REVERSALS OF NATURAL MAGNETISATION WITHIN THE IRON GRIT OF SUSSEX

by

JOSEPH EDWARDS

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ABSTRACT

A horizontal band of iron grit less than six inches thick, which can be found on top of the south Downs in Sussex, was found to be magnetised in two general directions. One direction was close to that of the earth's present day magnetic field (normal) while the other was antiparallel to this direction (reversed).

Part I describes the investigation of the spacial pattern, within the band, of normal and reversed parts. Normal and reversed volumes usually form thin layers running nearly horizontally. At one of the exposures there were five reversals of the natural polarisation over a vertical distance of 5 cms. Such a rapid sequence of reversals suggested that either the normal or the reversed polarisations were self reversed.

Part II describes some of the physical, chemical and petrological properties of the grit. Normally polarised specimens are compared with reversely polarised specimens. There does not appear to be any significant difference between them. This result, in contrast to the conclusion of Part I, implies that the reversals of the natural remanent magnetisation are a consequence of reversals of the earth's magnetic field.

Finally, in Chapter 10, an effort is made to decide which of the two theories (i.e. self reversal or field reversal) is more likely to be correct. The history of the grit, and in particular its magnetic history, is considered in the light of some of the experimental results obtained.

The grit has had a sedimentary origin and its natural remanent magnetisation has probably been acquired chemically during the formation of a hematite cement subsequent to deposition. The nature of the evidence makes it practically impossible to decide between self reversal and field reversal, although field reversal is a little more strongly favoured.

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Chapter I.

INTRODUCTION

The task of finding the cause of the earth's magnetism has already extended over a long period of time, but as yet the problem remains unsolved.

The first indication that the earth possessed a magnetic field was the discovery of the principle of the magnetic compass by the Chinese probably over a thousand years ago. Although little was made of this discovery at first, the problem of revealing the origin of the earth's magnetic field has later proved to be a stiff challenge both to the ingenuity of the experimenter and to the skill of the theoretician.

In 1600 Gilbert suggested that the magnetic field was of internal origin as a result of a 'model experiment' using a sphere of lodestone. Over 200 years later, in 1832, Gauss analysed geomagnetic observations to demonstrate mathematically the truth of Gilbert's suggestion, and it is now certain that the present day field is closely analagous to a field which would be produced by a dipole situated at the centre of the earth having a direction close to that of the earth's axis of rotation. However, the internal origin of the earth's magnetism is still uncertain.

In order to find the mechanism causing the earth's magnetic field it is now necessary to learn not only about its spacial distribution at the present time, but to discover how the field varies with time. It might then

be possible to analyse the results obtained in such an investigation to give a satisfactory account of the mechanism producing the magnetic field.

The history of the earth's magnetic field has recently been studied by measuring the remanent magnetisation of rocks of different ages. The remanent magnetisation of a rock is believed to be a 'fossil magnetisation' in the respect that its direction is a memory of an ancient field that initially magnetised the rock. In many cases this ancient field is believed to be the earth's magnetic field as it was when the rock was first formed. By this procedure it is becoming possible to trace back changes in the earth's magnetic field over the last 500 million years of geological history.

As a result of studying the natural remanent magnetisations of rocks of different types and ages from over the earth's surface, rock magnetic workers are usually able to agree that for 500 million years the earth's field has been that of an axial dipole, as indeed is the present field. Some quantitative estimates by Wilson (1960)[1] and Weaving (1960)[2] indicate that ancient fields might have been about the same strength as the present field. However, an unexpected result has been obtained during the course of these investigations. About 50% of all rocks, both igneous and sedimentary, of a given age from a given continent are found to be magnetised in the opposite direction to the other 50%. This result gives rise to two possible theories, both consistent with the axial dipole theory, regarding the history of the earth's field. They are (1) that the axial dipole has

retained the same sense as its present day sense, and (2) that the axial dipole has at times been reversed during the past 500 million years.

The first theory requires that all reversed natural remanences are self reversed.

The second theory implies that some reversed natural remanences are not self reversed, and includes the possibility of many reversals of the earth's field during the last 500 million years.

