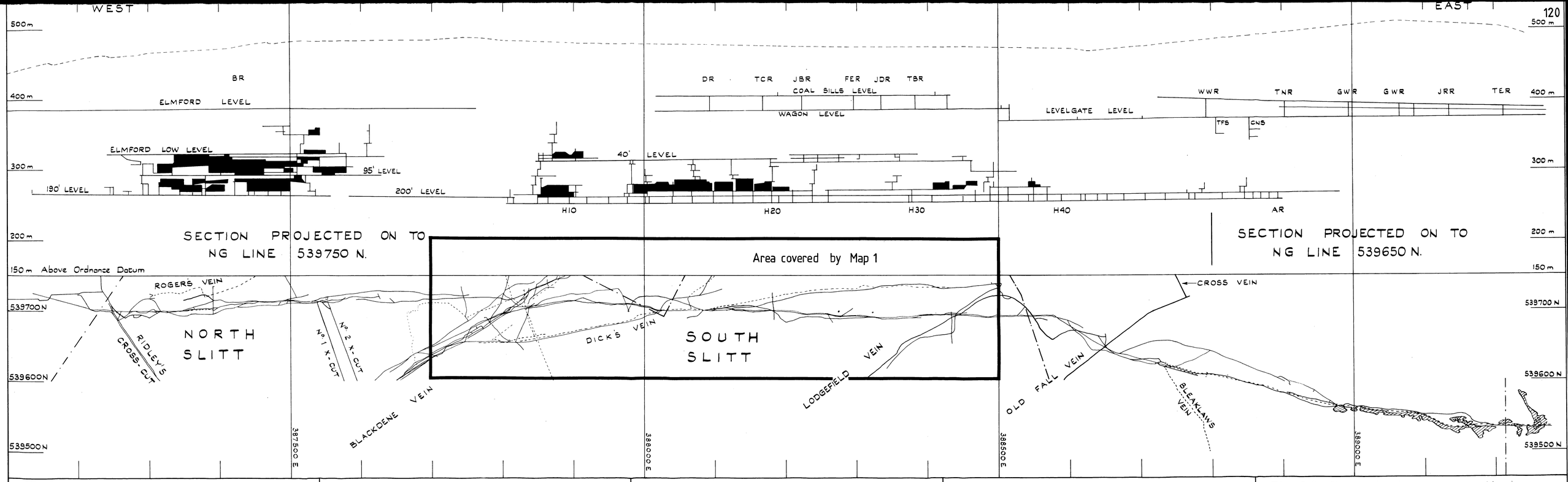
Fig. 6.1 Location of fluorspar mines in the northern Pennine orefield.
⚒ -developed mines; ⚒ -abandoned mines; • -trails.
(modified after Greenwood and Smith, 1977)

6.2 Blackdene Mine

Blackdene Mine (NY868390) was originally worked for lead by the Beaumont Company in the nineteenth century. Fluorspar mining began in the 1940's when the mine was obtained by the United Steel Companies Limited; since nationalisation it has been owned by the British Steel Corporation. Fluorspar production from Blackdene upto the end of 1976 was 213,395t (Greenwood and Smith, 1977).

The Horse Level, driven in the Six Fathom Hazle and Three Yard Limestone along and parallel to Blackdene Vein, provided the original access to the mine. In 1965 an incline was driven from the surface to 60fm below the Horse Level, and from there the Main Haulage was developed just above the Whin Sill.

Only the ENE Blackdene Vein and ESE Slitt Vein have been worked to any extent at Blackdene Mine. Blackdene Vein intersects the Slitt Vein and apparently displaces the western extension of Slitt Vein northwards in the higher horizons (Fig 6.2). This has led to Slitt Vein west of Blackdene being known as North Slitt and to the east as South Slitt. Development in the lower levels of the mine has shown that Blackdene Vein does not in fact displace



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PLOTTED FROM MINE PLANS - D. SMITH - 2/79.
CHECKED - D. A. GREENWOOD - 2/79.

Scale 1/2500.

BLACKDENE MINE
SLITT VEIN ORE-ZONES

Fig. 6·2 General plan and section of Blackdene Mine

the Slitt Vein. Both the Blackdene Vein and the North Slitt ore-zone are now considered worked out above the Main Haulage Level. The South Slitt ore-zone extends about 500m east of the intersection with Blackdene Vein on an east-west strike (plate 3). The Slitt Vein then turns onto an ESE trend, known as South Slitt extension, and immediately becomes poor. Some fluorspar ore reserves remain in the Six Fathom Hazle along the South Slitt ore-zone on the 40ft level.

Over the last few years a major internal incline (the Whin decline) has been sunk down into the Whin Sill beneath South Slitt with developments at 50ft (No.1 level) and 100ft (No.2 level) below the Main Haulage Level. The vein in the Whin decline continues to be mineralized, and the prospects for a similar extension of mineralization beneath North Slitt are good.

6.2.1 Whin Sill development

The oreshoot in the Whin is remarkably straight on the east-west trend, and shows little hade. Vein widths average 2m, with well defined cheeks and little brecciation of the wall-rocks. However, mineralized stringers are common and appear to fill second-order shears striking north of east: a direction in keeping with their generation by sinistral strike-slip movement along

the main vein. The sinistral offset of an upward transgression in the Whin Sill by the Slitt Vein on the Main Haulage has already been described (section 3.3.3) At the eastern end of the No.1 Level, the Whin is seen to transgress sharply downwards, and again the transgression is offset sinistrally on the opposing walls of the vein. In the metamorphosed mudstones to the east of the transgression, the vein is less well defined, with riders of mudstone and hydraulic fracturing of the wall rocks.

The vein filling in the Whin is conspicuously banded, but lacks the fine repetitions of minerals seen in Groverake Mine. A typical cross-section of the vein is shown in Figure 6.3. Movement along the vein appears to have been concurrent with mineralization: many early mineral bands have been brecciated and re-cemented by later phases; sulphides may be deformed or streaked out. Renewed movement along the vein did not necessarily occur along its centre, but may have split earlier mineral phases. The abundance of carbonates in the vein is unusual, and Dunham (1948) has suggested that these are the products of metamorphism of the Whin Sill.

Horizontal slickensides are present along the walls of the vein, and along some of the individual mineral bands. The centre of the vein sometimes contains a fluorite gouge with vertical slickensides.



Plate 3 Slitt Vein, Blackdene Mine showing fill of massive purple fluorite



Plate 4 Blackdene Vein, Blackdene Mine showing possible mineralized joints intersecting the vein at a small angle.

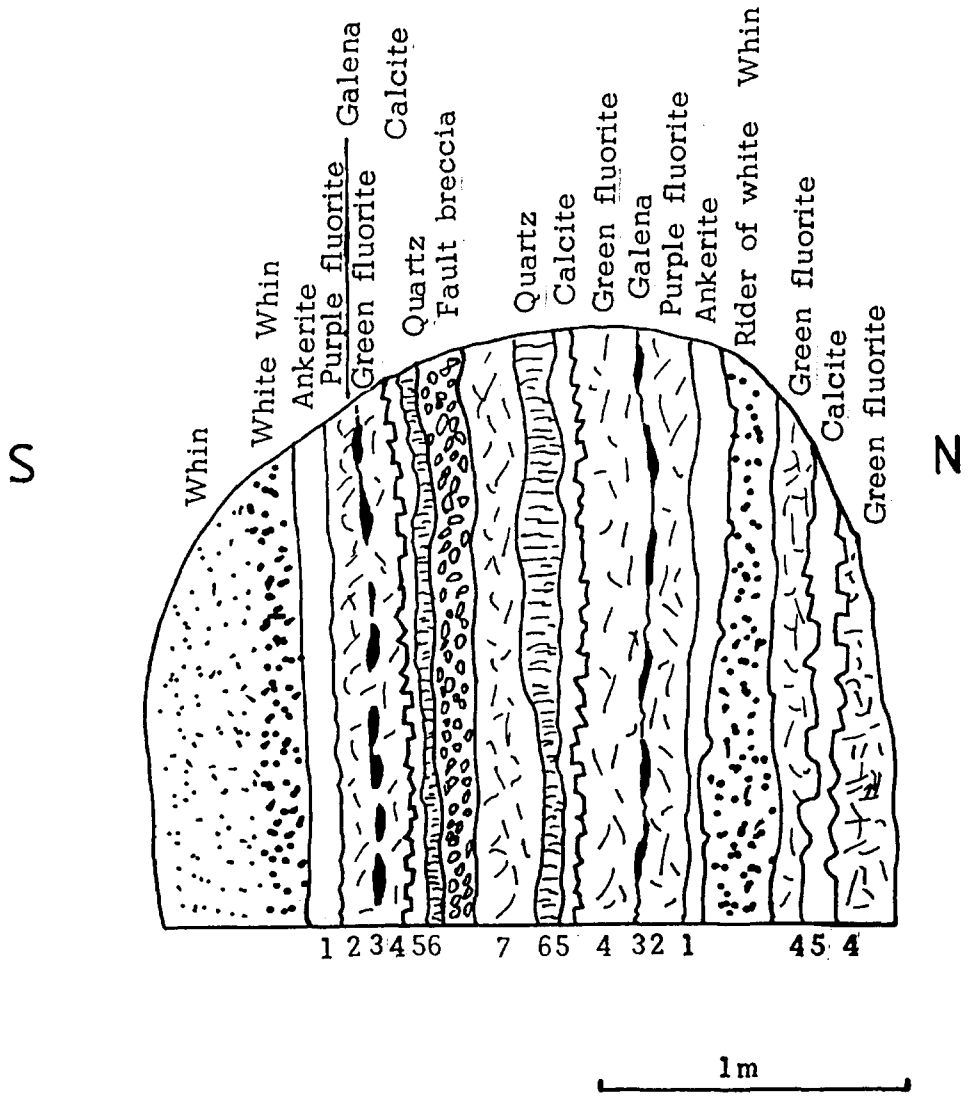


Fig.6.3 Typical section across Slitt Vein, No.2 level Whin decline Blackdene Mine, western forehead, April 1980. Numbers refer to order of deposition of minerals.

6.2.2. South Slitt Extension

The eastern end of the Slitt Vein within the Blackdene lease was developed on the 200ft sub-level as the South Slitt Extension. No stoping was done in this section of the mine, as the vein was considered too poor to work. East of 388,580E/539,670N (see Fig 6.2) the vein strikes generally ESE until turning east-west again near 389,000E/539,530N.

The Slitt Vein in the main South Slitt orebody averages 2m in width, and usually shows massive fluorspar infilling. It dips consistently north at 80 to 85 degrees. In contrast as the vein approaches the point where it swings onto an ESE trend branching becomes common, and riders within the vein are often brecciated. The dip of the vein in this section varies, and in some cases the dip is to the south. A bedding plane fault is present along the northern wall of the vein at 388,600E/539,685N. This fault consists of a 20cm thick layer of deformed shale with slickensides sub-parallel to the dip of the fault plane. The fault may be a thrust, but the relationships between it and the Slitt Vein are impossible to see due to arching in the level. East of this point the 200ft sub-level was driven in the wallrocks south of the vein, where it intersects several mineralized ENE and NNW stringers. The thickest stringer consists of 3cm of gouge

and calcite; it may represent the Old Fall Vein (388,655E/539,640N).

The 200ft sub-level rejoins the Slitt Vein at 388,790E/539,645N, and from here to the end of the development (389,100E/539,655N) the vein rarely exceeds one metre in width. The fluorite content of the vein is low; quartz and ankerite predominate. There is a strong central fracture or 'leader' along the vein, which is often gouge filled and shows horizontal slickensides. If riders within the vein are cut by the leader, the two halves are displaced sinistrally by 18m to 19m. The wall rocks either side of the vein are frequently brecciated, and consist of irregular to sub-rounded fragments cemented by ankerite. This fracturing differs from the sharp hydraulic breccias seen elsewhere in the mine and may be the result of mechanical fracturing. This would be in keeping with the other structures present which suggest the vein was generally under compression during mineralization, with little opening perpendicular to the walls.

East of the Blackdene lease boundary, the Slitt Vein turns onto an east-west trend again at 389,000E/539,300N. Plans produced during the Beaumont operations in the 1860's show the development of flats at this point in the Great Limestone. Complex banding and fracturing accompanying the change in vein strike may partly explain

the presence of flats: the fractures would channel a large volume of the hydrothermal fluids out of the vein into the limestone.

6.2.3 40ft level

The South Slitt ore-zone was developed on the 40ft level in the Six Fathom Hazle. At this horizon the vein is not a continuous structure, but consists of four overlapping en-echelon sections. The vein sections strike approximately N080 degrees east, and the spacing between them is 100 to 150m (Map 1). Only the most easterly vein section has been worked to any extent. It reaches widths of 5m of almost solid fluorspar (388,335E/539,692N) and has been stoped for a distance of 380m. The three remaining sections are less than one metre wide and are developed for 100 to 200m.

The ground between the en-echelon overlaps at the ends of the vein sections is broken by two main fracture trends; ENE and NNW. Most of these fractures are filled with less than a centimetre of iron stained quartz. However, a few of the ENE fractures are more substaintial (upto 0.8m wide). In addition to quartz, they contain fluorite, siderite and galena. The later minerals, especially the purple fluorite, are present along the middle lengths of the vein sections. Thus, there is an

apparent zonation of minerals along strike, with dominance of quartz at the ends of the veins, and fluorite along the mid-portion.

The North Slitt ore-zone has not been explored on the 40ft level during the present mining operations. Plans of the old lead workings show similar en-echelon veins on Elmford Low Level (approximately equivalent to the 40ft level on South Slitt).

Above the Six Fathom Hazle the Slitt Vein has been worked for lead from the Elmford and Levelgate Levels. Plans of these workings show large scale en-echelon structures in the Great Limestone upto 1000m long. Roger's and Dicks's Veins are individual echelon fractures.

6.2.4 East-north-east veins at Blackdene

Three ENE veins are exposed at Blackdene Mine:- Blackdene, Lodgefield and Old Fall Veins. Only the Blackdene Vein has been worked for fluorspar during the present operations, but is now considered worked out above the Main Haulage.

Blackdene Vein on the 190ft level and on the Main

Haulage (plate 4) consists of three overlapping en-echelon fractures striking N070E, aligned in a manner consistent with dextral strike-slip movement. In the Great Limestone the Blackdene Vein apparently offsets Slitt Vein dextrally by 100m, but on the Main Haulage, there is no displacement. This apparent offset in the Great Limestone can be explained by overlap of two en-echelon shears of Slitt Vein.

Lodgefield and Old Fall Veins have not been definitely recognized on the 200ft level, and they could be any of several ENE veinlets. On the 95ft level, an ENE vein is cut and displaced sinistrally 40m by the Slitt Vein. The intersection between the two veins is very sharp and there are definite differences in mineralogy between them. The ENE vein consists of 0.7m of massive purple fluorite, with a discontinuous central band of galena. The Slitt Vein shows marginal banding of ankerite, quartz and green fluorite, with a central fill of massive white fluorite.

6.2.5 Summary of structures at Blackdene

The Slitt Vein at Blackdene Mine displays distinct variations in structure both along strike and with depth. In the main part of the mine, at and just above the

horizon of the Whin Sill, the Slitt Vein is a continuous east-west fracture. To the east the vein curves onto an ESE trend until turning east-west again at Slitt shaft (NY905392). On following the Slitt Vein upwards, above the Whin Sill, at Blackdene, it breaks up into a number of en-echelon shears. The length and strike of these shears varies between different beds or units of beds.

6.3 Allenheads Mine

The Allenheads Mine was the largest single lead producer in the northern Pennines, with over 260,000t of concentrates produced between 1729 and 1896 (Dunham, 1948). In 1971 the mine was renamed the Beaumont Mine. New development was commenced in this year by the British Steel Corporation for fluorspar, which was believed to be present as back-fill in old stopes and in the virgin vein beneath the old workings. Since August 1979 development and production has temporarily stopped.

6.3.1 Sources of information

Prior to its reopening as a fluorspar mine, direct observations of the underground geology were impossible. However, the old lead workings at Allenheads are well documentated in the bargain books and agents' reports

produced during the period of working by the Beaumont Company in the eighteenth and nineteenth centuries. In addition to these records there are many mine plans and sections preserved; of which the most interesting are a series of plans (at a scale of 40ft to the inch), together with surveyors' notebooks, produced during the 1860's and 1870's under the management of T Sopwith. A wealth of geological information can be deduced from these latter plans. They record the positions of the veins and minor fractures, and each level on the plans is coloured by its stratigraphic horizon (Greenwood, 1971). Several small scale plans of the complete Allenheads workings have been published by Smith (1923) and Dunham (1948). Plans of current workings have been produced at a scale of 1:500, and show the new developments and their correlation with old workings. These records have formed the basis of the following description of the vein structures at Allenheads.

6.3.2 Vein systems

During the eighteenth and early nineteenth centuries the principal workings at Allenheads were on the Old and Wentworth veins (Fig 6.4). To the east of East End Shaft, the Old Vein-Wentworth Vein system trends east-west until turning N085E near to its intersection with Henry's Vein. West of East End Shaft Old Vein turns N082W; an east-west branch, known as Diana Vein, is associated with flats in

the Great Limestone. At its western end near Craigshield Shaft, Old Vein is intersected by Bretton Vein. Bretton Vein strikes N080E on the eastern side of its intersection with Old Vein, but turns east-west to the west of the intersection. The main production from the Old Vein-Wentworth Vein system was derived from Vein ore-shoots, up to 2m wide and extending from the Firestone down to the Four Fathom Limestone, with substantial flats in the Great Limestone.

Workings on Henry's Vein formed the mainstay of the mine's production in the latter half of the nineteenth century, until the mine's closure as a lead producer in 1896. This Vein shows an anomalous NNE course when compared with other north-easterly veins in the orefield, and is unusually wide, up to 6m in the High Slate Sill. A total length of 2,600m was worked on Henry's Vein in strata from the High Slate Sill down to the Three Yard Limestone. Two short veins, Grindstone and Henrietta, parallel Henry's Vein near to its intersection with Wentworth Vein, but neither appear to have been extensively worked.

The remaining veins at Allenheads fall into two groups. The first group consists of NE to ENE veins, the principal of which are Great, Coronation and Christopher Mill's veins. Most of the development in these veins was in the Great Limestone; where vein widths rarely exceed

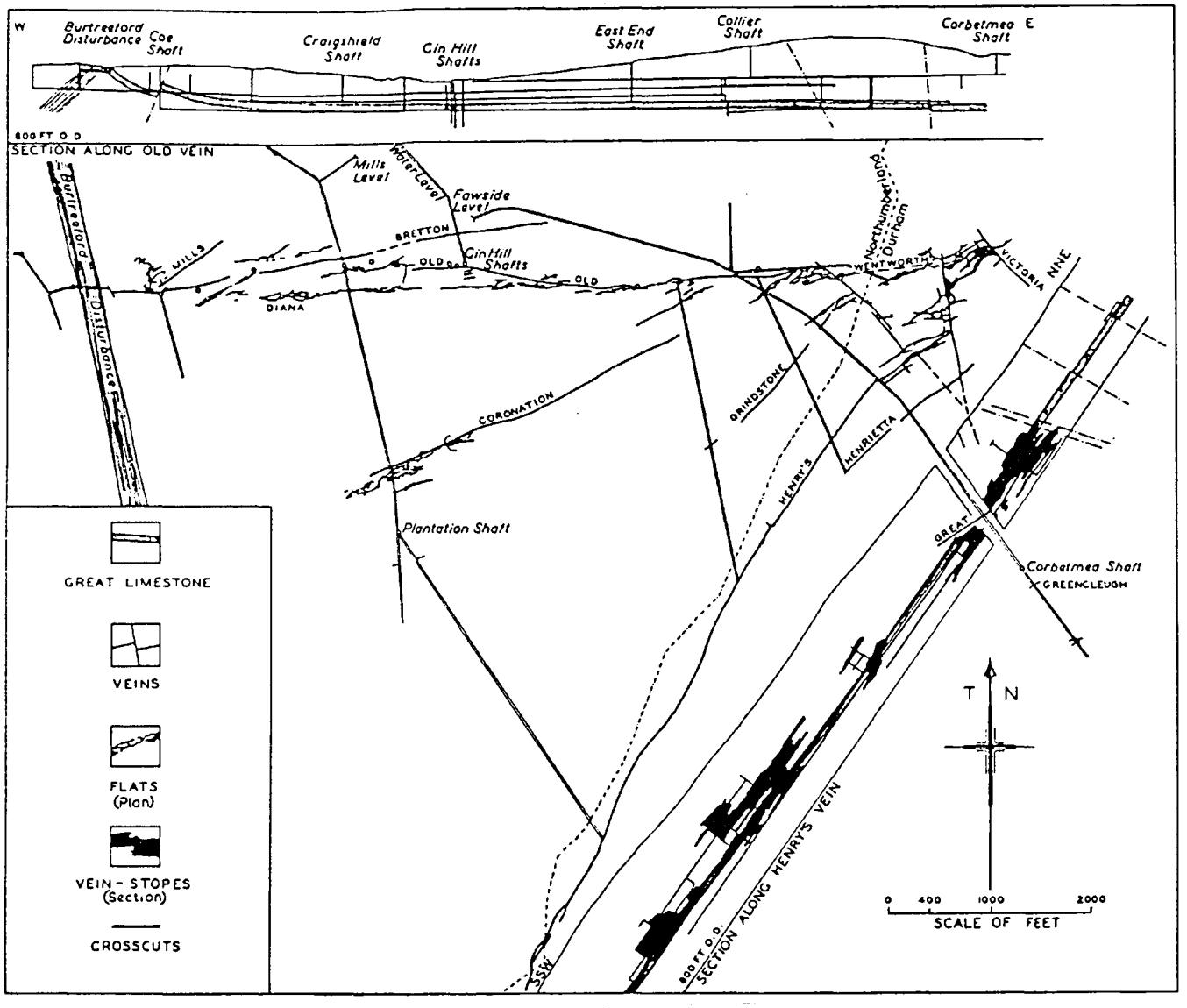


Fig. 6.4 Plan and sections of Allenheads Mine (from Dunham, 1948)

1.5m. The other group of veins are NW-SE or north-south striking cross-veins. These appear to be poorly mineralized, but are associated with flats in the Great Limestone.