If one wishes to learn about the mechanism causing the earth's magnetic field it becomes essential to know which of these theories is correct.

That the earth's magnetic field has never reversed but that all reversely magnetised rocks are self reversed was first seriously considered by Graham (1949)[3]. He found some sedimentary rocks of Silurian age which contained both normal and reversed polarisations. He also identified in this stratum a rare fossil which was claimed to have existed during a relatively short geological period. Graham considered that this period was too short to explain the presence of the reversed remanences by a reversal of the earth's field during the formation of the stratum, and decided that a more likely explanation would be in terms of a self reversing mechanism. He asked Neél to consider theoretically the possibility of such a mechanism and Neél postulated 4 plausible ways by which a rock might finally become polarised in an opposite sense to the magnetising field, (Neél 1951)[4]. Since then a limited number of rocks (Nagata 1951, Carmichael 1961[6]) and synthesised substances (Gorter and Schulkes) have been discovered

or produced which show self reversing properties in the laboratory.

If the earth's field has always maintained its present sense, all reversed rocks must be self reversed. However, when subjected to simple thermal and demagnetisation tests in the laboratory the majority of reversed rocks do not show any self reversal properties. To proceed any further, either the tests devised to reveal self reversing mechanisms in rocks must be made more detailed, or the second theory (that of field reversal) must be either proved or disproved. The most convincing piece of evidence supporting field reversal in the past is given by the cases where rocks have been baked after their formation by igneous lavas, sills or dykes. In a recent survey Wilson (1962)[8] has considered 52 such cases. In 49 of these there is agreement between the directions of magnetisation of the baked and baking rock, whether this be normal or reversed. The remaining three disagree. This evidence very strongly suggests that the earth's magnetic field has reversed its sense many times in the past few hundred million years. The evidence also suggests that self reversals do occur in the field, but that they are relatively rare phenomena. On the basis of this direct experimental evidence it will be assumed as a working hypothesis that reversals of the earth's field have taken place.

The final proof of field reversal might take the form of tracing a given reversal of the field at a certain epoch right across the globe. This would require dating accurately the period that the rocks had acquired their remanence. However this procedure can only be successfully carried out if

the fraction of reversed rocks which are self reversed is so small that their numbers can be statistically ignored. At present if one requires to know the sense of the earth's field at some ancient epoch it becomes essential to know which reversed rocks indicate a reversed field and which do not. The difficulties involved in deciding whether or not a given reversed rock which shows no self-reversing properties does or does not indicate a reversed field are apparent when some typical experimental results are considered.

Hospers (1954)[9] carried out an extensive investigation of Tertiary Icelandic lava flows. About half were magnetised normally and about half reversed, with few intermediate directions. No difference was detected in the laboratory between the magnetic properties of the normal and reversed rocks and it was concluded that the most probable explanation was that the earth's field had reversed several times during the Tertiary period. From the periodicity of the alternation of normal and reversed rocks, and from the absence of intermediate directions, Hospers concluded that the earth's field probably reversed about every half-million years during the Tertiary period, and that the reversal period was probably not greater than 10,000 years.

More recently, Cox et al (1963)[10] have investigated the magnetic properties of six radiometrically dated volcanic flows of Pleistocene and late Pliocene age from California. Three of these flows were normal and three were reversed. Samples of these rocks were microscopically

examined and some were subjected to simple thermal and demagnetisation tests in the laboratory. No evidence was found to suggest that the remanence of any of these flows was self reversed. The data suggested that field reversals had taken place during the formation of these flows and that the periods between the reversals were either $\frac{1}{2}$ million or 1 million years long.