6.3.3 Vein structures in the Great Limestone

The workings in the Great Limestone at Allenheads are the most extensive and best documented. A careful study of mine plans has enabled the drawing of a detailed plan of the veins in the Great Limestone (Map 2). It is clear from this plan that many of the veins in the Great Limestone are not continuous structures, but are composed of several, often overlapping, en-echelon sections. The principal veins showing this internal en-echelon structure are Bretton, Old, Diana, Wentworth and Henry's veins.

The remaining veins show no en-echelon arrangement, being typically straight along the strike. These veins generally strike NE or NW, and, with the exception of Coronation Vein, do not appear to be extensively mineralized. These observations are consistent with normal dip-slip movement.

During its period of working as a lead mine,

replacement flats in the Great Limestone were an important source of lead ore at Allenheads. Old mine plans show that these flats are composed of several individual tubular bodies of ore. These orebodies frequently follow a 'leader'; a narrow, mineralized fracture. Replacement may occur either side of a leader, or the leader may form a 'cheek' (boundary) to the flat. Leaders are present along Bretton, Old, Diana-Wentworth and Henry's Vein, and are aligned at 10 to 20 degrees to the main vein.

6.4 Whiteheaps Mine

Whiteheaps Mine operated as a lead producer, firstly under the London Lead Company, and later by the Derwent Mining Company until 1883. Fluorspar mining by Hunstanworth Mines Limited commenced in 1924, and has continued intermittently since this date (Dunham, 1952). The ESE White Vein forms the main ore-bearing structure at the mine. It is cut by several mineralized east-west fractures varying from 1 to 2km in length: Poor, Red, Shield's and Company's veins (Fig 6.5). Two major ore-zones at Whiteheaps and Sikehead have been exploited on the White Vein. Vertical continuity of the oreshoots at Whiteheaps is enhanced by the presence of thick sandstone filled wash-outs in the Grit and Coal sills (Smith, 1974).

The Whiteheaps ore-zone is centred around the twin

Whiteheaps shafts (NY948467), which were sunk during the lead mining period to the 80fm level at the base of the Great Limestone. The principal lead workings at Whiteheaps shaft were above the 40fm level in the Grit Sills. The shaft was reopened to the 80fm level in the late 1950's but the veins proved to be disappointing and exploration was abandoned (Greenwood and Smith, 1977).

The Sikehead oreshoot (NY955464) lies some 800m east of the Whiteheaps shafts, and was again exploited during the lead mining period from two shafts to the 79fm level (Ruth's and Ellen's shafts). Exploration for and production of fluorspar is now concentrated on the Sikehead oreshoot. Access to this area is provided by a new surface incline, driven at 1 in 4.5 from the eastern side of Boltsburn. At present the vein is being worked on the 80fm level at Sikehead; most of the vein above this having been worked out by the lead miners.

6.4.1 Sikehead oreshoot

The Sikehead oreshoot consists of two parallel east-west vein sections. The northern most vein is known as the Red Vein, but is here called the Red Vein of Sikehead to distinguish it from the other Red Vein near the Whiteheaps shafts. The White Vein lies 10m to the south of the Red Vein of Sikehead.

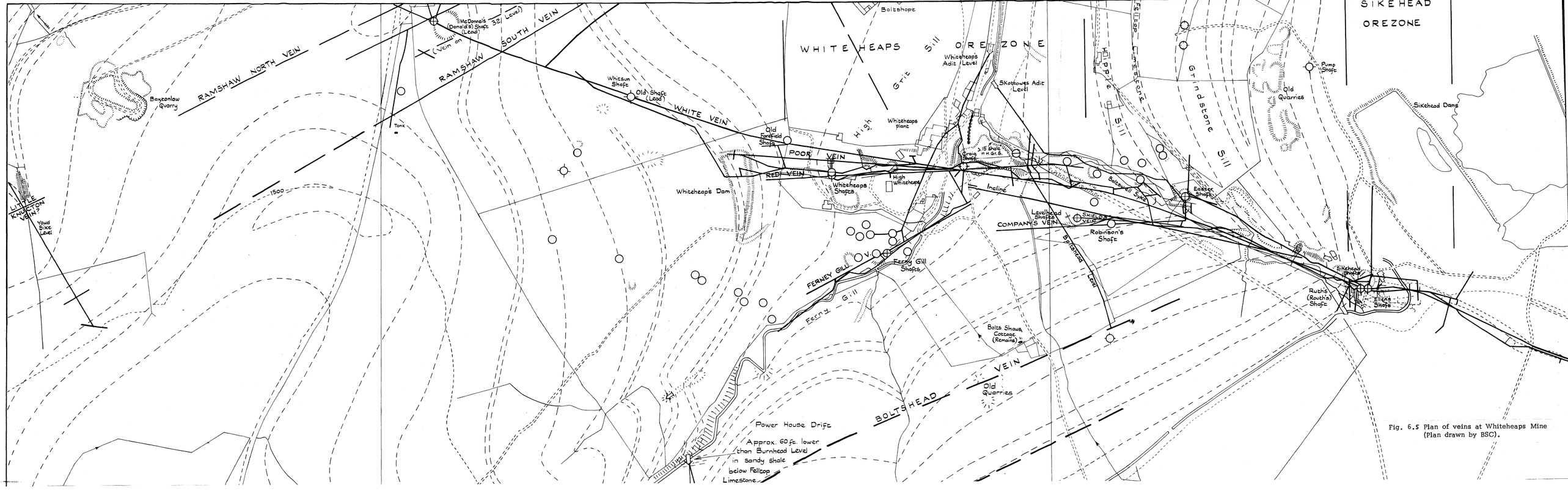


Fig. 6.5 Plan of veins at Whiteheaps Mine (Plan drawn by BSC).

On the 40fm and 50fm levels, most of the Sikehead oreshoot was found to have been extensively worked for galena by the 'Old Man'. Mapping by the BSC geologists on the 50fm level (Fig 6.6) has shown that 80m east of Ellen's shaft the two east-west veins form an ESE vein fracture, which continues to north of Sikehead. This ESE vein was developed for 400m to the east on the 50fm level, but proved too narrow and siliceous to work. Eighty metres east of Ellen's shaft is another ESE striking vein, which may continue to the south of Sikehead as the 'Sun Leg', which is seen on the 40fm level above. Thus, the Sikehead oreshoot is developed between two overlapping en-echelon ESE fractures.

On the 80fm level the Red Vein of Sikehead and the White Vein are 15m apart (Map 3). The ground between them is highly brecciated, with quartz and fluorspar cement. A cross-cut south from the oreshoot has cut a 15cm wide fault striking N313E. The throw on the fault is difficult to determine due to moderately large variations in the dip and strike of the beds. To the north of the fault, the cross-cut is driven in a sandstone (possibly the Low Coal Sills). A coral band, probably equivalent to the Frosterley Marble Post of Weardale (Fairburn, 1978), is exposed in the Great Limestone at the forehead of the cross-cut 10m south of the fault. This fault may be equivalent to the Sun Leg present on the 40fm level.

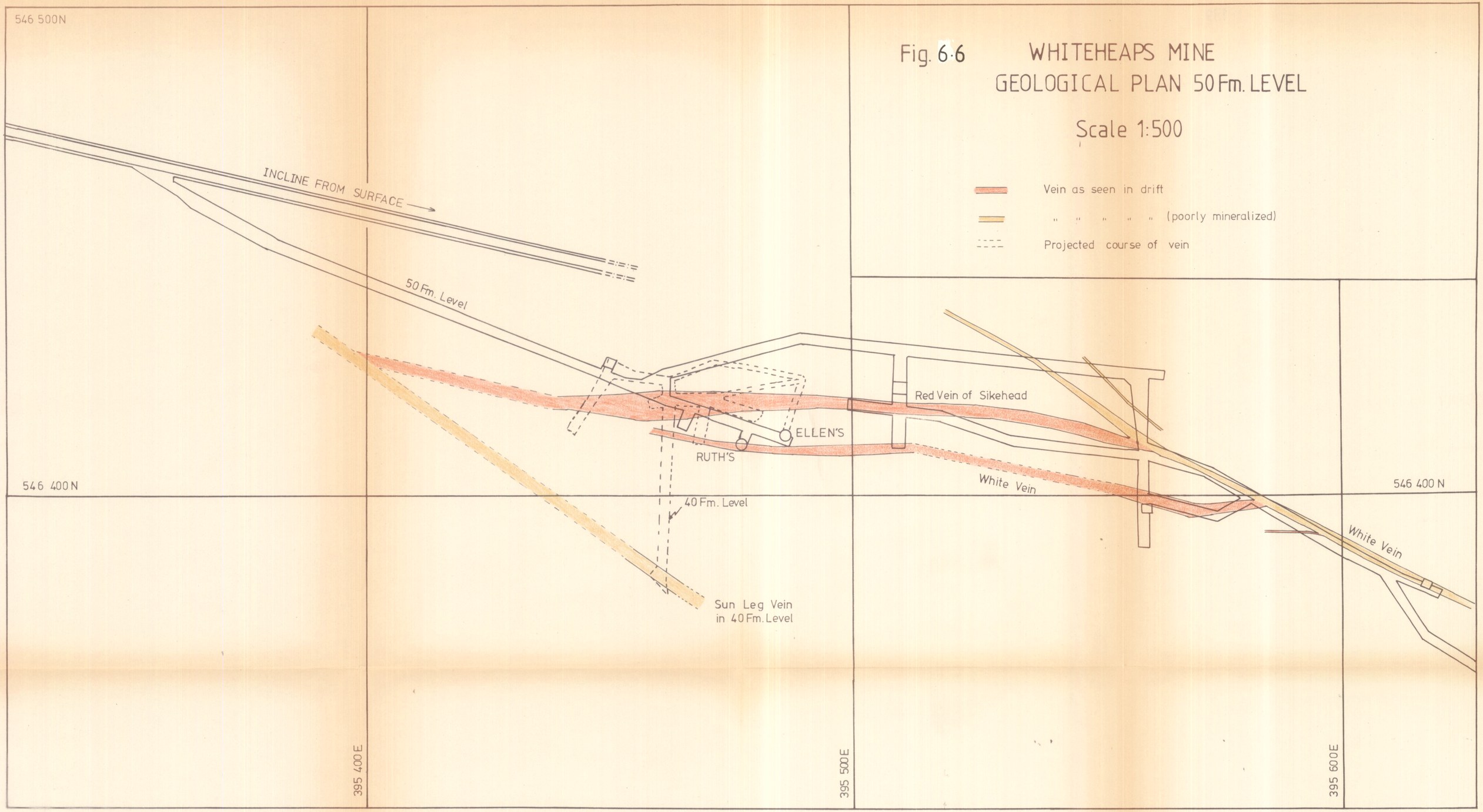


Fig. 6·6 WHITEHEAPS MINE

GEOLOGICAL PLAN 50 Fm. LEVEL

Scale 1:500

Vein as seen in drift

" " " " " (poorly mineralized)

Projected course of vein

There is no development to the east of the Sikehead oreshoot on the 80fm level. To the west of Ellen's shaft the Red Vein of Sikehead thins rapidly, and many WSW stringers link it to the White Vein to the south (395,455E/546,405N). West of this point the White Vein has proved exceptionally wide; over 4m in places. The vein filling consists of quartz, white fluorspar, calcite and sulphides: fluorspar grades about 30%. Multiple banding of minerals is common in the vein and much of the vein filling is highly fractured, causing the vein to 'run' on excavation.

6.5 Other Mines

Of the remaining active fluorspar mines, only three (Groverake, Redburn and Cambokeels) are described here. Most of the structures in these mines do not differ greatly from those already described. However, they do display a few important features not seen in the other mines.

6.5.1 Groverake Mine

Groverake Mine (NY895441) is the largest producer of

fluorspar in the orefield, with total production of 430,000t of fluorspar to the end of 1976 (Greenwood and Smith, 1977).

The main oreshoot lies along a 1km stretch of the east-west Groverake Vein (Fig 6.7). The eastern end of Groverake Vein cuts through the Red Vein of Rookhope, but there is little modern development along the Red Vein. Access to the mine is provided by two shafts, -the Whimsey Shaft to the 80fm level, and the Drawing Shaft to the 50fm level, and two adits, -the Rake Level and the Firestone Incline. The 50fm and 60fm levels command the Great Limestone, and much of the vein above this was slit by the lead miners. Fluorite remaining as the northern wall and as back-fill in old workings, has accounted for most of the fluorspar production.

On, and above, the 60fm level, the Groverake Vein appears to be a continuous fracture along strike. However, vertical branching is common and refraction is evident between the different lithologies of the wall rocks. These features are consistent with dip-slip movement or opening perpendicular to the vein walls (with little or no wrench movement). These observations are supported by the mineral banding in the vein on the 60fm level at 390,100E/544,100N. Where the vein is 2.5m wide, and consists of alternate bands of white chalcedony and green fluorite with discontinuous bands of sulphides. The

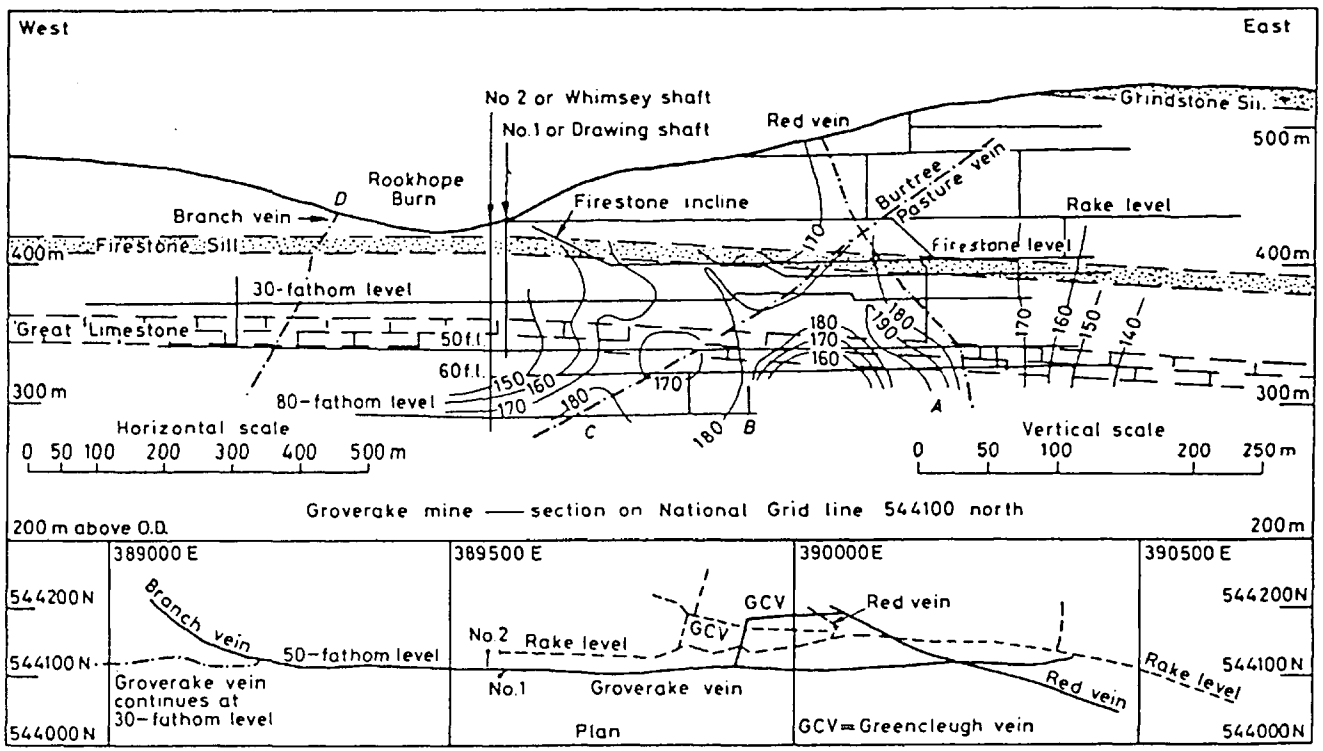


Fig.6.7 Plan and section of Groverake Mine; contours show mean homogenization temperatures for fluid inclusions in fluorite (from Greenwood and Smith, 1977)

average width of a chalcedony or fluorite band is 1cm, and a typical section across the vein contains 300 such bands. Each mineral band may have been deposited after a small movement along the plane of the vein in the manner described by Sibson et al (1975).

Further east on the 60fm level (390,250/544,100N), the Groverake Vein passes through the Red Vein (of Rookhope). There are no obvious offsetting relationships between the two veins. The intersection between them consists of an area of intense fracturing and mineralization; much of it as replacements in the Great Limestone. Early silica and blue fluorite commonly occur along bedding plane openings fed by small veinlets. The abundance of early phase sulphides, especially chalcopyrite, suggests that the intersection acted as a feeder for the mineralization. This notion is supported by high fluid inclusion homogenization temperatures in this area (Smith, 1974).

On the 80fm and 96fm levels, the vein is only partly developed, just above the Six Fathom Hazle. The vein at this depth is no longer straight, but consists of several east-west sections linked by the narrower ESE striking sections. The structures are similar to those seen in the Six Fathom Hazle on the 40ft level at Blackdene, but the vein fracture at Groverake is still continuous (having not fully developed into overlapping en-echelon shears).

6.5.2 Redburn Mine

A previously untried stretch of the Red Vein between Groverake and Boltsburn mines was explored in 1964 by a 1 in 3 incline from Red Burn (NY927432). Two east-west ore-zones were discovered and were subsequently exploited from a new shaft as Redburn Mine. Near to the shaft the eastern ore-zone consists of a 6.8m wide and 310m long belt of mineralization, including 3.7m of massive fluorspar (Greenwood and Smith, 1977). The western ore-zone occurs between 1200m and 1950m west of the shaft, and consists of a complex of branch and loop veins in both the horizontal and vertical planes (Fig 6.8). Between the two ore-zones the Red Vein consists of en-echelon and looped faults, with many barren cavities. These openings are interpreted by Greenwood and Smith (1977) as potential orebody cavities which were isolated from the mineralizing solutions.

6.5.3 Cambokeels Mine

The Cambokeels Mine (NY935382) is developed on the site of old lead workings along the Slitt Vein. A new

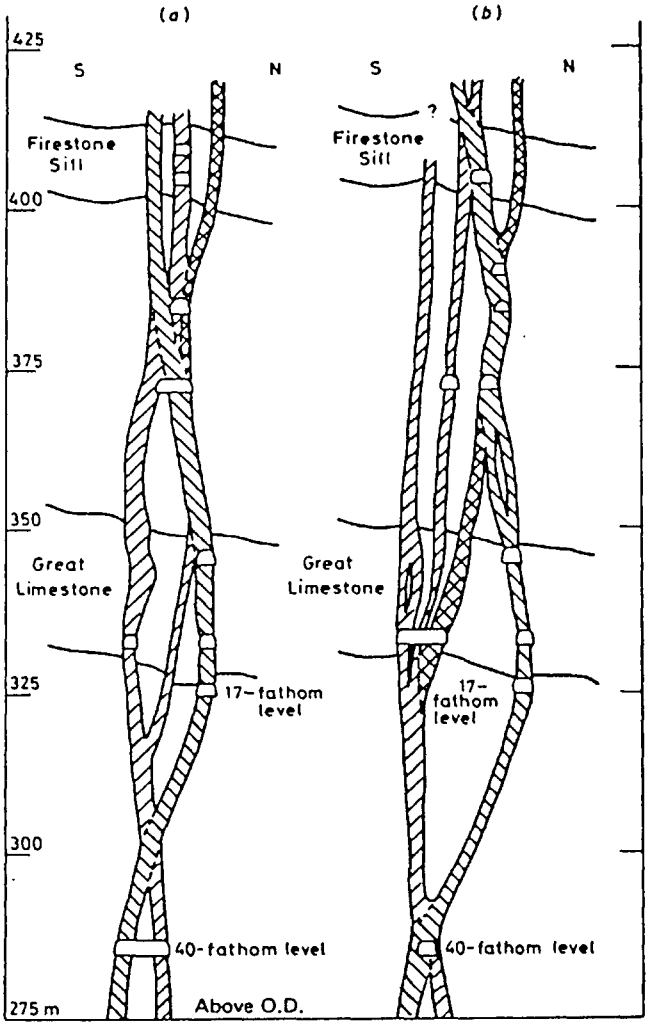


Fig. 6.8 Vertical vein branching in western ore zone, Redburn Mine: (a) 6m west of no.5 raise; (b) 19m east of no.5 raise. (from Greenwood and Smith, 1977)

incline was sunk beneath the old workings, and levels developed at 200m, 240m and 280m. The 200m Level is situated 200m above Ordnance Datum and the 240m and 280m levels are 40m and 80m below the 200m Level.

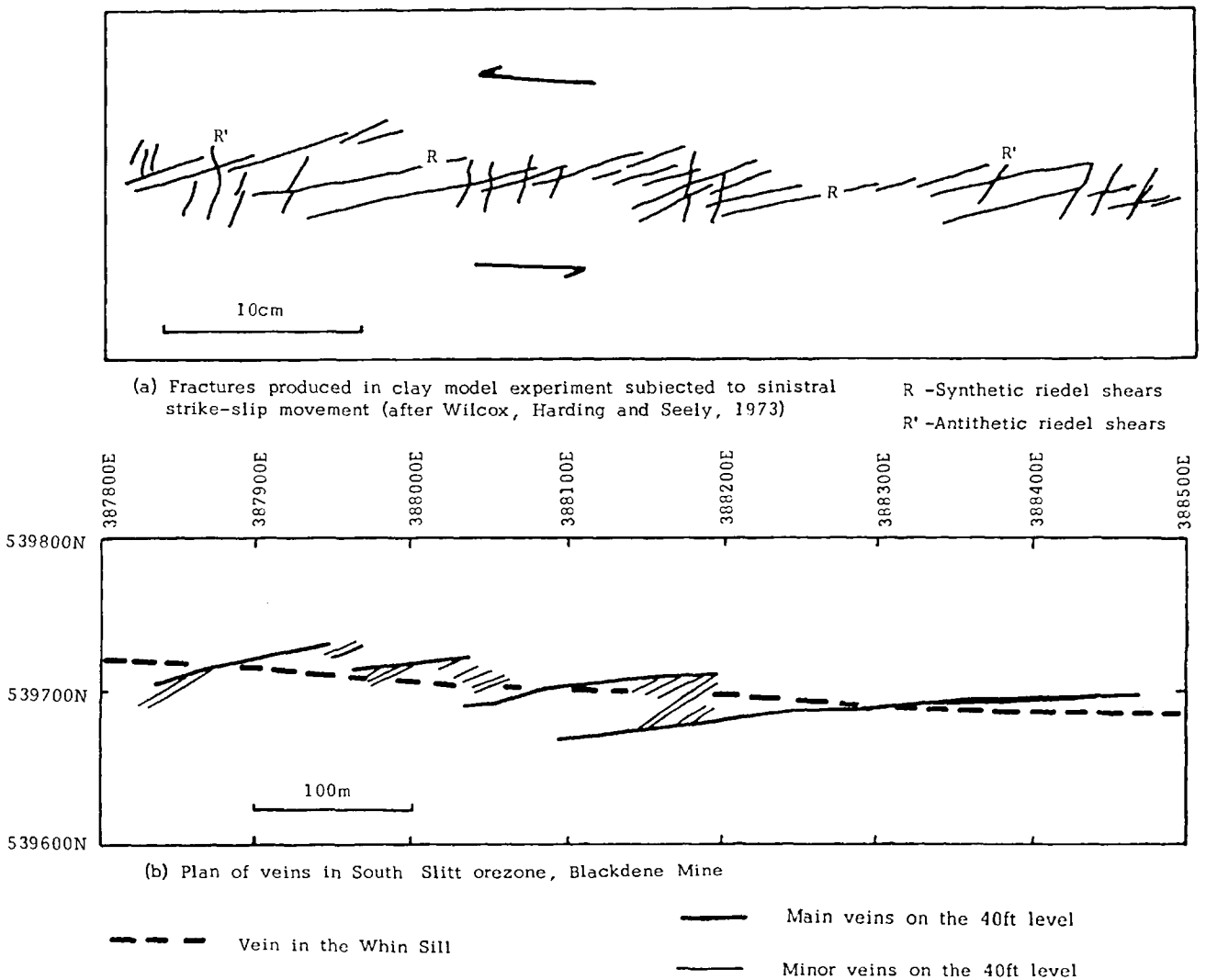
Two parallel veins (the North and South leads) are present on the line of the Slitt Vein at Cambokeels. The North Lead is generally narrow and poorly mineralized. A similar structure occurs at Blackdene, where it is known as the 'Blue String'. The South Lead is upto 3m wide, and on the 200m Level is filled with massive fluorspar. But on the 240m Level (in the Tynebottom Limestone) the fluorspar in the vein is very pod-like, and on the 280m Level (in the Whin Sill) the vein filling is dominantly quartz. It appears that the base of the fluorite zone has been reached on the 280m Level.

6.6 Interpretation of ESE vein fracture formation

The theories and structures associated with strike-slip faulting have been described in Chapter 4. The aim of this section is to compare these structures with those seen in the active fluorspar mines of the northern Pennine orefield.

6.6.1 Blackdene Mine

Wilcox et al (1973) have described the generation of riedel shears in the strata overlying a strike-slip fault. Figure 6.9a shows the theoretical arrangement of riedel shears above a sinistral strike-slip fault. Figure 6.9b is a simplified diagram of the vein structures in the Whin Sill and Six Fathom Hazle on the South Slitt ore-zone at Blackdene Mine. There is a striking similarity between the geometry of fractures in the Six Fathom Hazle at Blackdene and the synthetic riedel shears. The Slitt Vein in the Whin Sill is a major, continous fracture, comparable with the wrench fault underlying the riedel shears in Figure 6.9a. The similarities between these two diagrams suggests to me that the en-echelon shears in the Six Fathom Hazle at Blackdene are synthetic riedel shears, generated by sinistral strike-slip movement along the Slitt Vein in, and below, the Whin Sill. The fractures in the Great Limestone on Slitt Vein were also generated by riedel shearing, but on a larger scale. Reactivation of pre-existing joints could explain en-echelon patterns of this type, however the joints in the Six Fathom Hazle on the 40ft Level strike at 60^{o} to 70^{o} (see p. 113): that is 10^{o} to 20^{o} north of the vein strikes. Opening of the ENE joint could not therefore be responsible for the generation of the vein shears on the 40ft Level, but this mechanism may have formed the ENE stringers linking the overlapping ends of the main en-echelon shears.



(a) Fractures produced in clay model experiment subiected to sinistral strike-slip movement (after Wilcox, Harding and Seely, 1973)

(b) Plan of veins in South Slitt orezone, Blackdene Mine

Fig.6.9 Comparison of riedel shears and veins in South Slitt orezone, Blackdene Mine

Veins at a high angle to the main Slitt Vein, which could be interpretated as antithetic riedel shears are lacking. However, the ENE veins show evidence of a component of dextral strike-slip movement, in addition to normal dip-slip movement. The ENE veins are parallel to pre-mineralization joints; which could have acted as planes of weakness during the period of fault movement along the Slitt Vein. Failure along these joints took place in preference to the formation of new antithetic shear fractures. It is significant that Lodgefield and Old Fall Veins are almost absent below the 200ft level; suggesting that riedel shearing started to develop at, or above this horizon.

6.6.2 Allenheads

(a) Veins in the Great Limestone

The en-echelon veins in the Great Limestone at Allenheads also bear a resemblance to synthetic riedel shears (Map 2). The groupings of these riedel shears suggests that four main strike-slip faults are present; Bretton Vein, Diana-Wentworth Vein, Old Vein and Henry's Vein. The riedel shears on Bretton, Diana-Wentworth and Old veins are arranged in a manner indicative of sinistral strike-slip movement. The arrangement of the riedel shears on Henry's Vein are consistent with dextral strike-slip

movement. The synthetic riedel shears range in length from 200m to 500m; slightly shorter than similar shears in the Great Limestone on Slitt Vein at Blackdene Mine. Antithetic riedel shears are rare at Allenheads and have only been recognized at the eastern end of Wentworth Vein. They offset Wentworth Vein sinistrally, and are related to the northern end of Henry's Vein.

The orientations of the 'leaders' in the flats of the Great Limestone are similar to the second-order shears of Price (1968), suggesting that these fractures were generated by second-order shearing, during a period of renewed movement along the main riedel shears. The arrangement of the second-order shears are consistent with the direction of movements already given for Bretton, Old, Diana-Wentworth and Henry's veins. Plans produced by the Beaumont Company show numerous minor stringers and barren fractures. Some of these are parallel to leaders and are probably more second-order shears. The remainder appear to be parallel to the joint directions (Carter, 1977).

(b) Veins at depth in Allenheads

In predicting the possible vein structures at depth below the Great Limestone at Allenheads, it is necessary to draw on observations made at other quarter-point vein workings in the orefield. At Blackdene Mine old lead miners' plans show the Slitt Vein to consist of three or

more en-echelon shears in the Great Limestone, each about 500m long. As already described, current workings in the Six Fathom Hazle on the 40ft level at Blackdene, also show the vein to consist of several en-echelon shears, but these are shorter than those in the Great Limestone above (between 100m and 200m long). On the 200ft level, in the shale below the Scar Limestone, and in the Whin Sill below this level, the vein is apparently a continous fracture.

By comparison with the Slitt Vein at Blackdene, it would be expected that at Allenheads this downward change in vein structure could occur on Bretton, Old, Diana, Wentworth and Henry's veins, all of which show evidence of strike-slip movement. Information on the vein structures below the Great Limestone at Allenheads is limited, mainly due to the smaller scale of the old lead workings when compared with those in the Great Limestone. However, a cross-cut from the western end of BSC's main haulage incline on Old Vein did intersect mineralization at about the horizon of the Six Fathom Hazle. The vein was not developed at this horizon, but it was striking parallel to the riedel shears in the Great Limestone above, suggesting that riedel shears are also present at this horizon.

Below the Six Fathom Hazle nothing is known of the Old Vein system (taken to include Bretton, Old, Diana and Wentworth veins). On a large scale the Old Vein system consists of two east-west sections (Bretton and

Diana-Wentworth veins) linked by an ESE fracture (Old Vein), a pattern which is similar to that displayed by the Greencleugh and Groverake Mine. Greencleugh and Groverake veins are large synthetic riedel shears related to sinistral strike-slip movement along the Red Vein. Allenheads lies approximately on the strike extension of the Red Vein from Groverake, although the Red Vein has not yet been recognized at Allenheads. However, the Old Vein at Allenheads has the same strike as the Red Vein at Groverake and may represent the continuation of the Red Vein. If this is the case, then the the restriction of the Old Vein to between Bretton and Diana-Wentworth veins must be explained. There are two possible explanations:

Firstly, the Old Vein may have only propagated up to the Great Limestone, and above, between Bretton and Diana-Wentworth veins because of the high strain developed near to its intersection with them. Elsewhere the Old Vein did not reach the Great Limestone.

The second possible explanation is that the vein is present throughout, but is only mineralized near to its intersection with other veins. Where the Old Vein is barren or poorly mineralized it may have been missed by the 'old man'. This appears to be a more plausible explanation, and has been observed on other quarter-point veins. High fluid inclusion temperatures from fluorites on Henry's Vein at High Underground Shaft suggests that this

area is a centre of mineralization (Waugh, Pers. Com.). The strike extension of Old Vein passes near to here, (east-west fractures to the NW of High Underground Shaft may be synthetic riedel shears related to the Old Vein). The intersection of Henry's and Old Vein would provide a vertical channel-way for mineralizing solutions.

(c) Summary of structural relationships at Allenheads

(i) The fundamental structures at Allenheads are Henry's and Old veins. Old Vein is believed to be an extension of the Red Vein at Groverake Mine.

(ii) Bretton and Diana-Wentworth veins are large scale synthetic riedel shears, generated by sinistral strike-slip movement along the Old Vein at depth (Fig 6.10).

(iii) Upward propagation on Bretton, Diana-Wentworth, Old, and to a lesser degree Henry's veins has taken place by en-echelon riedel shearing. Vertical differences in the vein structures are due to differences in rock properties and changes in the stress field during fracturing.

(iv) Renewed movement along veins has resulted

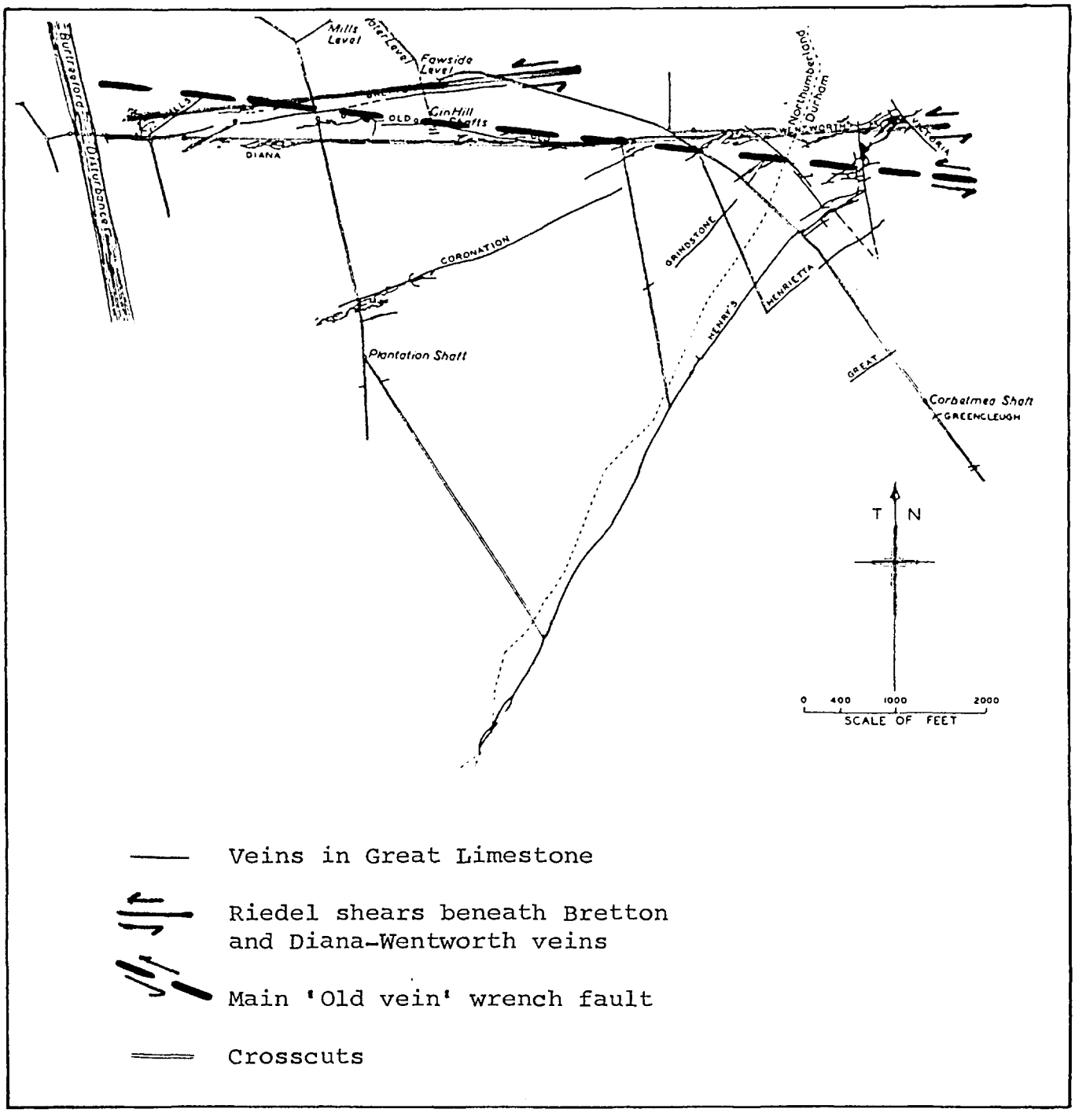


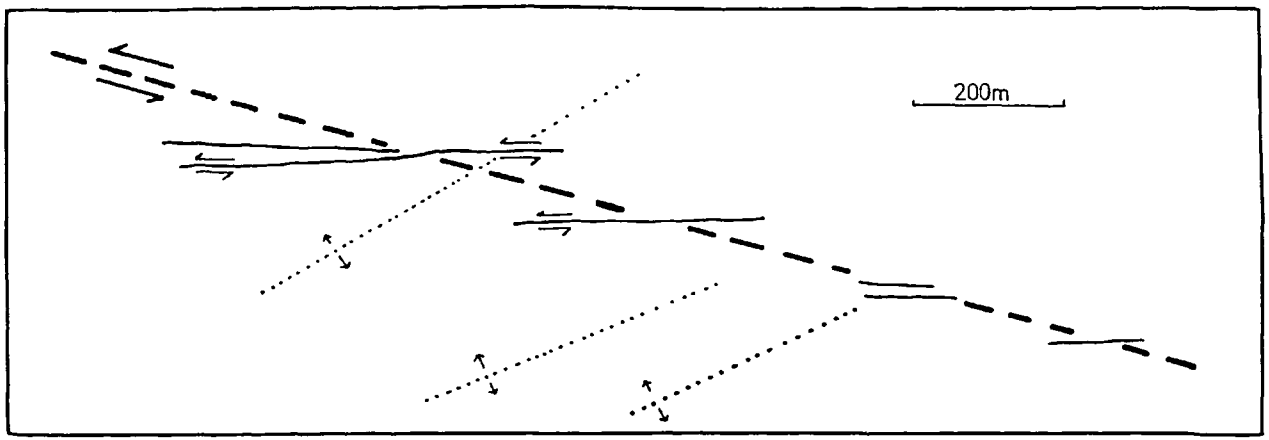
Fig.6.10 Plan of Allenheads Mine, showing interpretation of veins at depth (mine plan from Dunham, 1948)

in the formation of second-order shears. These are particularly evident in the Great Limestone, where they form leaders to replacement flats.

6.6.3 Whiteheaps Mine

Again, at Whiteheaps Mine the arrangement of the east-west Poor, Shield's, Red and Company's veins are analogous to synthetic riedel shears generated by sinistral strike-slip movement at depth (Fig 6.11a). Farneygill and Boltshead veins may have been generated as antithetic riedel shears at this time, they show a more northerly strike than other ENE veins in this area, and are approximately perpendicular to the main White Vein.

Following the development of the riedel shears, the main wrench fault (the White Vein) was propagated upwards on a fairly straight ESE trend; in places cutting through the earlier riedel shears (Fig 6.11b). At Sikehead there is a break in the White Vein structure, and the main vein continues as an overlapping en-echelon fracture, 90m to the north. This arrangement of en-echelon veins, coupled with sinistral strike-slip movement would result in a region of extension between the two vein segments, thus giving rise to the Sikehead oreshoot.

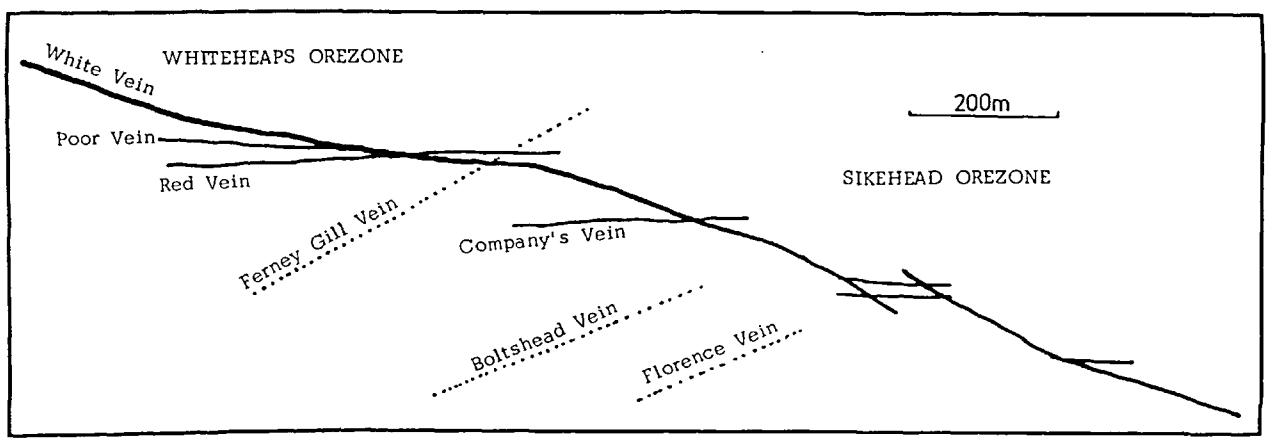


(a) Development of synthetic riedel shears and normal faults due to sinistral wrench movement at depth

Wrench fault at depth

Synthetic riedel shears

Normal faults



(b) Upward propagation of main wrench fault

Fig. 6.11 Generation of vein structures at Whiteheaps Mine

6.7 Exploration potential of the active mines

6.7.1 Allenheads

Several geological factors are necessary for the formation of a fluorspar oreshoot; these include the presence of an opening in the vein fracture to receive the mineralizing solutions, the proximity of vein intersections to channel the hydrothermal fluids, and the spatial position with respect to the mineralogical zonation. The controls of these factors on the location of fluorspar oreshoots at Allenheads are discussed below:

(a) Structurally favourable openings

Openings along a vein fracture are produced by changes in strike or hade of the vein. For a vein showing sinistral strike-slip movement, openings are produced where there is an anticlockwise change in vein strike. For dextral strike-slip veins, openings are produced where there is a clockwise change in vein strike. Openings on veins with normal dip-slip movement are produced where there is an increase in dip (decrease in hade) of the vein fracture. In the northern Pennine orefield changes in strike along veins showing strike-slip movement form the widest oreshoots. Thus, at Allenheads the widest orebodies

would be expected on Bretton, Old, Diana-Wentworth and Henry's veins, which all show evidence of strike-slip movement.

Major east-west shears, such as Bretton and Diana-Wentworth veins are structurally favourable fractures for large oreshoots; as exemplified by Groverake Vein at Groverake Mine. On these veins particularly favourable sites for vein openings are where their strike turns anticlockwise, towards the ENE. This occurs on Bretton Vein near Fawside Level mouth, and on Diana-Wentworth Vein east of East End Shaft. Smaller shears in the Great Limestone may also be favourable.

The Old Vein at depth strikes adversely for wide oreshoots, but associated riedel shears in the Great Limestone may have been open during mineralization.

On Henry's Vein, below the Great Limestone, openings would have occurred where the vein turns clockwise onto a NE trend. This occurs around, and to the north of, High Underground Shaft, and in the region where the vein is intersected by Plantation Crosscut.