It seems likely from these results that field reversals between periods of the order of a million years have taken place in the past. However, it has been extremely difficult to account for some of the experimental results obtained. For example, Almond et al (1956)[11] measured the natural remanence at different depths of a 5 feet long core which had been drilled vertically through a volcanic tuff of the Triassic system in Tasmania. The core was polarised in a normal sense with the exception of a depth of 5 inches which was reversely magnetised. The tuff was produced as a result of volcanic activity and was laid down rapidly under sedimentary conditions. Possible explanations of this result include (1) that the earth's field was reversed during the laying down of the reversed 5 inches of tuff but normal while the rest was laid down, and (2) that the earth's field was in either a normal or a reversed state whilst the whole 5 foot of tuff was being laid down and that either the reversed or the normal remanence is self reversed. If we assume an average rate of sedimentation of 780 feet per million years (obtained from data taken from Holmes Revised Time Scale 1959)[12] the five inches of tuff were probably laid down in a period of time

less than 600 years. Possibility (1) requires then that the period of this particular reversal is less than 0.1% of the time of the reversals studied by Hospers and Cox. Possibility (2) requires that a physical or chemical difference should exist between normal and reversed specimens, but Almond et al did not detect such a difference.

It is evident that before a curve representing the history of the earth's field can confidently be obtained one must be able to clearly distinguish between self reversed and field reversed rocks. A full knowledge of self reversing mechanisms in nature as well as in synthetic substances is required. A possible case of self reversal was discovered by Nairn (1960)[13]. Nairn found that a band of ferruginous deposit called the iron grit which occurred in Sussex was polarised in two general directions: one of these was close to the present day field direction (normal) and the other antiparallel to this (reversed). The maximum thickness of this band was stated to be less than six inches, implying that, whatever the nature of its formation were, it was very swiftly formed relative to a geological time scale. For example, if the grit were deposited under sedimentary conditions, and if an average rate of sedimentation of 780 feet per million years is assumed (obtained from Holmes Revised Time Scale)[12] the grit would have been formed during a period of the order of 10^3 years. If we also use the estimates of Hospers (1954) and Cox (1963) and assume that the average time between reversals of the earth's field is of the order of a million years, it

appears that the formation of the grit and possibly the period during which it became magnetised took place in about 0.1% of the time that the earth's field remained in one sense. The observation of two oppositely directed polarisations in six inches of grit was therefore considered to be a most unusual result, and there was therefore the possibility of a self reversing mechanism as an explanation. Since one of the chief aims of rock magnetism is to detect and reveal mechanisms of self reversal in nature, the iron grit of Sussex was made the basis of an investigation.

PART I

FIELD AND GENERAL RESULTS.

Chapter 2

GEOLOGICAL DESCRIPTION OF THE IRON GRIT OF SUSSEX

The map, FIG.2.1 shows the horizon of the grit and the positions of suitable exposures. This horizon extends for about 16 miles from Washington in the east to Cocking further west. Over this distance the grit exists as a definite band and forms a sharp dividing line at the base of the Gault, between the Gault clay and the underlying Folkestone sands, both of which belong to the Cretaceous system. Its thickness reaches a maximum of about six inches near Fittleworth, but it becomes thinner near each end of the horizon before finally disappearing. After its extinction, a nodule bed described by Kirkaldy (1935) forms the base of the Gault.

FIG 2.2 is a schematic vertical section generally observed at the exposures. The clay immediately above the grit is often coloured blood red; clay not in contact with the grit is blue-black. All the clay is stiff and dense. The sand just below the grit is of a red-brown colour. It is coarse and is sometimes mixed with a few streaks of pale clay. Lower down the clean, yellow Folkestone sands are seen.

Photograph P1 shows the Marley Brick and Tile Company quarry near Storrington, which was one of the best exposures of the grit. The colour variation of the sand, which is being quarried, adds much beauty and interest to this scene. The grit which is present along the top surface of the sand is not visible in this photograph, but is shown in photograph P2