(b) Vein intersections

For vein openings to be mineralized, channel-ways for the hydrothermal fluids must have been present during mineralization. Old and Henry's veins both appear to be major strike-slip fractures and thus would have acted as channel-ways for the mineralizing fluids. Openings on these two veins would have been accessible to mineralization.

Locally, the flow of fluids may have been concentrated at the intersection of Old and Henry's veins, and at the intersections of either vein with other veins in the mine area. The hypothetical extension of Old Vein should intersect Henry's Vein near High Underground Shaft. It is significant that fluid inclusion homogenization temperatures of fluorite back-fill in Henry's Vein, near High Underground Shaft, are comparable to other major oreshoots in the orefield (Greenwood and Smith, 1977). The intersection of Old Vein with Bretton and Diana-Wentworth veins would also have provided channel-ways for hydrothermal fluids. Structurally favourable openings on Bretton and Diana-Wentworth veins would therefore have been accessible to mineralization.

Thus, the majority of vein openings would have been accessible to hydrothermal fluids during mineralization.

Whether these fluids deposited fluorite would depend on the position of the vein openings in relation to the regional and local mineral zonation.

(c) Mineral zonation

Although within the fluorite zone of Dunham (1934), Allenheads lies about 8Km to the east of Rookhope cupola of the Weardale Granite (Bott, 1967, and Dunham et al, 1965). The mineral zonation in the orefield is believed to be centred on this and other cupolas. Away from the granite cupolas there is a lateral, and partly vertical, zonation in the gangue mineralogy of the veins, in the sequence quartz-fluorite-carbonates-barite. The boundaries between the mineral zones to the west of the Rookhope cupola would plunge gently westwards. Observations of the junction between the fluorite and quartz zones at Cambokeels Mine have shown that there is a not a sharp change from one mineral to other. Instead there is a gradual increase in one mineral over the other, often leading to the formation of 'pods' of one mineral within a host of the second.

The distribution of carbonates in the orefield is poorly known, but the chief minerals in this zone are ankerite, siderite and dolomite, with subordinate calcite. The Old Vein in the Great Limestone at Allenheads consists

of a carbonate (ankerite-siderite) gangue with pods of fluorite. This suggests that the vein at this point is near to the junction between the carbonate and fluorite zones. It would be expected that fluorite would increase over carbonates with depth on Old Vein, but fluorite would not be expected to become dominant until at least below the Four Fathom Limestone. The junction between the carbonates and fluorite would rise to the east, and fluorite would be expected to appear at higher stratigraphic levels to the east. Henry's Vein in the Great Limestone at High Underground Shaft is in the fluorite zone.

Summary of fluorspar targets at Allenheads

The potential for wide fluorite oreshoots exist on: (1)Bretton and Diana-Wentworth veins near to their intersections with the Old Vein. However, in the western part of the mine area fluorite would not be expected to be dominant in the veins until at least below the Four Fathom Limestone. (2)Good possibilities for fluorite on Henry's Vein occur around and to the north of High Underground Shaft, and to the south of this in places where the vein turns clockwise onto a NE trend. The former site has probably been already worked by the 'old man'. Two possibilities for the latter occur between Kearton's and Plantation crosscuts, and to the south of Plantation Crosscut.

6.7.2 Groverake Mine

The persistence of the Groverake Vein below the 96fm level is unproved, but with comparison to the Slitt Vein at Blackdene, the oreshoot may be expected to continue. However, the potential for fluorspar reserves at depth may be minimal. The vein in the 96fm level contains a high proportion of quartz, which suggests that the base of the fluorspar mineralization may have been reached.

CHAPTER 7 STRUCTURE AND MINERALIZATION OF THE NENTHEAD AREA

7.1 Introduction

The compact group of mines centred on Nenthead (NY7782446) form part of the larger mining district of Alston Moor (Fig 7.1). Alston Moor was the main lead producing area west of the Burtreeford disturbance, and the principal zinc mining region in the orefield. Serious mining in this district did not commence until the mid-eighteenth century. In 1715 the land was confiscated from the Earl of Derwentwater (because of his support for the 1715 rebellion), and assigned to the Commissioners of Greenwich Hospital. The Commissioners subsequently leased veins, and then areas of mineral ground to companies and individuals.

The most important leasee was the London Lead Company, who held upto 40% of the mineral leases, including most of the major mines. In the nineteenth century the London Lead Company consolidated their workings around Nenthead, and constructed a unified system of underground haulage levels (horse levels), serving the bigger mines. Many of these underground levels are still accessible today for several kilometres. Drainage of the mines was facilitated by the construction of the Nentforce Level, which was commenced from Alston in 1776 by

Fig. 7·1 The Mining District of Alston Moor

- Major workings
- Small workings
- Veins (numbered veins are named below)

1 Lough Slitts
2 Blagill
3 Sunnyside
4 Sinclair
5 Dupont
6 Liverick
7 Robinson
8 Treloar
9 High Raise 1st Sun
10 " 2nd Sun
11 Nentsberry Green North
12 " Sun
13 Nentsberry Haggs North
14 " Sun
15 Brownlyhill North
16 " North Middle
17 " Middle
18 " Sun
19 " Moss cross
20 " West High cross
21 " High cross
22 Gudhamgill Moss North
23 " Burn cross
24 Rampgill cross
25 Patterdale cross
26 Great cross
27 High Fairhill cross
28 Low " "
29 Smallcleugh cross
30 Rampgill Sun
31 Hangingshaw
32 Nenthead Field
33 Dowgang North
34 Dowgang
35 Brigal Burn
36 Caplecleugh North
37 " Sun
38 Middlecleugh North
39 Middlecleugh
40 " 1st Sun
41 " 2nd Sun
42 Longcleugh
43 " 1st Sun
44 " 2nd Sun
45 Caplecleugh
46 Browngill North
47 Thaughtergill Syke

1 Km

ALSTON
GARRIGILL
NENTHEAD

Thorngill
Blagill
Nentforce Level
Hudgillburn
Holyfield
Dowpotsyke
Tynebottom
Haggs
Brownlyhill
Wellhope shaft
Rampgill
Caplecleugh
Smallcleugh
Middlecleugh

Slote
Manor House
Whittewall
Thorngill
Fistas Rake
Blagill cross
Baylehill
Carrs
Rough Tongue
High Raise
Brownlyhill
Wellgill cross
Nentsberry
Jacob Teasdales
Hudgill
cross
Middle fell
High Baylehill
Farnberry Field
Limekiln
Farnberry
Holyfield old
Quaker
Milligans
Redgroves
Nattrass old
Hudgill veins
Gudhamgill
Jug
Flow Edge
Flow Edge Sun
Honeybee
Dowpot Syke
Gutter gill
Craggreen
Staggy burn
Black Syke
Fletcheras
Hundy Bridge
Gratty
Cowperdyke
Garrigill Burn
Taylors Syke
Bentyfield
Browngill
Browngill Sun
High Scar
Dryburn Washpool
Archys
Black Ashgill
Cowhill cross
Cowslitts cross
Galligill
Middle
Galligill Syke
Grassfield
Syke cross
Greengill
Greengill East cross
Greengill cross
Pity Mea
Scaleburn
Rampgill
Rampgill 2nd Sun
Wellhope knot

N

74 76 46 44 75 78 42 45

M.F.Critchley 1981

Greenwich Hospital.

In 1882 the London Lead Company leases passed to the Nenthead and Tynedale Zinc Company, who were succeeded by the Vieille Montagne Zinc Company in 1896. During the operations of these two companies, the production of zinc increased. Mining declined during the 1940's, and the Vieille Montagne Company's leases passed to Anglo-Austral Mines in 1949, but little ore has been produced since that date. Total production for the Nenthead area is in the order of 330,000 tons of lead concentrate and 195,000 tons of zinc concentrate.

7.2 Vein and fault structures

Veins of all three major sets are present on Alston Moor (Fig 9.2). The network of ENE and NNW veins around Nenthead form a reticular pattern. East-west veins are variable in their strike direction and continuity.

7.2.1 ENE veins

At Nenthead, the greatest proportion of ore has been won from the ENE veins. The ENE veins appear to fill normal faults, with small vertical throws of upto 4m.

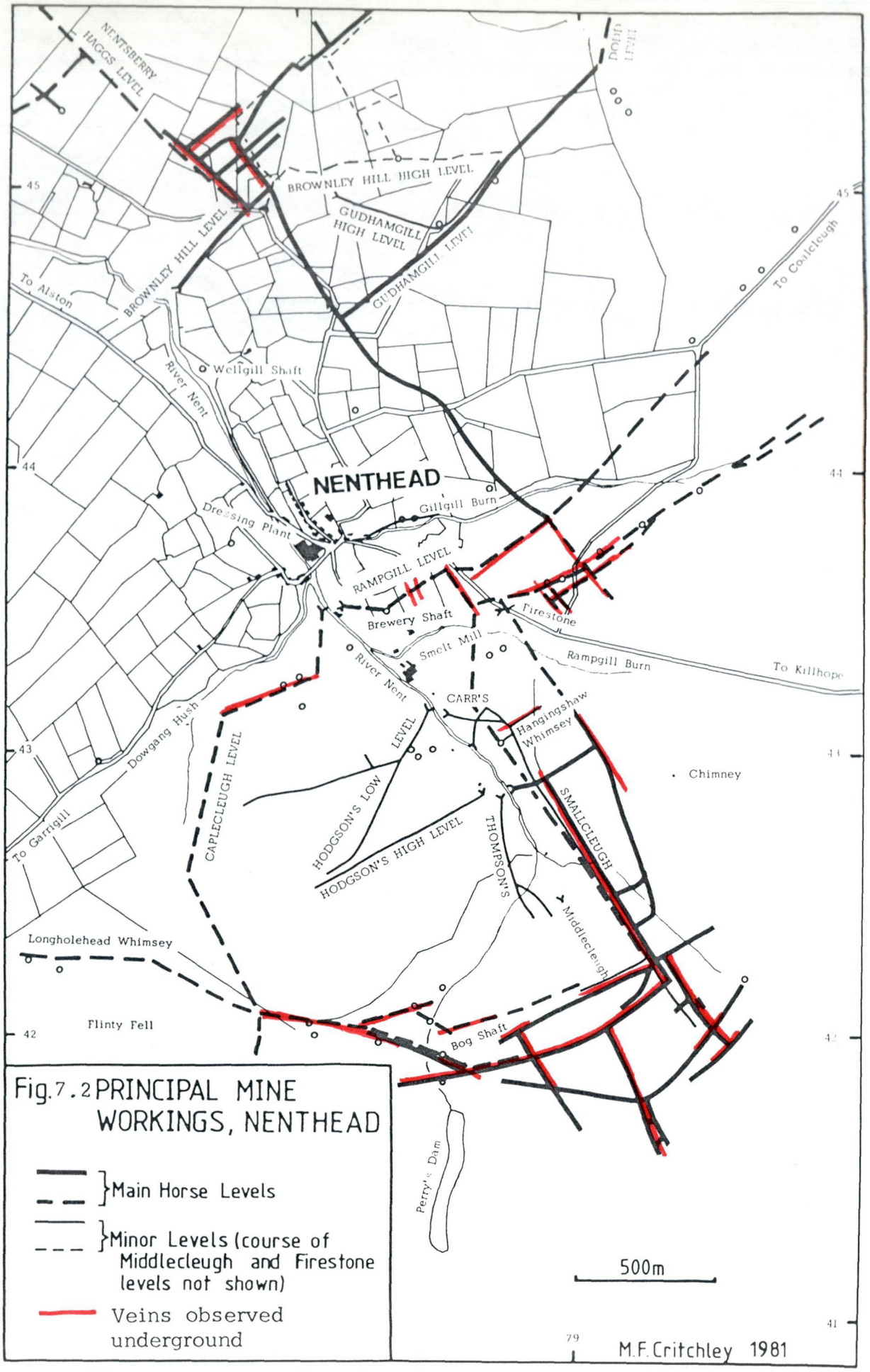


Fig.7.2 PRINCIPAL MINE WORKINGS, NENTHEAD

Main Horse Levels

Minor Levels (course of Middlecleugh and Firestone levels not shown)

Veins observed underground

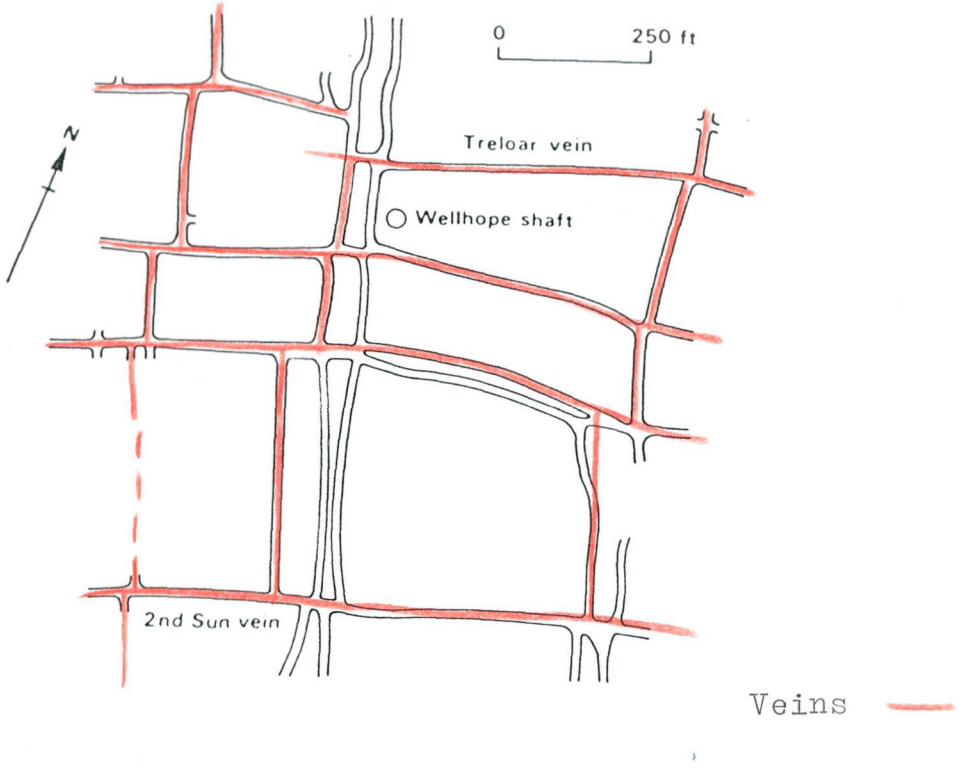


Fig.7.3 Displacement of NNW veins by ENE veins in the Wellhope Shaft area of Nentsberry Haggs Mine (from Smith, 1980)

Changes in the hade of the veins have resulted in the formation of ribbon oreshoots (see section 3.3.1). Horizontal slickensides are present along many of the vein cheeks, and these may be covered by either undisturbed crystal growths, or a veneer of sheared and fractured minerals. The period of horizontal movement along the ENE veins must post-date their formation by normal faulting; or elsewhere the horizontal slickensides would not have been preserved. The association of the slickensides with undisturbed and crushed minerals suggests that strike-slip movement occurred prior to mineralization on some veins, but on others it took place during or after mineralization. An example is seen on the Longcleugh Vein in Middlecleugh Level, where the vein has the orientation $233^{o}/70^{o}W$. Slickensides on the vein walls pitch $15^{o}W$, and are partly covered by cubes of green fluorite. A thin gouge fills the centre of the vein, and this contains vertical slickensides.

Horizontal movement along the ENE veins can also be inferred from the displacement of NNW veins. A plan (Fig 7.3) of the sub-level workings in the Wellhope shaft area of Nentsberry Haggs Mine (NY779467), shows that the ENE veins displace the NNW veins dextrally by upto 17m. Some development levels in the NNW direction are offset by lesser amounts, but it cannot be certain that these levels are driven along the same vein either side of an ENE vein. Elsewhere in the orefield, Smith(1980), infers sinistral strike-slip movement along the ENE Burtree Pasture Vein at

Burtree Pasture Mine, based on the mapping of folded wallrocks.

7.2.2 NNW cross veins

North-north-west cross veins are well developed in the Nenthead region. The principal cross veins are:- Hudgillburn-Greengill-Blackashgill, Cowhill, Cowslitts, Carrs and Wellgill cross veins. The throws on the cross veins are variable, but they generally have large normal displacements; Carrs Vein has a throw of 77m to the NE in Loveladyshield Level (NY760462). Cross veins having large throws are rarely mineralized. Dunham (1948) suggests that they may have been choked by dragged-in shale prior to mineralization. Oreshoots on cross veins with small displacements are comparable in size to those on the ENE veins although mineralization is restricted to the vicinity of their intersections with the ENE veins (Dunham, 1948). Parallel to the larger NNW veins are many subsidiary fractures, which have little or no displacement.

Evidence of strike-slip movement is also present along the NNW veins, again horizontal slickensides on the vein cheeks are covered by later minerals (plate 5). In Smallcleugh Mine, the Smallcleugh Cross vein, between Middlecleugh Second Sun and Longcleugh veins, displaces

several ENE veins, dextrally by about 3m. Smallcleugh Vein and the ENE veins are vertical at this level, and the horizontal displacements of the ENE veins cannot be explained by apparent shifting due to vertical downthrow of a hading vein, but only by actual strike-slip movement along the Smallcleugh Vein.

Forster (1821), gives other examples of the sideways shift of ENE veins by NNW veins in the Nenthead district. He describes an apparent 150ft (45m) dextral shift of Rampgill Vein by Patterdale vein (Fig 7.4). Patterdale Vein down throws to the east by 7m, and dips at 80° in this direction, Rampgill Vein dips about 80° north in the Great Limestone. Purely normal dip-slip movement on the Patterdale Vein would produce an apparent 1.3m dextral displacement of Rampgill Vein (Fig 7.5). Thus, actual dextral strike-slip movement must have occurred along Patterdale Vein to account for the 45m shift of Rampgill Vein.

7.2.3 Flats

Large quantities of lead and zinc ore were extracted from 'flats' in the Great Limestone around Nenthead (Wallace, 1890). Three forms of flat mineralization have been observed in the Nenthead mines. The first type was most economically important, and consists of void linings

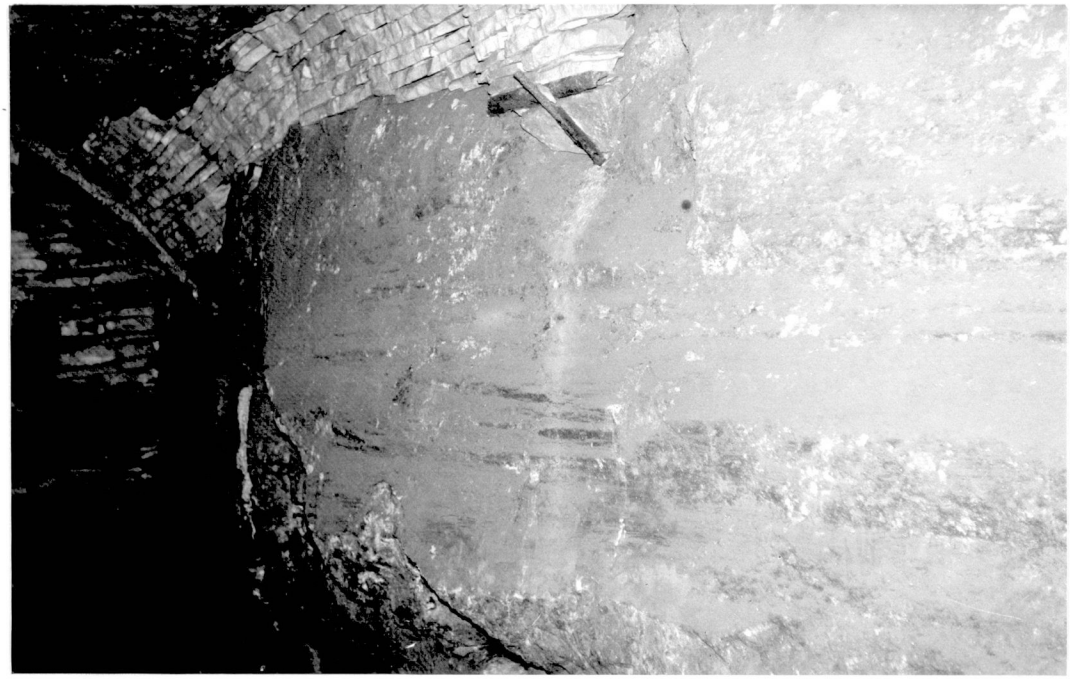


Plate 5 Horizontal slickensides on wall of Smallcleugh Vein, Nenthead

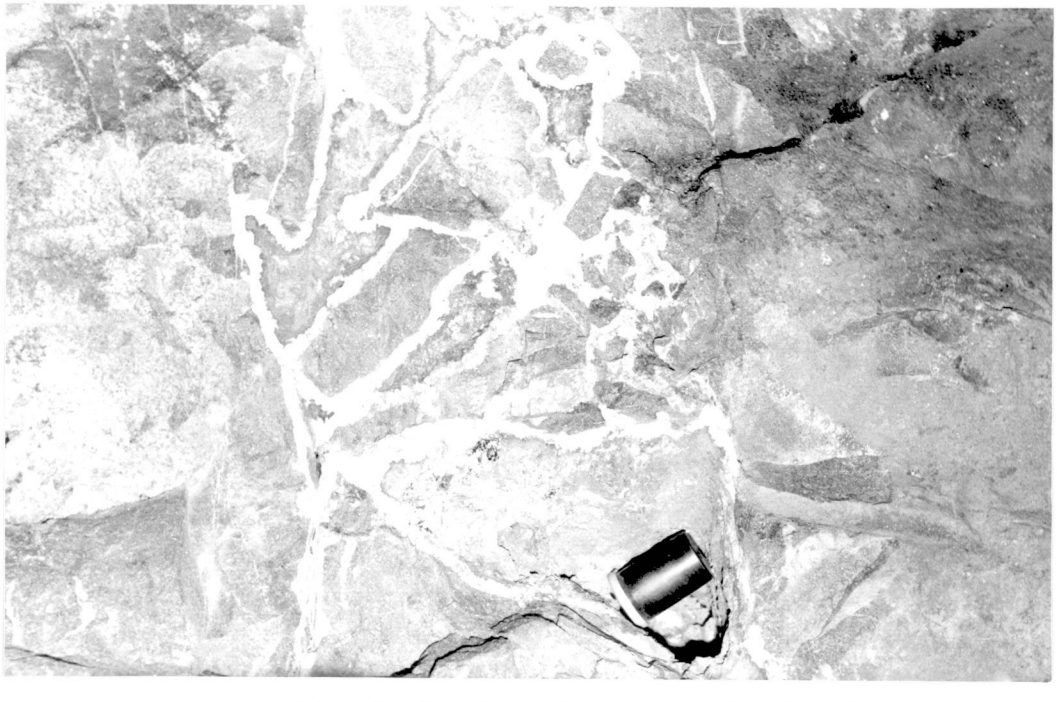


Plate 6 Possible hydraulic fracturing in the Great Limestone, Smallcleugh Mine, Nenthead

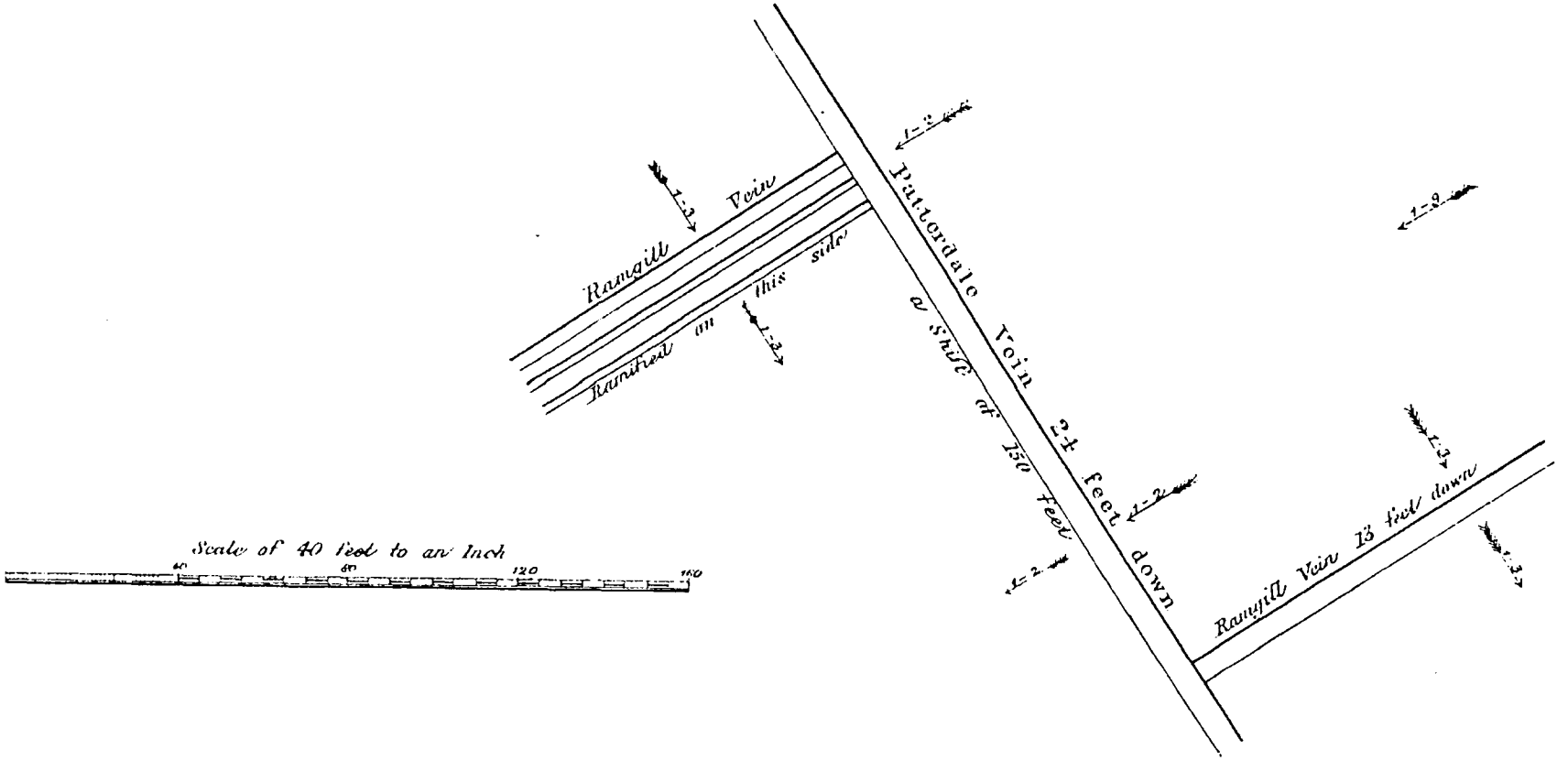
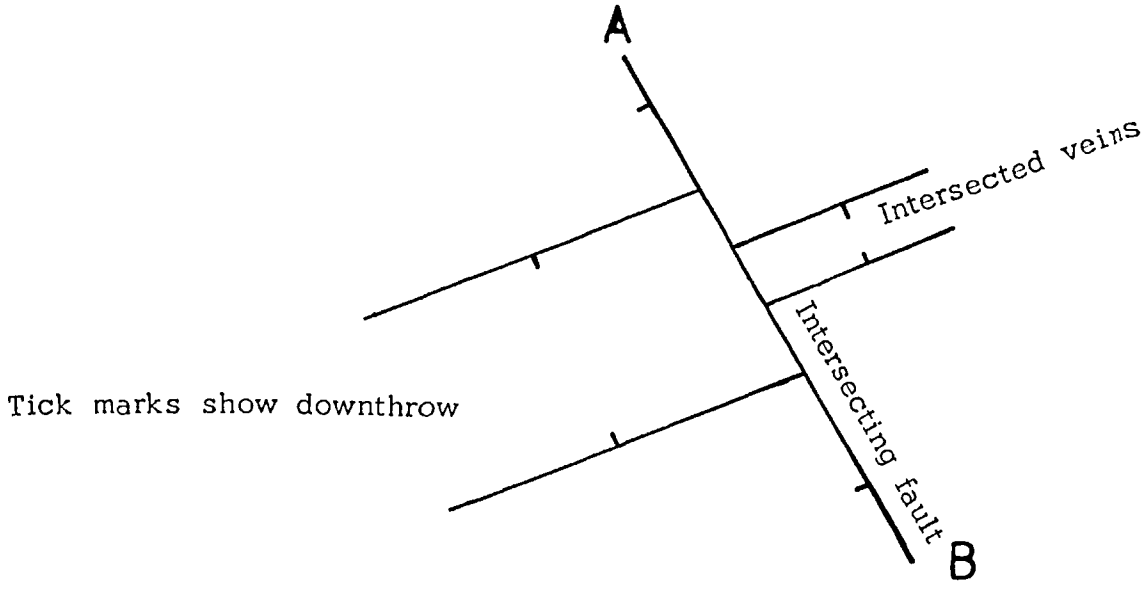
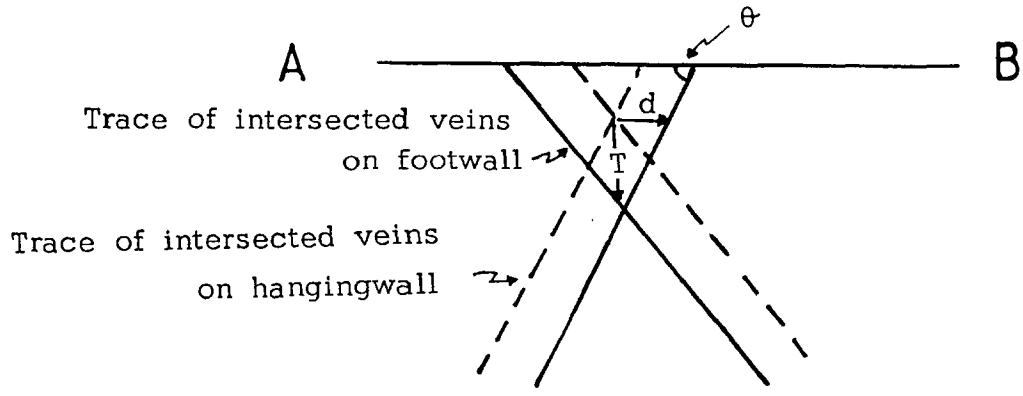


Fig.7.4 Displacement of Rampgill Vein by Patterdale Vein (from Forster, 1821)



(a) Plan of vein-fault intersections



(b) Section along fault plane from A to B

T = Throw on fault

d = Apparent horizontal displacement of intersected veins

θ = Plunge of intersected veins on fault plane

The displacement (d) is calculated from the formula:

$d = T/\mathrm{Tan}\theta$

Fig. 7.5 Calculation of apparent horizontal displacements of veins by a normal fault

of sphalerite, galena and quartz. The limestone surrounding the voids is often highly decomposed. The second type of flat mineralization comprises of veining associated with sharp brecciation of the limestone (plate 6). Galena and sphalerite may occur with quartz in the cement between the breccia fragments. Actual replacement of the limestone by sulphides is rarer, and constitutes the third type of flat mineralization. Generally, the sulphides replace fossil fragments in the limestone. Apparent replacement of the limestone by large amounts of galena are probably the result of the total infilling of cavities within the limestone.

7.2.4 Browngill Vein system and other east-west veins

The Browngill Vein is regarded as a principal channel of mineralization (Dunham, 1948). To the north and west of Garrigill (NY744415), the vein strikes 079°, and is known as Dryburn Washpool Vein. To the NW of Garrigill, the Tynebottom Mine (NY738419) worked flats in the Tynebottom Limestone. The grade of ore in these flats was less than comparable flats in the Great Limestone (Wallace, 1861).

A line of shafts and surface workings alongside the Garrigill to Nenthead road mark the position of the

Browngill vein to the east of Garrigill. This ground was developed underground from the Whitesike Level (NY756426). In the neighbourhood of Longholehead Whimsey (NY770423), the Browngill Vein strikes roughly east-west. Five hundred metres east of the Whimsey, the vein turns onto an ESE trend, and Dunham (1948) states that the vein curves into the NNW Archy's Cross Vein. Observations underground in the Caplecleugh Mine suggest that the Browngill Vein continues through Archy's and Black Ashgill cross veins on the ESE trend as Longcleugh Vein.

East of Carr's cross vein (NY793418), Longcleugh Vein appears to curve sharply onto a NE striking trend. Dunham also suggests that the Middlecleugh veins curve off the north side of the Browngill vein. However, in the sub-levels between Smallcleugh and Caplecleugh horse levels the Middlecleugh Second Sun Vein is cut through by the Browngill Vein, and continues on the SW side of the latter. This suggests that the Middlecleugh Second Sun Vein is a normal ENE vein, and is cut through by the later Browngill Vein. A similar explanation may be invoked to account for the NE portion of the Longcleugh Vein, and the main Browngill fracture may continue to the ESE.

Several other important east-west veins occur in the Alston area. To the north the Slote-Thorngill Vein was worked for lead and barytocalcite at the Blagill Mines (NY740476). Redgrooves Vein (NY740449) and the Hudgillburn

veins (NY752448) are arranged en-echelon along an ESE line.

7.3 Mineral distribution

Moore (1982) suggests that mineralization in the Nenthead region can be related to the operation of a convective cell, about 5km across. He outlined the cell based on the occurrence of workable zinc deposits. During the present investigation, samples of mineralized material were collected from in-situ in the old underground workings (Fig 7.6). These samples were used to investigate the mineral distribution around Nenthead. Sphalerite was collected in the hope that it could be used to obtain a picture of the temperature distribution over the area during mineralization. Unfortunately, the fluid inclusions in the sphalerite proved to be too small, or were totally fluid filled, and therefore could not be used to find homogenization temperatures.

The distribution of Pb, Zn and Cu sulphides and fluorite gangue are shown on Figure 7.7. The Pb and Zn sulphides show an even spatial distribution over the area sampled. Fluorite and chalcopyrite however, are restricted to the vicinity of the Browngill Vein. Secondary nickel and cobalt occur at the Tynebottom Mine on the Browngill Vein; early primary Ni-Co-As bearing sulphides have also

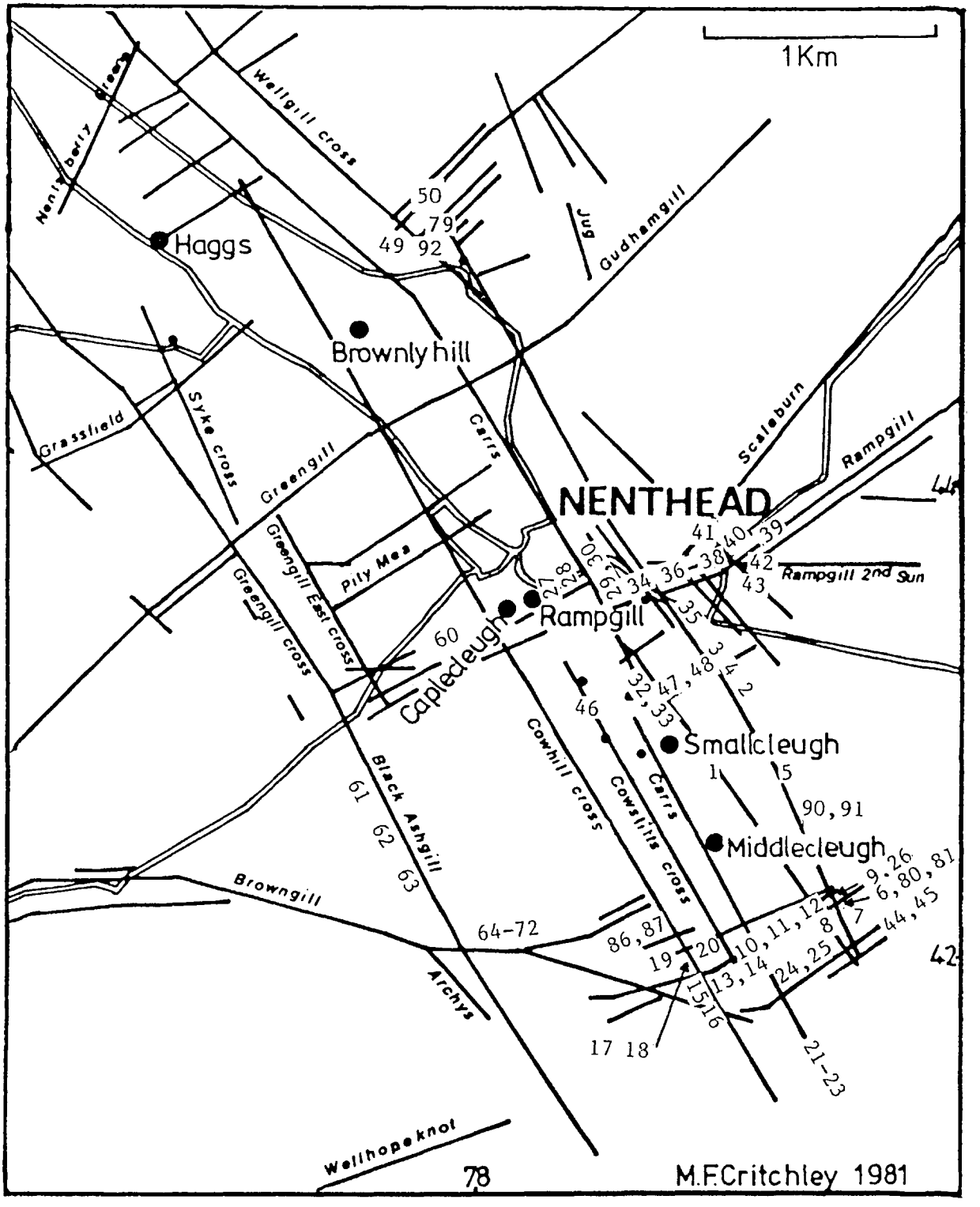


Fig. 7.6 Location of samples collected from the Nenthead area

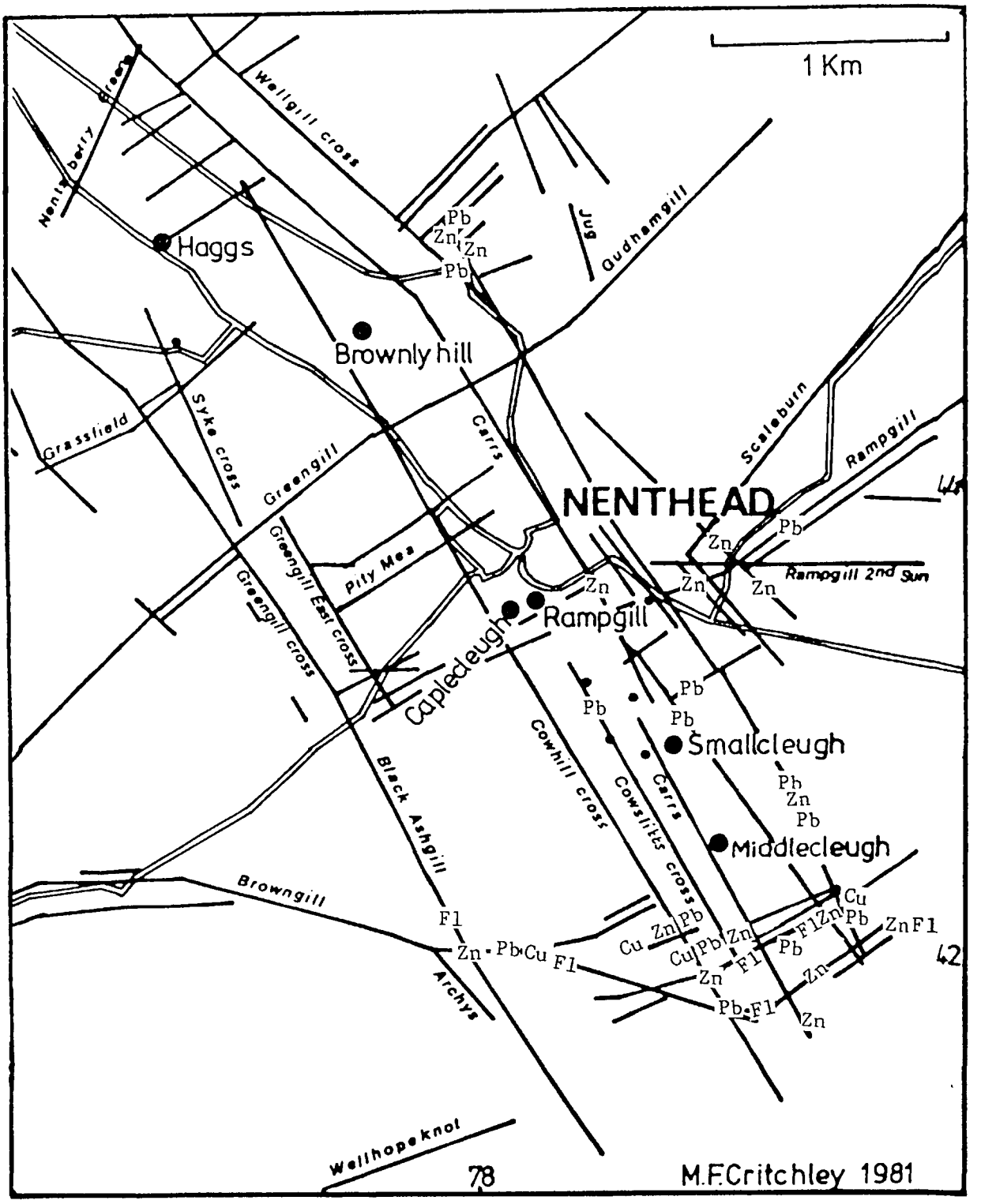


Fig. 7.7 Distribution of minerals in the Nenthead area;
Pb- galena; Zn- sphalerite; Cu- chalcopyrite;
Fl- fluorite.

been discovered in this mine (Vaughan and Ixer, 1980). Elsewhere in the orefield these minerals have been found in centres of mineralization, and the evidence supports Dunham's notion that the Browngill Vein was the main feeder for mineralization in the area.

In the Wellhope Shaft section of Nentsberry Haggs Mine (NY779467), the intersections between ENE and NNW appear to have acted as feeders for the mineralization. In the vicinity of these intersections, all veins carry coarse galena, with sphalerite and pyrite, and a quartz-ankerite-barite- witherite gangue (Dunham, 1948). Away from the intersections the Zn/Pb ratio increased, due to the decrease in galena; barite and witherite increased in quantity.

7.4 Discussion and summary

The changes in hade of the ENE and NNW vein-fractures with lithology, and the vertical offsets across them, suggest that these fractures were formed by normal dip-slip shear failure. The lack of consistent vertical offsetting of one vein set by another suggests that the fractures formed simultaneously. After their formation the ENE and NNW fractures were subjected to horizontal movements prior, to and during mineralization. The direction of the compression causing these horizontal movements

could have either been north-south or east-west. Slight changes in the orientation of s_1 from place to place would have resulted in the change from sinistral to dextral movement along a given vein, because of the small angle between the strike of the fractures and the principal stress directions.