BASE OF GAULT IN SUSSEX SHOWING SITES OF SAMPLES

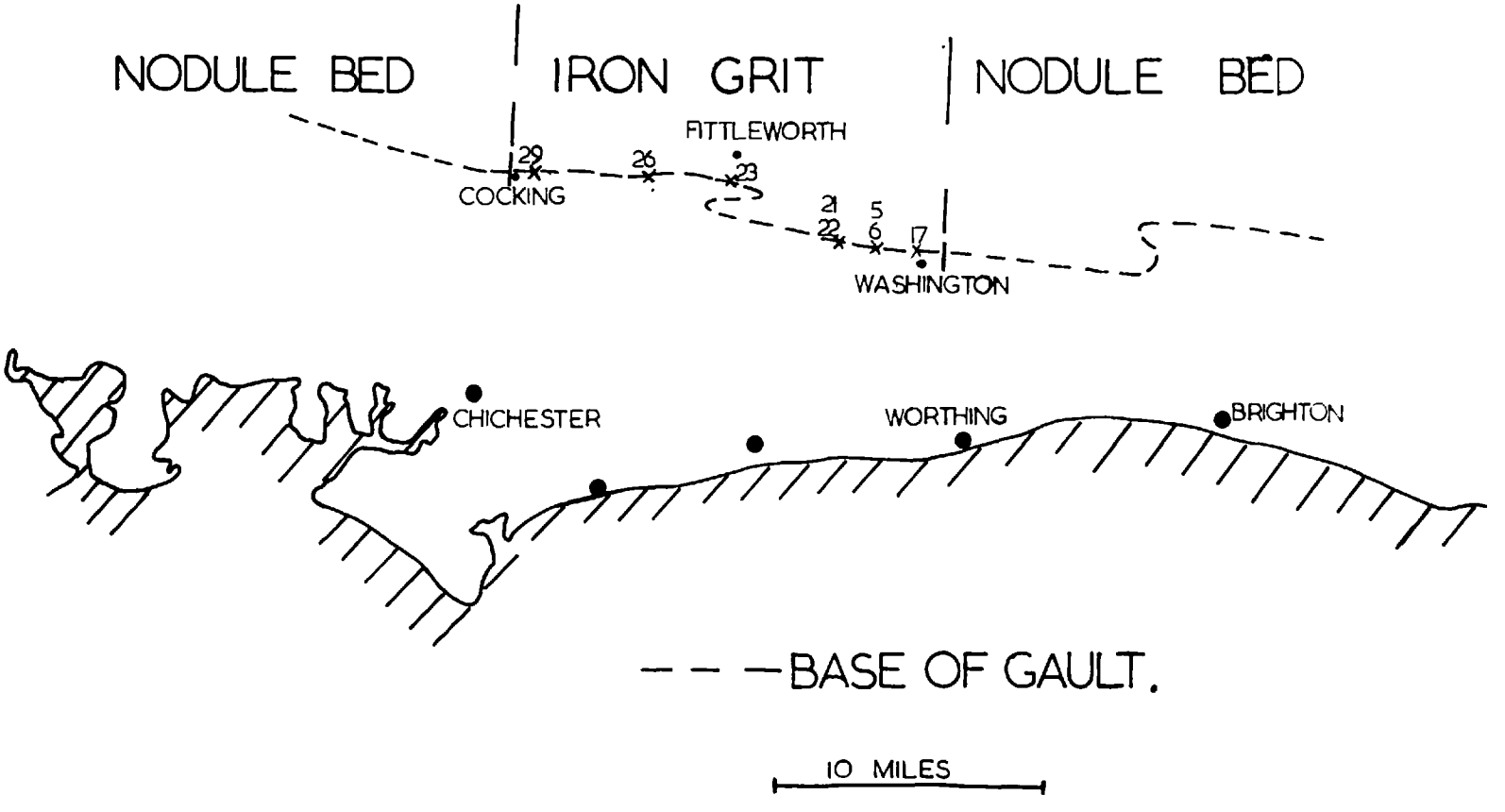


FIG 2.1

SCHEMATIC VERTICAL SECTION OF BASE OF GAULT

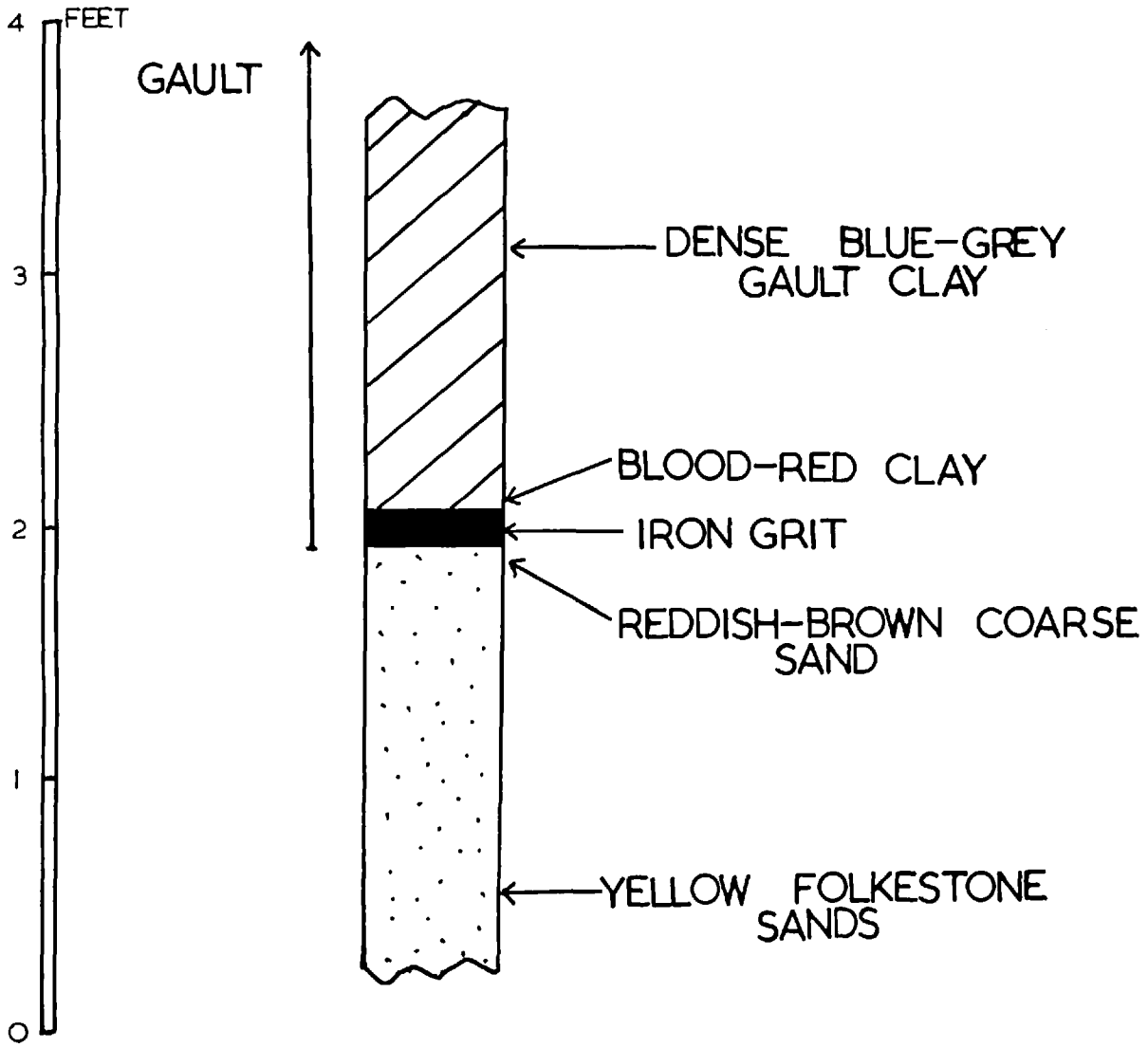


FIG 22



P.1

MARLEY BRICK AND TILE QUARRY, STORRINGTON



P.2

GRIT EXPOSED ALONG TOP OF QUARRY.



P.3

SAND PIT, FITTLEWORTH STATION.

which was taken at close quarters. The clay above the grit is of no great thickness at this site and forms the soil at the top of the quarry. The clay is thicker at the site near Fittleworth station where photograph P3 was taken, but is mainly covered by grass. The band-like structure of the grit running between the clay and sand is clear in this photograph.

The upper and lower surfaces of the grit, although generally horizontal, are rather irregular and humps or dips about a cm. or more above or below the mean level of each surface are not unusual. In the hand the grit is a light reddish brown colour and is seen to consist of white rounded pebbles of various sizes (the average diameter is about 0.5 cm) which are set in an apparently fine grained matrix which is usually coloured red but which sometimes has a darker appearance. Plane sections cut vertically through the grit (see photograph P4, chapter 6) show veins of the red cement running usually in an approximately horizontal sense through the mixed pattern of pebbles and dark and red cement, but occasionally a red vein running in a vertical sense has been observed.