The Browngill Vein system has the appearence of a quarter-point vein fracture, it is however more variable in strike than quarter-point veins in Weardale. The sinuous nature of the vein, and its ESE strike suggest that the Browngill Vein fracture was formed in the same manner as the quarter-point veins of Weardale; that is by sinistral wrench faulting. This would imply that s_1 was aligned roughly east-west, and it would seem reasonable to assume that the wrench faulting occurred at the same time as the horizontal movements along the ENE and NNW veins. The en-echelon arrangement of veins at Hudgillburn Mine resembles the en-echelon shears on the 40ft level in Blackdene Mine. The arrangement of the veins at Hudgillburn is consistent with their generation as riedel shears, due to sinistral strike-slip movement at depth.

Mineralization occurred during or after the period of strike-slip movements along the vein fractures. The mineralization fluids were probably channelled up the intersections between the fractures and then flowed laterally along the veins. The Browngill Vein system

formed a major channel way for the fluids, suggesting that this is a deep seated fracture.

CHAPTER 8 MATHEMATICAL ANALYSIS OF STRUCTURES

8.1 Intrusion of the Whin Sill and dykes

The spatial relationships between the Whin Sill and dykes suggest their intrusion to be coeval. At Closehouse Mine (NY851237), dolerite is intruded within and to the south of the Lunedale-Closehouse fault system (Hill and Dunham, 1968). A small dolerite sill extends away from one of these dykes into the sandstone above the Scar Limestone. The relationship of the sill to the dyke is not clear, but it would be reasonable to assume that it was fed from the dyke. To the north of the orefield, dykes are exposed both above and below the conjected horizon of the Whin Sill; within the orefield, dykes are rare.

Price (Pers.Com.), has suggested that many sills were fed by dyke-like intrusions. The spatial relationships of the Whin Sill and dykes suggest the sill to have been fed by the dykes, but direct evidence is lacking. Assuming this process to have occurred, it is possible to calculate the stress conditions at the time of intrusion of the Whin Sill into the sediments of the Alston Block.

8.1.1 Mechanisms of whin intrusion

Consider a dyke feeding a sill (Fig 8.1), it is first necessary to estimate the depth of the sill at the time of the intrusion. Creaney (1980) has estimated the depth of burial of the Great Limestone at the time of the whin intrusion as 1.5-2km; say 1500m. Typically, the Whin Sill is intruded at the base of the Single Post Limestone (226m below the top of the Great Limestone). Thus, the total depth from surface to the top of the Whin Sill is taken to be 1726m. For magma to be intruded into consolidated rocks, the pressure of the magma (P_m) has to overcome the stresses acting at the time of intrusion, plus the tensile strength of the rock.

For a dyke intrusion the following equation must be satisfied;

$$P_m = s_H + T_{11} \quad \text{eqn. 8.1}$$

where, P_m = magmatic fluid pressure

s_H = Horizontal stress

T_{11} = Tensile strength, parallel to bedding

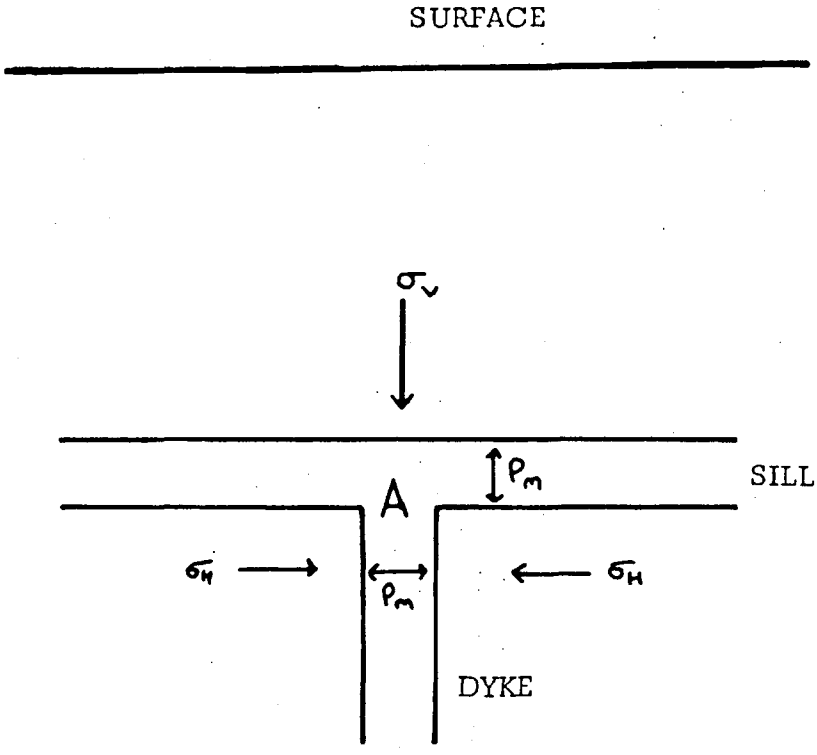


Fig.8.1 Dyke feeding a sill

For the sill intrusion the following equation must be satisfied;

$$P_m = s_V + T_p \quad \text{eqn. 8.2}$$

where, P_m = magmatic fluid pressure

s_V = vertical stress

T_p = Tensile strength perpendicular to bedding

Where the dyke feeds the sill (A on Fig.8.1);

$$P_m(\text{dyke}) = P_m(\text{sill})$$

Therefore;

$$P_m = s_H + T_{11} = s_V + T_p \quad \text{eqn. 8.3}$$

For the given problem;

$$s_V = hpg$$

where, h=depth from surface to base of Whin Sill

p = average density of sediments

g = accelaration due to gravity

Let

$L = 1726m$

$p = 2500kg/m^3$

$g = 9.8m/s^2$

Then; $s_V = 4.23x10^7 Pa$

Data on the mechanical properties of the rocks in the Tyne-Tees Tunnel give the following average values for the tensile strength of rocks in the orefield;

$T_p = 0$ (no strength across bedding planes)

$T_{11} = 6x10^6$ Pa

Therefore, from eqn 8.3,

$$s_H = s_V + T_p - T_{11}$$

Therefore; $s_H = 3.63x10^7 Pa$

If the dyke fills an extension fracture then s_H must be s_3. Therefore, the horizon where the dyke feeds the sill is where the effective minimum stress ($s_3 - P_m$) changes from acting horizontally to vertically.

8.1.2 Mode of intrusion of the Whin Sill

The simple model above would suggest that the sill was intruded exactly at the horizon where the effective

minimum stress (s_3-P_m) changes from horizontal to vertical, irrespective of the strata at that horizon. However, as Burns (1877), noted, the sill is invariably intruded beneath a limestone, and is underlain by shale. This can be explained if the tensile strength of the rocks perpendicular to the bedding is not zero. The harder strata, particulary the more massive limestones within a bedding unit, may have a tensile strength perpendicular to the bedding approaching that parallel to the bedding. Thus, the pressure of the magma, although able to overcome the tensile strength of the shale, may not be great enough to fracture the limestone.

Dunham (1948), states that there is little evidence of the forceful emplacement of the sill. Fyfe et al (1978), note that hot fluids under high pressure and associated with an intrusion, often cause the disintergration of sandstone and limestone contact rocks. These rocks then behave in a plastic manner by grain flow. On cooling the sedimentary rocks will recrystallize, and will take on the appearance of metamorphically hardened rocks; all evidence of movement will be lost. The theory suggests that as the Whin Sill was intruded the pressure of the magma overcame the vertical stress, reducing the effective vertical stress to zero. Thus, the sediments above the Whin Sill can be envisaged as 'floating' on the magma at the time of the sill's intrusion. This would provide an explanation for the fact that there was little assimilation of the country rock by the intrusion. The

vertical distances between beds above and below the sill have not been increased by the presence of the sill. Smythe (1930), suggested that the lack of thickening when the Whin Sill is present was due to horizontal movements along the plane of the intrusion. The 'floating' of the sediments above the sill predicted by the stress model outlined above would allow horizontal movements to occur.

In the sediments overlying the Alston Block, the Whin Sill shows many transgressions or changes in its stratigraphic horizon. Each change in horizon takes place along a roughly north-south line (Dunham, 1948). Russell and Smith (1979), suggest that the sill was fed from a basic magma chamber along the line of weakness of the Burtreeford disturbance. This is supported by the work of Creaney (1977 and 1980) who showed, from coal ranks and petrology, that the intrusion of the Whin Sill was associated with an anomolous heat zone along the line of disturbance (Fig 8.2).

Transgressions in the horizon of the Whin Sill are often sharp, with relatively large vertical jumps. Dunham (1948), has shown that the sill generally transgresses to higher stratigraphic horizons away from the Burtreeford disturbance (Fig 2.5). The transgressions in the sill can be explained by its intrusion into already domed sediments and/or by lateral changes in magma pressure. If the sediments were already domed prior to the intrusion of the

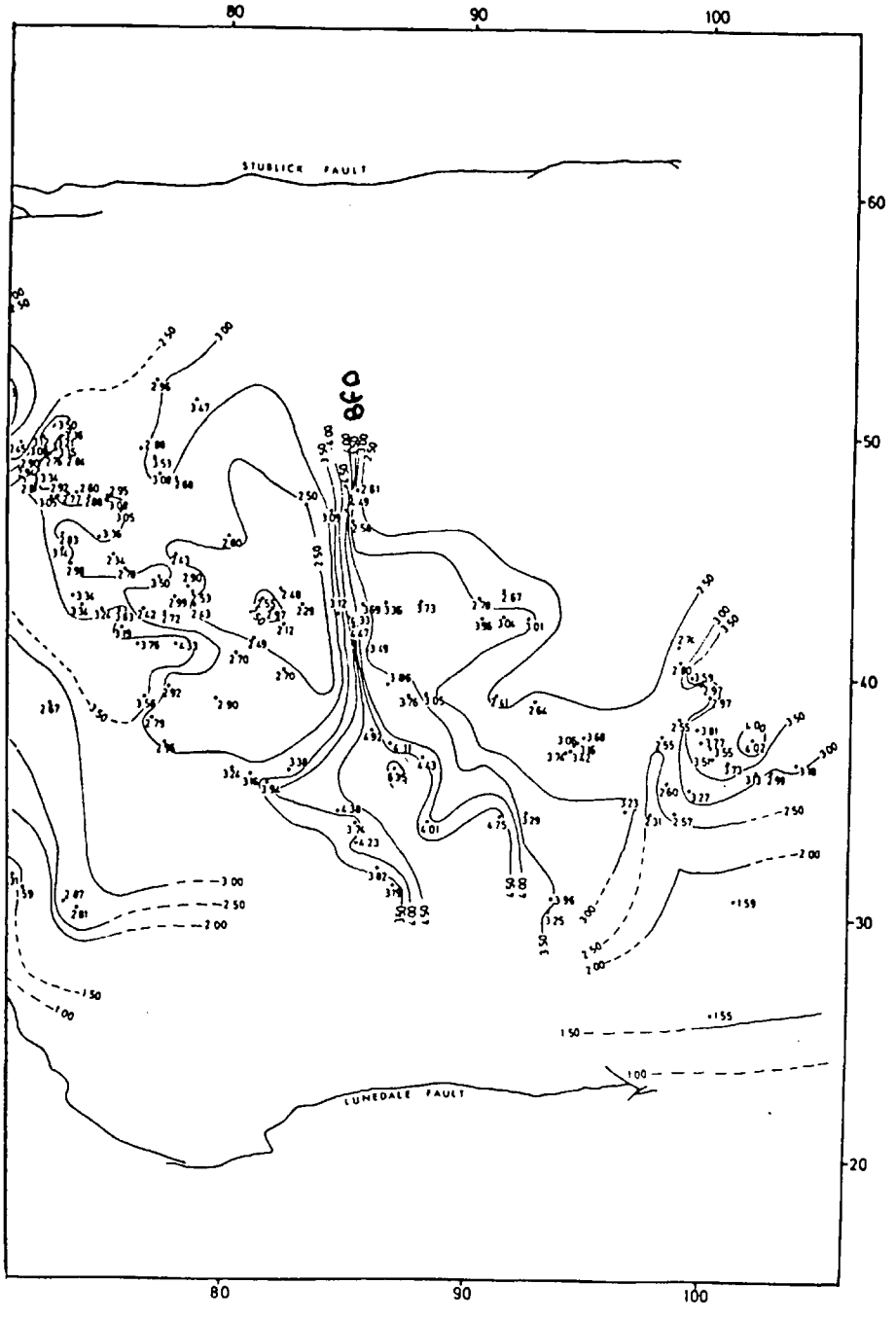


Fig. 8.2 High heat flow along the Burtreeford disturbance, revealed by high vitrinite reflectance of coal (from Creaney, 1980)

sill, and the land surface was approximately horizontal at this time, then the plane (effective neutral surface) at which the magma pressure equalled the vertical load, would have been at a constant depth below the surface. If the sediments were domed, then this plane would have cut across successively higher stratigraphic units away from structural highs of the dome. Away from the structural highs of the sill, it would be easier for the sill to intrude the line of weakness provided by a bedding plane, rather than cut horizontally across the strata. Following a bedding plane away from a structural high, the sill would be carried below the effective neutral surface. The inbalance between the pressure of the magma and the stresses acting would induce a tendency for the magma to rise vertically, but this would only occur if a vertical line of weakness was met, or the pressure of the magma overcome the tensile strength of the confining bed above.

The sill would attempt to be at or near the effective neutral surface, and would transgress stratigraphically upwards away from the structural highs of the folded sediments.

The second mechanism for transgressions in the Whin Sill relies on lateral changes in the magma pressure. If the whin was intruded along the north-south line of the Burtreeford disturbance, and then spread out laterally, it could be envisaged that the pressure of the magma in the sill decreased away from the disturbance. High magma pressure around the disturbance would result from the

upwelling of the magma. If the stress decreased laterally away from the disturbance, then this would have provided a driving mechanism for the magma to flow horizontally. The decrease in pressure away from the disturbance would also cause a systematic elevation away from the disturbance of the horizon at which the magma pressure equalled the vertical load (effective neutral surface). Thus, again assuming a flat topographic surface, the Whin Sill would have tended to migrate to higher stratigraphic horizons away from the Burtreeford disturbance. Again the sill would not be expected to be intruded at precisely the same horizon as the effective neutral surface, but would be also controlled by the harder strata.

Neither of the two mechanisms for transgressions in the Whin Sill fully explain the known distribution of the intrusions. As shown in section 3.2.1, the highest parts of Teesdale Dome are not along the Burtreeford disturbance, but above the Rookhope and Tynehead cupolas of the Weardale Granite. It would thus be expected that the sill would be at the lowest stratigraphic horizons over the cupolas: infact the sill is intruded at the lowest horizons in the vicinity of the Burtreeford disturbance. The second mechanism cannot explain local downward transgressions in the sill away from the Burtreeford disturbance. Possibly a combination of both mechanisms was operative at the time of intrusion. Higher level sills, such as the Little Whin Sill may belong to different periods of intrusion, injected at lower

pressure. This is supported for the Little Whin Sill by the chemical evidence of Dunham and Kaye (1965), who note a different composition for this sill when compared with the main Whin Sill.

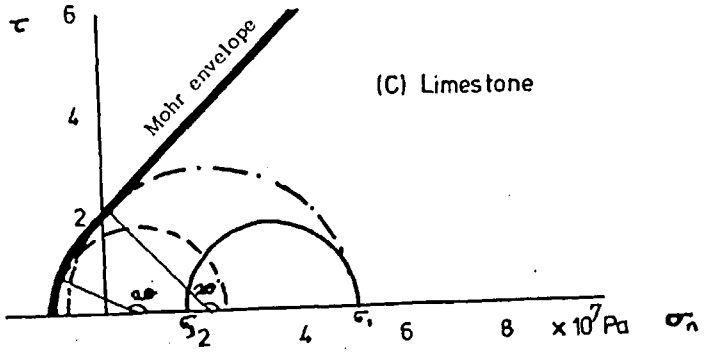
8.2 Vein fracture formation in the orefield

8.2.1 Formation of ENE and NNW vein fractures

Many of the ENE and NNW vein fractures show evidence of their formation by normal faulting (p. 43). As Anderson (1951) has shown normal faults imply that the maximum principal stress (s_1) was vertical, and the minimum principal stress (s_3) was perpendicular to the strike of the fault in the horizontal plane. Dunham (1948) and Smith (1974), have explained the ENE and NNW vein fractures as extensional failure structures, resulting from stratal extension due to updoming. If this was the case then the vein fractures would be expected to be vertical in all lithologies, which they are clearly not. For shear failure to have occurred, it was necessary for either s_1 to increase or s_3 to decrease. For the maximum principal stress to increase there must have been an increase in the vertical loading; this could only occur if rapid sedimentation occurred above the Alston Block. However, the vein fractures post-date Carboniferous sedimentation and vertical loading was unlikely to have increased.

Alternatively, a decrease in s_3 could occur in two ways: either by uplift and horizontal extension; or by an increase in the fluid pressure in the rock. An increase in fluid pressure would reduce the effective stresses of both s_1 and s_3 by the same amount.

As an example, it is possible to calculate the stress conditions for normal faulting in limestone, sandstone and shale, buried to a hypothetical depth of 2km: the base of the Carboniferous on the block was estimated to be about 2km below the surface at the time of mineralization by Smith (1974). The stress conditions in the rocks at this depth (Mohr circle) and the stresses necessary for faulting (Mohr envelope) are shown in Figure 8.3. In the shale (Fig 8.3a), the stress conditions at 2km would be close to those necessary for failure; only a slight decrease in s_3 would cause compressional shear failure. Similarly, in the sandstone (Fig 8.3b), only a small reduction in s_3 or a small increase in fluid pressure would also cause compressional shear failure. In the limestone (Fig 8.3c), the initial stress conditions would be stable. A large increase in fluid pressure in the limestone would take the Mohr circle into the region of tension and extensional shear failure would occur. A large decrease in s_3 would also cause extensional shear failure in the limestone. Wide oreshoots are common in many of the limestone units of the orefield (Dunham, 1948).



The initial stress conditions are:
$\sigma_1 = 5.09 \times 10^7$ Pa
$\sigma_3 = 5.09 \times 10^7 / (m-1)$

Where, m = Poisson's Number

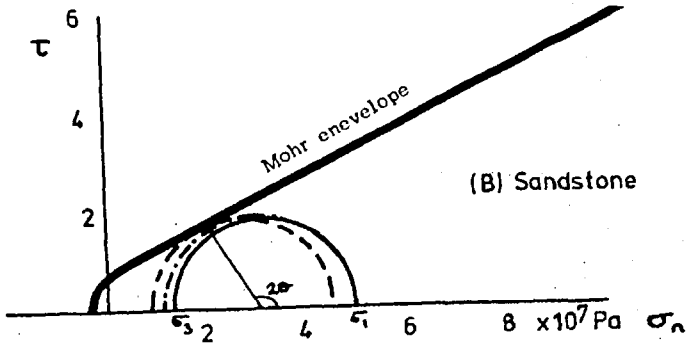
For Lst. m = 4
Sst. m = 5
Shale m = 4

The Mohr envelope of failure is defined by the equation:

$$\tau = 2T + \sigma_n \mu$$

Where, μ = Coef. of friction
T = Tensile strength

For Lst;
$\mu = 1.0$ $T = 1.0 \times 10^7$ Pa
For Sst;
$\mu = 0.5$ $T = 3.58 \times 10^6$ Pa
For Shale;
$\mu = 0.45$ $T = 2.0 \times 10^6$ Pa
(rock property data from Tyne-Tees Tunnel)

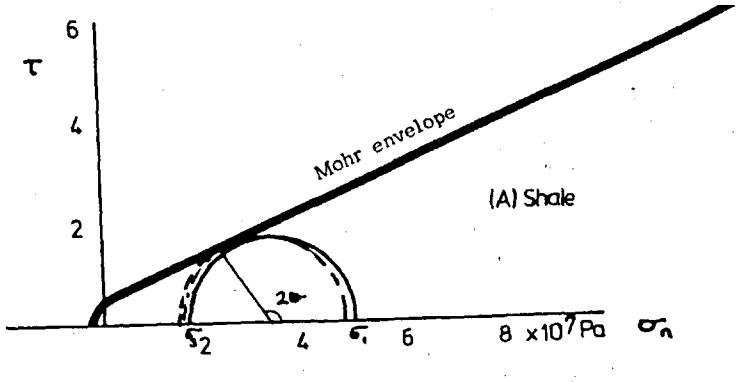




Initial stress Mohr circle

Stress circle after decrease in σ_3

Stress circle after increase in fluid pressure



At failure, the angle 2θ will be:

For Sst. and Shale for failure with decrease in σ_3 or increase in fluid pressure
2θ(Sst) = 120^0
2θ(Shale) = 114^0

Therefore, faults in Sst. will dip at 60^0 and faults in shale at 57^0.

For Lst. Failure with decrease in σ_3:
$2\theta = 175^0$ Faults will dip at 87.5^0

Failure with increase in fluid pressure:
$2\theta' = 145^0$ Faults will dip at 72.5^0.

Fig. 8·3 Mohr circles and envelopes for a Limestone, Sandstone and Shale

Extensional shear failure coupled with vein refraction would provide a mechanism for the formation of large cavities.

An increase in fluid pressure causing faulting could have resulted from the introduction of fluids by the de-watering of the surrounding basinal sediments. Alternatively, uplift of the Carboniferous sediments associated with the formation of the Teesdale Dome, would have resulted in horizontal extension of the strata and a reduction in the horizontal stresses including s_3. It is difficult to distinguish in the field between faults produced by a increase in fluid pressure and those produced by a decrease in s_3 by stratal extension. It is felt, but cannot be proved, that the formation of the Teesdale Dome was responsible for the reduction in horizontal stresses and the formation of the ENE and NNW vein fractures.

8.2.2 Formation of ESE veins by strike-slip faulting

The formation of strike-slip fractures requires an unusual combination of stresses (Price, 1966): it requires that the intermediate principal stress (s_2) be vertical (Anderson, 1951), and that the stress ratio (s_1/s_3) is large enough to cause faulting. Price (1966) suggested a method by which s_2 would be vertical during horizontal

compression, and this is outlined below:

Consider stress in rock under gravitational loading only:

$$s_y = s_x = s_z/(m-1)$$

Where;

s_y, s_x = Horizontal stresses

s_z = Vertical stress

m = Poisson's number

With the addition of extra compressive stress (c_y) in the y-direction, the resulting horizontal stresses are;-

$$s_y' = s_z/m-1+C_y \quad \text{eqn 8.4}$$

$$s_x' = s_z/m-1+C_y/m \quad \text{eqn 8.5}$$

Strike-slip is known to have occurred in the Whin Sill on the Slitt Vein at Blackdene Mine. It is possible to calculate the stresses acting at the time of the vein fracture formation by strike slip faulting;-

If, $s_1 = s_y'$ and $s_3 = s_x'$
and; m = 4.0 (for Whin Sill)

Then:

$s_1 = s_z/3 + C_y$

$s_3 = s_z/3 + C_y/4$

Further, Price (1966) has shown that;

$$\frac{s_z(m-2)}{(m-1)} < C_y < \frac{s_z m(m-2)}{(m-1)} \quad \text{eqn. 8.6}$$

For the Whin Sill;

$$s_z*2/3 < C_y < s_z*8/3$$

At the base of the Whin Sill, 1726m below the surface;

$$s_z = hpg = 1726x2500x9.8 = 4.23x10^7 Pa$$

For s_2 to be vertical at the horizon of the whin, at the time of fracturing, the additional compression in the y-direction (east-west) must be between the limits given by the eqn. 8.6.

Therefore;

$$2.82x10^7 < C_y < 11.28x10^7$$

The second condition for strike-slip faulting states that the ratio of s_1 to s_3 must be large enough to cause fracturing. According to Price (1966), the maximum value of s_1/s_3 is ;

$$s_1/s_3 = (m-1) \quad \text{eqn. 8.7}$$

For the Whin Sill, therefore;

$$s_1/s_3 < 3$$

At failure, the stress conditions are as follows (Price, 1966);

$$s_1 = s_L + Ks_3 \quad \text{eqn. 8.8}$$

Where, s_L = 50% of the uniaxial compressive strength of the rock

K = A constant, typically 4.0

For the Whin Sill, uniaxial compressive strength = 5.14×10^8Pa.

Therefore;

$$s_L = 0.5 * 5.14 \times 10^8 = 2.57 \times 10^8 \text{Pa}$$

and

$$s_1 = 2.57 \times 10^8 + 4.0 s_3$$

For failure at the base of the Whin Sill, the horizontal stress in the x-direction (north-south) is s_3. Assuming that there was no change in s_3 (which is the stress due to gravity loading) between the intrusion of the Whin Sill and the formation of the quarter-point vein fractures,

then;

$$s_3 = 3.63x10^7 Pa.$$

Therefore, substituting in eqn. 8.8

$$s_1 = 2.57x10^8 + 4.0*3.63x10^7$$
$$= 4.02x10^8 Pa = s_y$$

and s_1/s_3 ratio

$$= 4.02x10^8/3.63x10^7 = 11.08$$

But as the ratio of s_1/s_3 cannot exceed 3.0, then failure could not have occurred in the postulated stress conditions. However, if there was lateral expansion in the x-direction concurrent with the compression in the y-direction, then there is no mathematical limit to the s_1/s_3 ratio. Consider the additional stress C_x in the x-direction, then

$$s_y' = s_1 = s_z/m-1+C_y+C_x/m \quad \text{eqn. 8.9}$$

$$s_y' = s_3 = s_z/m-1+C_x+C_y/m \quad \text{eqn. 8.10}$$

As before, at the base of the Whin Sill

$$s_1 = s_y = 4.01x10^8 Pa$$
$$s_2 = s_z = 4.23x10^7 Pa$$
$$s_3 = s_y = 3.63x10^7 Pa$$

Substituting the values for the principal stresses in eqns. 8.9 and 8.10;

$$1/3*4.23x10^{7}+C_y+1/4C_x = 4.02x10^{7} \quad \text{eqn. 8.11}$$
$$1/3*4.23x10^{7}+C_x+1/4C_y = 3.63x10^{7} \quad \text{eqn. 8.12}$$

Solving eqns. 8.11 and 8.12 simultaneously;

$$C_y = -4.057x10^{8}Pa \text{ (compressive)}$$
$$C_x = 7.922x10^{7}Pa \text{ (tensile)}$$

This analysis vindicates the statement by Price (1966), that for strike-slip faulting to occur there must be lateral expansion concomitant with lateral compression. The compression in the northern Pennines at the time of formation of the ESE vein-fractures was aligned roughly east-west, and expansion took place in the north-south direction.

8.2.3 Secondary faulting

Many large strike-slip faults, for example, the San Andreas Fault, are not straight, but consist of several linear and curved sections. They are associated with several sets of systematic minor faults. Chinnery (1963),

has analysed the stress changes which accompany strike-slip faulting, and has developed a mathematical model for the formation of second-order faults at the ends of a strike-slip fault (Chinnery, 1966a). Chinnery's model is based on Steketee's (1958), elastic theory of dislocations, and assumes that displacements and changes in stress that occur during faulting are independent of the initial stress conditions. The changes in stress during faulting can be added to the initial stress field to give the stress field after movement has ceased.

Chinnery (1966a) used as a model an initial straight fracture, 200km long and 10km deep with a horizontal displacement of 5km across the fault plane (Fig. 8.4). The strain at a given point is defined by the rate of change of displacement with distance. The strain can be found by differentiating the displacement equations. Alternatively, the strains can be found from the change in displacement between two points close together. The stress changes can be found from the strains using Hooke's Law.

A series of computer programs were written to calculate the stress changes at the surface due to a wrench fault in an isotropic elastic material. The stress changes produced by the faulting were added to the initial stresses, and the final stresses were displayed as the stress invariant (s_x+s_y), the maximum shear stress, and the maximum shear stress trajectories.

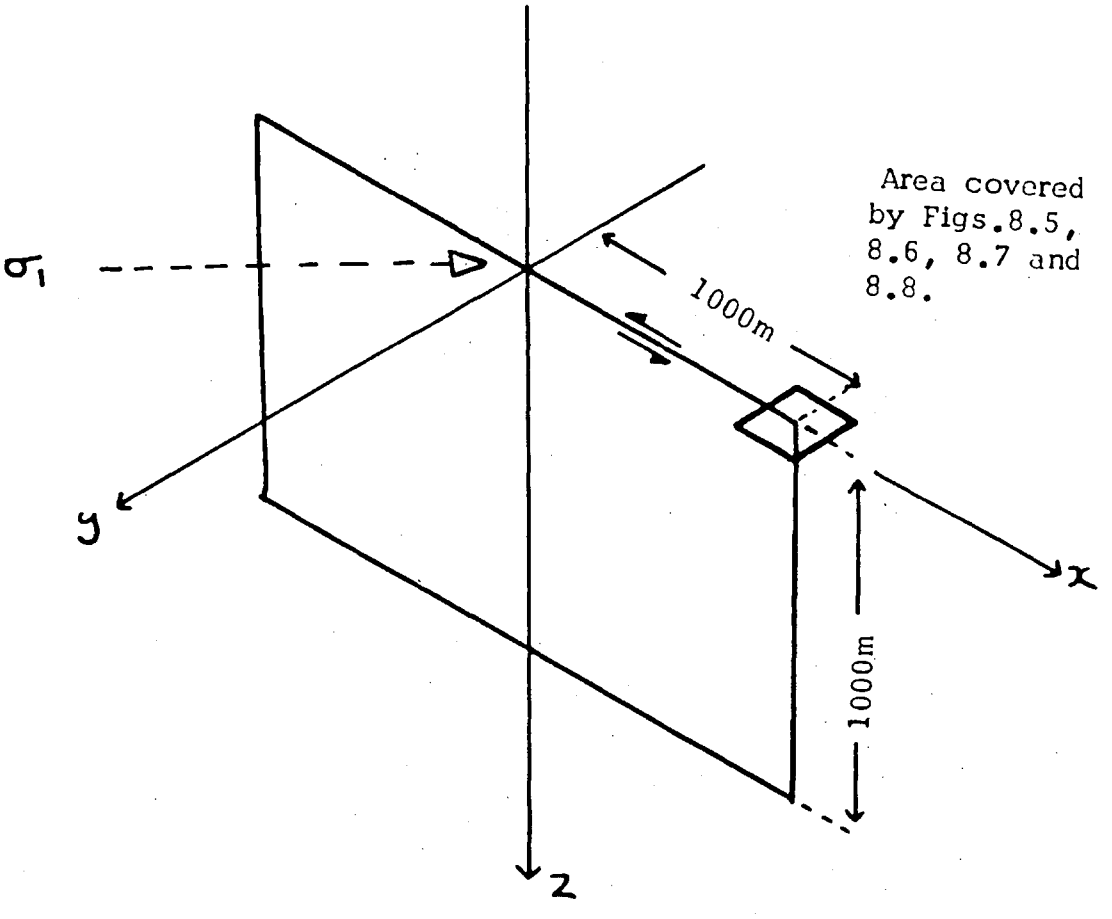


Fig.8.4 Wrench fault model used in calculation of secondary faulting

The model chosen was for a fault 1km. long, 1km. deep and cutcroping at the surface. The mechanical rock properties used were: Young•s Modulus (E) = 0.8×10^8pa and Poisson's number (m) = 0.2. The stresses after a sinistral movement of 0.1 and 1.0 metres were calculated at the surface for this fault model. The initial stress conditions at the surface were taken to be those calculated to be acting in the east-west and north-south directions from the analysis in section 8.2.2. These were a compressive stress of -4.057×10^8Pa in the east-west direction and a tensile stress of 7.922×10^7Pa in the north-south direction.

Results of stress modelling

The final stress trajectories after sinistral movement of one metre along the fault are shown in figure 8.5. As can be seen from this diagram, the stress trajectories show the greatest evidence of deflection on the northern side of the fault plane, but nowhere do these distortions extend for more than 35m from the end of the fault. The contours of maximum shear stress (Fig. 8.6) show two main lobes extending away from the end of the fault in the NE and SE directions, plus a smaller lobe in the NW direction. The maximum shear stress before faulting can be calculated from the following equation:

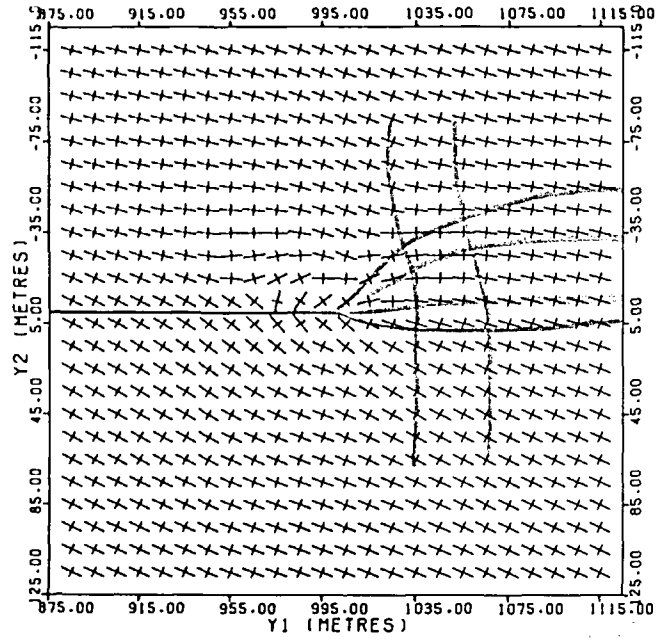


Fig. 8.5 Stress trajectories, fault model 1.

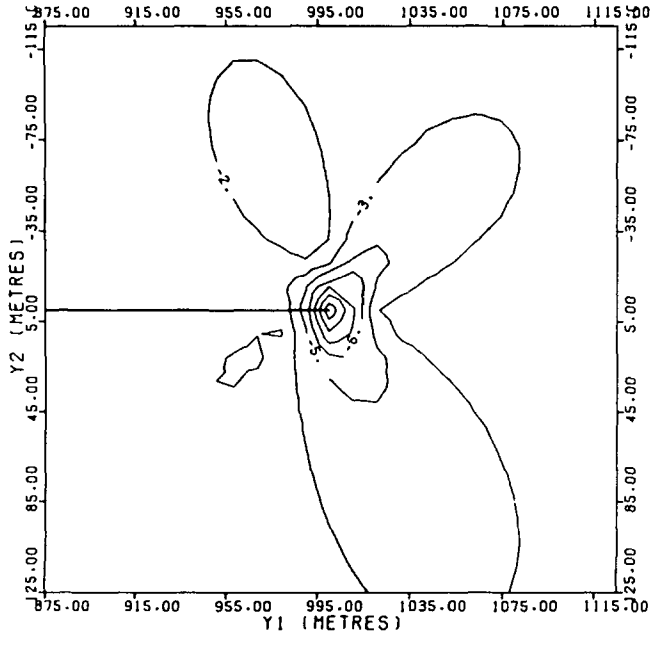


Fig. 8.6 Maximum shear stress contours, fault model 1
Contours are in values of 10^8 Pa.

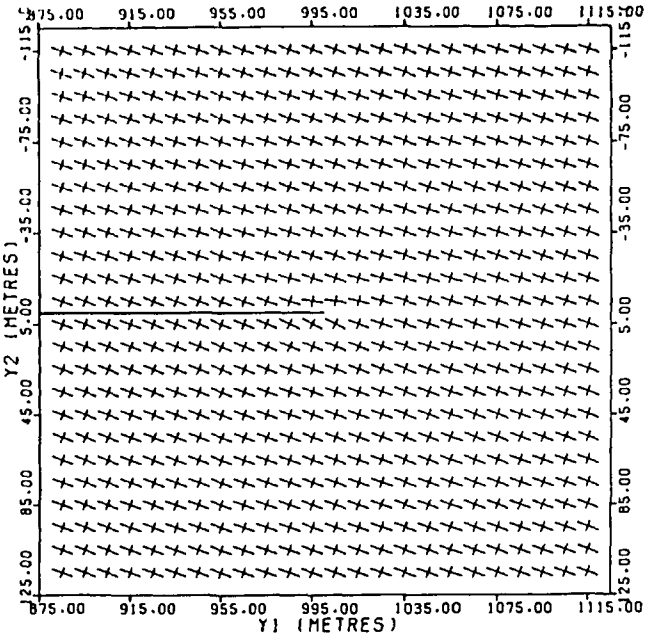


Fig.8.7 Stress tracjectories, fault model 2.

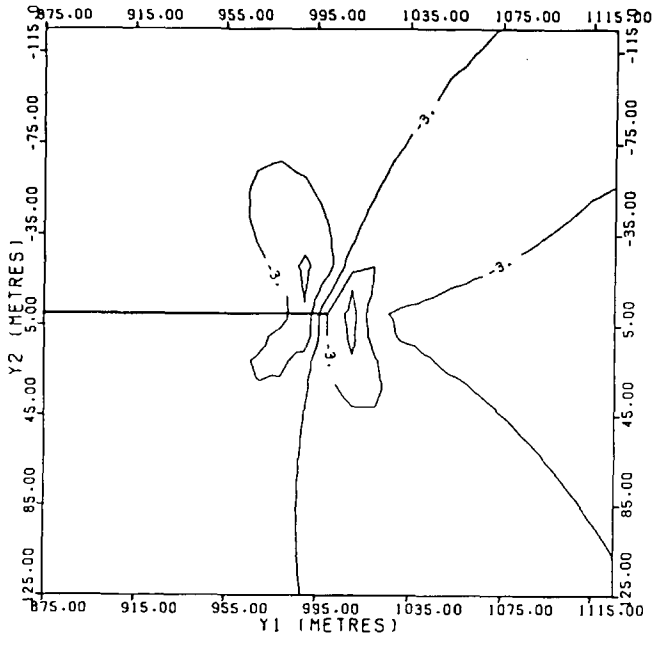


Fig.8.8 Maximum shear stress contours, fault model 2. Contours are in values of 10^8 Pa.

$$T_{max} = 0.5*(s_1-s_3) \quad \text{eqn.8.13}$$

substituting values for s_1 and s_3 into equation 8.13, it is found that $T_{max} = -2.42x10^8$Pa. According to Chinnery (1966a), secondary faults are likely where the maximum shear stress after faulting exceeds that before faulting. Refering to figure 8.7, it can be seen that this situation only occurs within the two stress lobes extending away from the fault to the NE and SE. Secondary faults and would only be expected within these two lobes. The orientation of possible secondary faults are shown in figure 8.5. The most likely secondary faults are those which would tend to extend the fault to the east. These faults would form at 30^o to s_1. On the northern side of the fault plane, the secondary faults tending to extend the main fault would show curved traces, whilst to the south they would trend parallel to the main fault.

The formation and direction of the secondary faults are dependant on the amount of movement along the main fault plane. Figures 8.7 and 8.8 show the resulting stress trajectories and maximum shear stress contours after a movement of 0.1m along the fault plane. As can be seen, there is little distortion in the stress field and maximum shear stresses after faulting, hardly exceeds that before faulting.

The stresses calculated from the mathematical models are those resulting from one movement only of the fault plane and not the total movement over a period of years. Sibson et al (1975) have suggested that movement along a fault plane often occurs in small steps, rather than all at one time. It has been suggested (p. 143) that each mineral band in a quarter-point vein of the orefield was deposited after a movement along the vein. If this was the case, then it is possible to calculate the average horizontal movement along the vein at each step. Taking a total movement of 30m along a quarter-point vein fracture (based on evidence from Blackdene Mine, p. 47), and 300 bands across the vein (based on evidence from Groverake Mine, p. 143), then the average slip during each period of movement would be 30/300 = 0.1m. This amount of slip is equal to the 0.1m slip used in the second model presented above. It is therefore concluded that the stresses resulting after a movement along a quarter-point vein, would be insufficient to form secondary faults. Even with movement of up to one metre along the vein fractures, the formation of secondary faults would be very limited.

CHAPTER 9 STRUCTURAL EVOLUTION OF NORTHERN BRITAIN: CALEDONIAN TO HERCYNIAN

The wealth of geological information available for northern Britain has allowed the construction of detailed accounts of the tectonic evolutions of many small regions. However, when attempting to assemble a coherent synthesis for larger structural units, the problem becomes more complex. Dunham (1948), for example, invoked seven periods of 'movement' to explain the generation of structures in the northern Pennine orefield from the Caledonian to late Hercynian (Fig 9.1). The first part of this chapter deals with the structural history of the Alston Block in the light of the structural interpretations described in chapters 3,5,6,7 and 8. The second part of this chapter is concerned with the structural evolution of northern Britain as a whole.

9.1 Hercynian structural history of the Alston Block

The evidence described in chapters 3,5,6,7 and 8 indicates that there were three distinct phases of tectonic activity during the Hercynian orogeny on the Alston Block. The first phase occurred during the late Carboniferous, but prior to the intrusion of the Whin Sill (p. 30). East-west compression produced folding in the basinal sediments surrounding the Alston Block, and

PERIOD OR OROGENY	MOVEMENTS IN NORTHERN PENNINE OREFIELD	PROBABLE REGIONAL STRESS OR MOVEMENT
Caledonian (Siluro-Devonian)	E.N.E. folding of Lower Palaeozoic rocks. Development of E.N.E. and W.N.W. cleavage	N.W.—S.E. compression
Early Carboniferous	Initiation of marginal hinge-lines, defining Alston Block	Progressive relative down-folding of adjacent areas to north, west and south
Inter-Carboniferous	Gentle warping of block	
Hercynian (Carboniferous-Permian interval)	1. Formation of Master Joints N.20—25° W, N.60—70° E. and E.—W. folds	N.—S. compression; folding Bewcastle anticline and possibly Stainmore syncline
	2. N.N.W. and E.—W. normal faulting along margins, depressing Alston Block relative to surrounding areas	Fault block movements
	3. N.N.W. thrusts and folding. Intrusion of Whin Sill. Intrusion of Whin Dykes in E.N.E. tension fissures	E.N.E. compression
	4. N.E. folding in Hunstanworth area	Rotation of block relative to adjacent areas; tear-faulting in Brampton district
? Late Hercynian	Formation of conjugate vein-fissures, N.N.W., E.N.E. and E.—W. to W.N.W., contemporaneous with gentle doming	Torsion due to gentle domal uplift
Tertiary	1. Intrusion of E.—W. dykes in linear échelon trending W.N.W.	Differential sideways movement
	2. N.N.W. and E.—W. normal faulting along margins, elevating block and tilting to east	Fault block uplift
	3. Slickensides in mineral veins, due to small sideways movements	

Fig.9.1 Structural evolution of the northern Pennine orefield, according to Dunham (1948)

resulted in the overfolding of the basinal sediments onto the block at the north, west and south margins. This overfolding gave rise to the apparent depression of the Alston Block relative to the sediments of the basin. Monoclinal folding occurred along the Burtreeford disturbance at this time, although the line of the disturbance may have already been initiated by the separation of the block between the two halves of the Weardale Granite (p. 39). With the exception of the Burtreeford disturbance, little or no major fracturing occurred in the Alston Block during the first phase deformation. In the sediments overlying the block early shear joints were generated in Teesdale.

The second tectonic phase was characterized by the uplift of the block, possibly by isostatic re-equilibrium following the cessation of Carboniferous sedimentation. The late Stephanian Whin Sill and associated dykes were intruded not long after the commencement of uplift (p. 37). In the basinal areas, the dykes followed ENE lines of weakness (p. 70). The dykes only penetrated the block along its north and south margins, and the Burtreeford disturbance; the main mass of the block was still rigid at this time. Continuing uplift caused lateral expansion of the sediments and a reduction in the horizontal stresses. This allowed the vertical stress to become the maximum principal stress, and conjugate ENE and NNW normal faults developed on the block under this stress regime. Monoclinal drape folds formed in the strata above the

normal faults. Upward propagation of the faults through the folds resulted in apparent reverse drags adjacent to the fault planes (p. 40). Further uplift brought the sediments closer to the surface, and tensile horizontal stresses developed. Extension joints formed when the tensile horizontal stresses exceeded the tensile strength of the rocks. As the block rose normal dip-slip movement may have occurred along its margins.

The third tectonic phase resulted in the formation of the quarter-point vein fractures by sinistral strike-slip faulting under an east-west compressive stress field. The quarter-point vein fractures were initiated in the basement of the block, and propagated upwards by riedel shearing (p. 147). Conjugate dextral wrench faults rarely developed, but strike-slip movement occurred along the already existing normal faults. Shear joints were also developed. Mineralization was contemporary with this phase of tectonic activity. Uplift apparently continued during this period and caused downthrow to the north along the Great Sulphur and Dun Fell veins. These veins were initiated as quarter-point type fractures by sinistral wrench movement, but were then subjected to hinged movement, with displacement increasing to the west, as the block was uplifted along the Pennine faults.

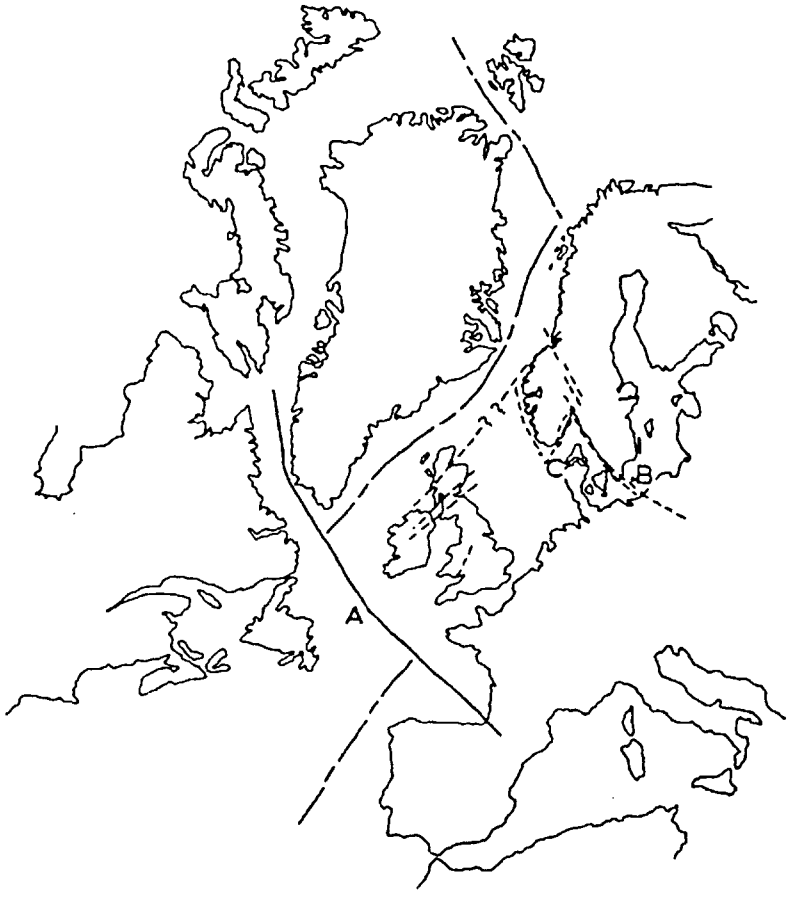
9.2 Caledonian tectonics in northern Britain

9.2.1 Opening of the Iapetus Ocean

The evolution of the northern Britain in the Lower Palaeozoic is the story of the opening of the Iapetus Ocean (Windley, 1977). The structures created during the opening and closing of this ocean played an important role during Carboniferous sedimentation and the succeeding Hercynian Orogeny. Major NW to NNW tectonic lineaments of North-West Europe may have acted as transform faults during the opening of the Iapetus. There is evidence from Norway that these fractures controlled the development basins in Eo-Cambrian times (Vokes, 1973). The best known fractures of this group are: the Labrador-Biscay line; Fennoscandia border zone; and the Skagerak coast lineaments (Fig 9.2). In northern England, major NW to NNW faults bound the Lake District, Alston and Askrigg blocks. These faults, and the proposed NNW basement faults below the Alston Block, could have formed during the opening of the Iapetus.

9.2.2 Closure of the Iapetus

Closure of the NE trending Iapetus Ocean occurred



Map showing the fit of North America, Greenland and Europe at the 500 fm contour, A—initial Labrador-Biscay line. B—Fennoscandia border zone. C—Skagerak coast lineaments.

Fig. 9.2 Structural lineaments of NW Europe (from Vokes, 1973)

between the early Ordovician and late Silurian by subduction beneath the NW and SE plates. After collision dextral strike-slip movement occurred along the Iapatus suture zone, which is now believed to underlie the Northumberland Trough. Similar ENE wrench faults have not been described on the SE plate (northern England), however, the Ninety-Fathom Fault and the Whin dykes of the Northumbria-Durham coalfield appear to follow fractures which could have been initiated during the closing stages of the Iapetus. During the Devonian, post-tectonics granites were intruded into deformed sediments overlying the then closed ocean.

9.3 Carboniferous sedimentation

The closure of the Iapetus Ocean resulted in the formation of the continent of Laurasia during the Devonian by the welding of northern Europe to the Greenland - North America landmass. The Mid European Sea separated Laurasia from Gondwanaland to the south (a land composed of the present continents of South America and Africa). England at this time was situated on the northern margin of the Mid European Sea and formed a shallow paralic marine shelf bordering Laurasia. The Carboniferous grabens and horsts of northern England appear to be connected with southward subduction of the sea beneath southern Europe (Johnson, 1981). The pull of the down going slab created north-south tensional stresses in the continental crust behind it

(Leeder, 1976). This north-south tension could have caused renewed movement along existing lines of weakness. Vertical movements along ENE trending Caledonian fractures would have allowed the relatively higher blocks with granite cores to rise and form horsts. Elsewhere, ENE elongated basins would have developed.

Continued north-south or SSE directed tension and vertical loading due to gravity caused the newly buried and lithified sediments in the basin to fracture by normal faulting along east-west or ENE lines. Locally, the release of stress due to the formation of the ENE normal faults would allow the stress acting in the ENE direction to take on the role of the minimum principal stress, and NNW normal faults would develop. The early development of conjugate normal faults would only occur in those areas which lacked a rigid basement. The fractures could have provided channel ways for basaltic and intermediate magmas, which were extruded as lavas over the Derbyshire massif and in the Midland Valley of Scotland. This magmatic activity can be seen as a precursor to rifting between Scotland and Greenland in the early Permian.

9.4 Upper Carboniferous structures in N.England

At the end of the Dinantian, the Iberian Peninsula collided with the South European microcontinent, and

formed the Namurian fold belts of Spain, France and Germany (Johnson, 1981). The collision may have caused a temporary change over to north-south compression, and resulted in the uplift and erosion of some Dinatian sediments in central and southern England. Renewed north-south tension accompanied the development of the Namurian and Westphalian sedimentary basins.

On the Alston Block, the east-west compression, coupled with failure in the basement granite caused the formation of the Burtreeford disturbance. On the margins of the Alston Block overfolding of the surrounding basinal sediments resulted in the apparent depression of the block along the northern, western and southern margins. This overfolding is now manifested by the upturning of the strata on the Alston Block towards these margins. The early shear joints seen in Teesdale (p. 102) may also have formed at this time.

In late Stephian times the Whin Sill and associated dykes were injected in response to new attempts at plate separation in northern Europe. Final separation occurred between Greenland and Scotland after the Whin intrusions (Russell and Smith, 1979), causing the end of Carboniferous igneous activity in northern Britain.

After the cessation of Carboniferous sedimentation,

isostatic uplift of the blocks with granitic basement occurred. Lateral expansion accompanied the uplift, reducing the horizontal stresses. Thus, the vertical stress became the maximum principal stress, and conjugate ENE and NNW normal faults developed on the Alston Block. With continued uplift, the tensile horizontal stresses became greater than the tensile strength of the rocks and extension joints developed.

9.5 Early Permian structures

During the early Permian, attempts at ocean rifting occurred in the central part of the North Sea, and along its eastern margin in Norway. The rifting took place along NNW lines of Caledonian weakness (Vokes, 1973). On the Norway coast, this rifting produced the Oslo igneous complex, and in the North Sea resulted in the formation of the Central Graben. The Central Graben represents a failed arm of the newly opened Atlantic Ocean to the north. The opening of the Central Graben produced east-west compression as the westward shift of Britain was resisted by the easterly force caused by the opening of the North Atlantic. The east-west compression caused strike-slip movement along the existing faults of northern Britain, and the generation of conjugate dextral and sinistral wrench faults. The wrench faults of north Northumbria and the quarter-point vein fractures of the Alston Block belong to this period of compression. Mineralization on

the Alston Block was contemporary with the compression.

CHAPTER 10 CONCLUSIONS

(1) Many of the Carboniferous structures in northern England have been influenced by the basement. A postulated series of NE and NW striking basement faults influenced Carboniferous sedimentation and the location of the Whin dykes. These basement faults are interpreted to have originated as strike-slip faults during the opening and closing of the Iapatus Ocean in Lower Palaeozoic times. On the Alston Block, the basement faults were destroyed by the intrusion of the Weardale Granite. They were rejuvenated after the formation of the vein fractures on the block, and moved horizontally, rotating the veins above them.

(2) The Weardale Granite provided a rigidity to the Alston Block until late Carboniferous times. The Burtreeford disturbance was formed by differential movement of the two halves of the Weardale Granite. Fracturing of the Carboniferous sediments above cupolas of the granite is less intense than elsewhere. This is due to rigidity provided by the granite. Away from the cupolas, where a thick succession of Lower Palaeozoic rocks underlie the Carboniferous strata, there is a more random distribution in the orientations of the faults and vein-fractures. The Lower Palaeozoic rocks contain many lines of weakness in several directions, and these lines of weakness influenced the Carboniferous fractures. The structural highs of the

Teesdale Dome coincide with the cupolas of the Weardale Granite, and the Carboniferous sediments are compacted around the granite.

(3) Transgressions in the horizon of the Whin Sill can be explained by a combination of its intrusion into sediments that were already domed, and partly by a decrease in magma pressure away from the Burtreeford disturbance.

(4) Most joints on the Alston Block post-date the intrusion of the Whin Sill, and most joints pre-date the mineralization. The jointing relationships in the Carboniferous strata of the block suggest that there were three main periods of joint formation:- (i) shear jointing with s_1 orientated ENE; (ii) extensional jointing; (iii) a second generation of shear joints, contemporary with mineralization, with s_1 orientated east-west. The joints show evidence of rotation and increase in density adjacent to some mineral veins.

(5) The vein fractures of the northern Pennine orefield fall into three groups. The ENE and NNW vein fractures were initiated as normal faults, prior to mineralization, by compressional or extensional shear failure. The ENE and NNW vein-fractures were probably formed during the continued uplift of the Alston Block, after the intrusion of the Whin Sill. The ESE vein fractures were formed as

sinistral wrench faults during a period of east-west compression. This compression also produced horizontal movements along the existing ENE and NNW fractures, and was coeval with mineralization. The ESE vein fractures appear to have originated in the lower parts of the stratigraphical succession, and were propogated upwards by riedel shearing.

(6) Mathematical analysis of stresses suggests that north-south expansion was active at the same time as east-west compression during the formation of ESE vein fractures. Computer modelling of the stresses generated by an ESE fracture undergoing wrench movement indicates that the stresses produced by faulting would be insufficent to cause the formation of extensive secondary faults.

(7) There were three tectonic phases to the structural evolution of the Alston Block during the Hercynian orogeny. The first phase occurred during the late Carboniferous, but prior to the intrusion of the Whin Sill. East-west compression during the first phase, resulted in overfolding of the basinal sediments onto the the Alston Block, and the formation of the Burtreeford disturbance and some early shear joints. The second tectonic phase occurred during the period of uplift of the Alston Block. Initially, the uplift folded the Carboniferous sediments into the Teesdale Dome. The Whin Sill was then intruded into the partly domed sediments. Continued uplift caused stratal extension and normal

faulting in the sediments. An increase in fluid pressure may also have helped during the formation of normal faults. Extension joints were also formed at this time, and downthrow occurred along the margins of the block. The third tectonic phase was characterized by renewed east-west compression. It resulted in the formation of the ESE vein fractures by strike-slip faulting, and horizontal movements along the existing faults. Mineralization occurred during this third phase of tectonic activity.

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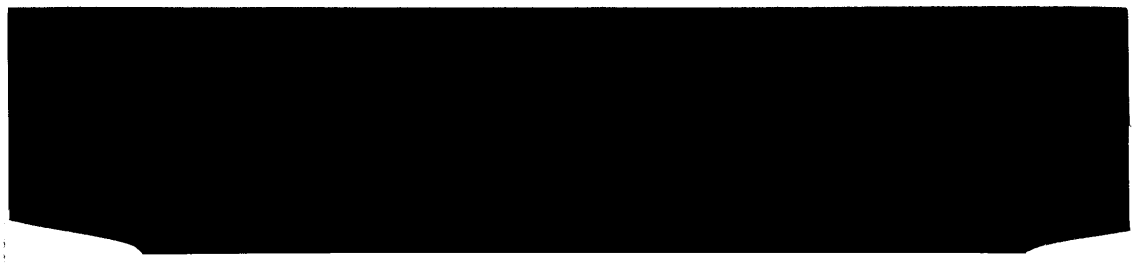
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Micro Fiche containing listing of Program FRACAN and output for Alston Geological Sheet 25.

MAP 1

BLACKDENE MINE GEOLOGICAL PLAN

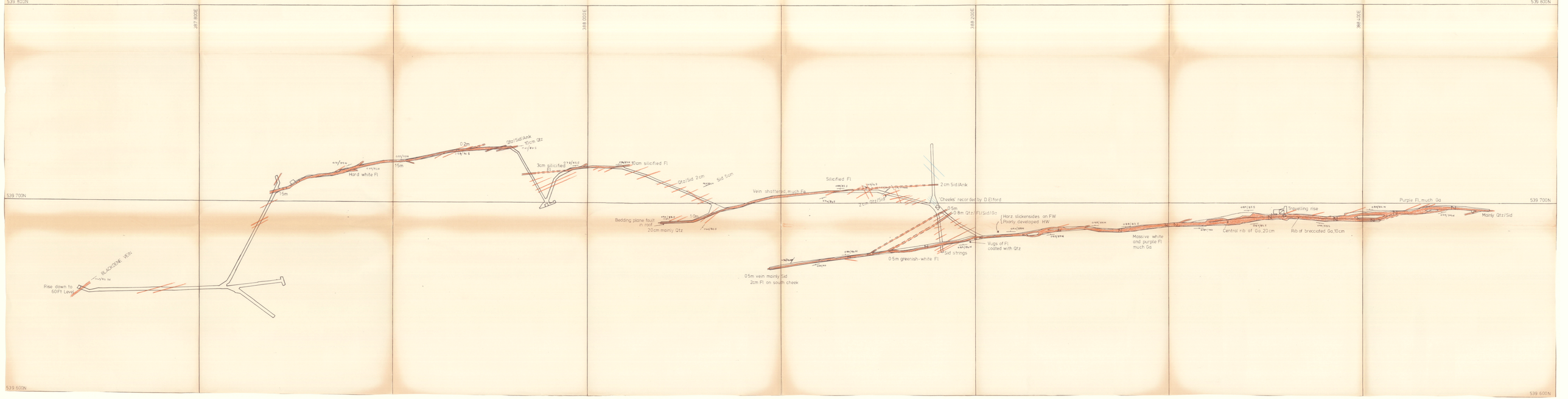
SCALE 1:500

SOUTH SLITT 40Ft. LEVEL

KEY

- Vein as seen in drift
- Projected course of vein
- Mineralized stringer
- Barren fracture
- Strike and dip of bedding
- Strike and dip of fracture or vein
- 0.5m — Width of fracture or vein

Ank	Ankerite
Fl	Fluorite
FW	Footwall
Ga	Galena
HW	Hanging wall
Sid	Siderite
Qtz	Quartz



FH 1813

Top of Great Limestone

TOP LEVEL

TOP LEVEL Passes through Burtreeford Disturbance to Lat/shale below N.G.H.

TOP LEVEL Passes into shale below Nattress Gill Hazle west of here

FH 1813

NOTE

TOP LEVEL is shown only west of Cow Shaft at 1270-1300 O.D. to illustrate the upturn of the beds near the Burtreeford Disturbance.

PLAT SHAFT

BENT SHAFT

CRAIGSHIELD SHAFT

LITTLE SHAFT

COW SHAFT

TOP LEVEL in Quarry Hazle west of here.

OLD WHIMSEY SHAFT

NEW WHIMSEY SHAFT

ALLENHEADS OLD VEIN

DIANA VEIN

NEW GIN LEVEL

Passes into Quarry Hazle west of this point

FAWSIDE LEVEL MOUTH

BRETTON VEIN

ALLENHEADS B.H. N°1

Great Limestone 1081 - 1102 O.D.

FAWSIDE LEVEL

INCLINE T.H. 4

KNOPLEY LEVEL

EAST END SHAFT

GEORGE GRAHAMS SHAFT

LOW UNDERGROUND SHAFT

HIGH UNDERGROUND SHAFT

COLLIER SHAFT

Marks Low water Level 1034 1064 O.D.

WENTWORTH VEIN

WEST

JEFFERY LEVEL

CROSS VEIN

ALLENHEADS B.H. N°2

QUARRY HAZLE LEVEL Passes into Quarry Hazle south of this point

PUMP SUMP

HIGH UNDERGROUND SHAFT

Collar 1089-1185 O.D.

Low Water Level 1052 O.D.

HERMITTA VEIN

John Kay's Cross Cut

Fawside Level

GREAT VEIN

CORBETMEA SHAFT

FH 1804

East-West fractures due to Red/Old vein at depth

of Henry's vein

HILL'S LEVEL

ALLENHEADS CROSS CUT

BELL'S STRING

CORONATION VEIN

In Great Limestone between these points Top G. Lat approx 1150 O.D

WILLIAM HEARON'S CROSS CUT

PLANTATION SHAFT

About 1227 O.D

PLANTATION CROSS CUT

In Great Limestone between these points

? Top G. Lat about 1225 - 1235 O.D

CAPTAINS VEIN

In Great Limestone between these points Top G. Lat. approx 1165 O.D

HENRY'S VEIN HORSE LEVEL

In Great Limestone between these points

Top G. Lat approx 1120 O.D

QUARRY HAZLE LEVEL Passes out of Quarry Hazle south of this point

PLANTATION CROSS CUT

True Meridian through centre of Gin Hill Shaft

HENRY'S VEIN

QUARRY HAZLE LEVEL Passes into Quarry Hazle south of this point

Northumberland Cross Cut

Joseph MacWilliams Sump 1841

HENRY'S VEIN HORSE LEVEL Passes into Great Limestone at this point Top G. Lat 1205' O.D

Thomas Renwick's Sump 1848-9 from Plantation Cross Cut down to Henry's Vein Horse Level (approx. 62 ft.) Great Limestone 1200-1255 O.D

MAP 2

BRITISH STEEL CORPORATION BEAUMONT MINE OLD LEAD WORKING IN THE GREAT LIMESTONE

SCALE 1/2500

Interpreted fault movement

- Anti-thetic Riedel shears
- Synthetic Riedel shears
- Second order shears
- Dip slip faults

KEY

- FAWSIDE LEVEL IN SHALE ABOVE RIDESTONE SILL
- B.O.G. WORKINGS
- LEAD WORKINGS JUST ABOVE THE GREAT LIMESTONE
- LEAD WORKINGS IN TOP PART OF GREAT LIMESTONE
- VEIN WORKINGS IN GREAT LIMESTONE
- LEAD WORKINGS JUST BELOW THE GREAT LIMESTONE
- OLD LEAD MINE SHAFTS

MAP 3

WHITEHEAPS MINE GEOLOGICAL PLAN

SCALE 1:250

SIKEHEAD 80 FATHOM LEVEL

M.F. CRITCHLEY 1981

KEY

- Vein as seen in drift
- Projected course of vein
- Mineralized stringer
- Barren fracture
- 120/90S — Strike and dip of fracture or vein

lst. Limestone

sst. Sandstone

Haulage Incline 1:4·5 →

62 Fm. Level

70 Fm. Level

80 Fm. Level

Ellen's Shaft

massive sst.

546 450N

546 400N

546 350N

395 400E

395 450E

395 500E

395 550E

395 600E

lst.

Fault

189/70W

Breccia zone

massive fluorite, much chalcopyrite

White Vein

silica and fluorite

sst.

Red Vein of Sikehead

Fluorite with much galena

banded fluorite and quartz

326/68S

Breccia zone

sst. breccia

silicified sst. breccia with galena

Quartz and fluorite

sst.

Quartz

218/80N

massive sst.

several shears with horizontal slickensides

Quartz strings

massive to flaggy light grey micaceous sst.

313/88N

1m. wide, poorly mineralized vein with white fluorite and quartz. Horizontal slickensides on footwall, ill defined hangingwall

base of Frosterley Marble exposed in roof of drift