A full geological description of the grit has already been given by Kirkaldy (1935).[14] Kirkaldy found no fossils in the grit, though he occasionally observed partially decomposed grains of glauconite (a hydrated silicate of potassium and iron . A greenish mineral that forms on ocean banks and whose presence in sands and sandstones is often regarded as evidence of marine deposition at no great depth). Kirkaldy concludes that the grit originated by the contemporaneous deposition of a layer of iron on the bed of the Gault sea. This iron precipitate has probably

suffered a certain amount of cementation and alteration at some later date. The Folkestone sands and Gault clay occur about half way through the Cretacecus system and are therefore about 100 million years old. The sand grains of the grit and possibly some of its iron contents, though probably not in their present form were probably laid down also at this time. The date at which the grit became comented into its present form is less certain. The grit tilts by 3^{o} in a southerly direction.

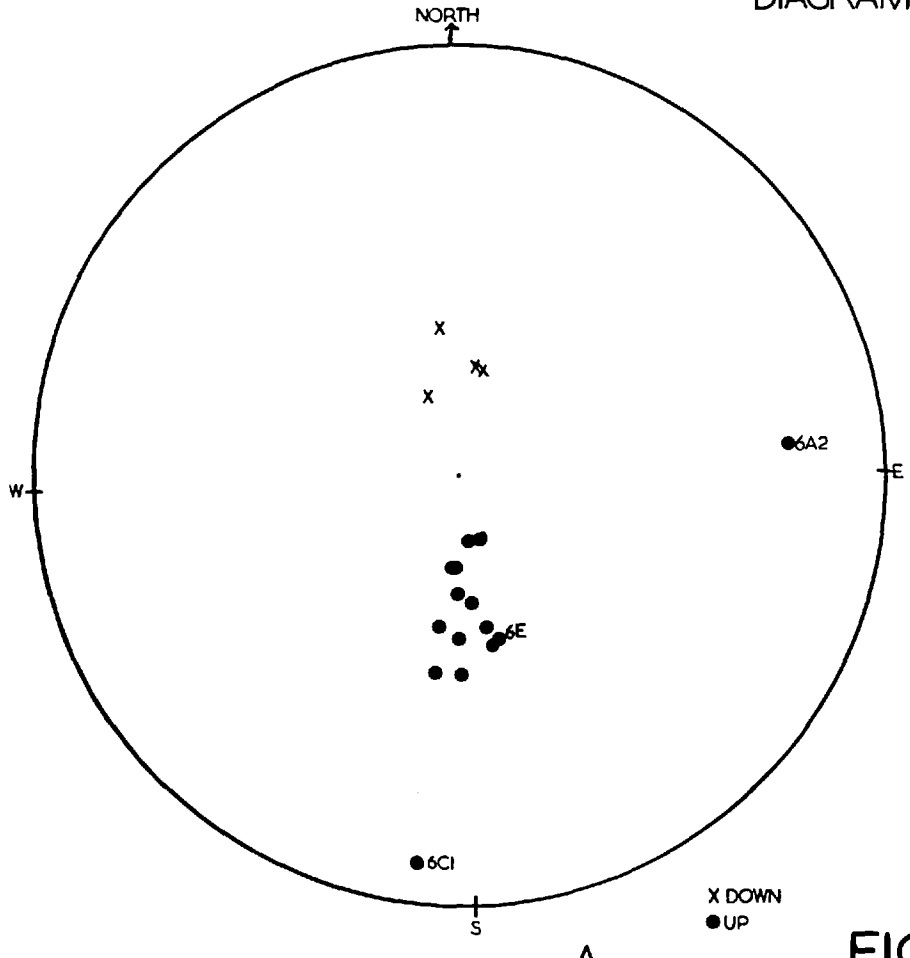
The positions of exposures of the iron grit which are suitable for palaeomagnetic work are described in Appendix 1(a).

Chapter 3

SOME PRELIMINARY MAGNETIC MEASUREMENTS AND THEIR IMPLICATIONS

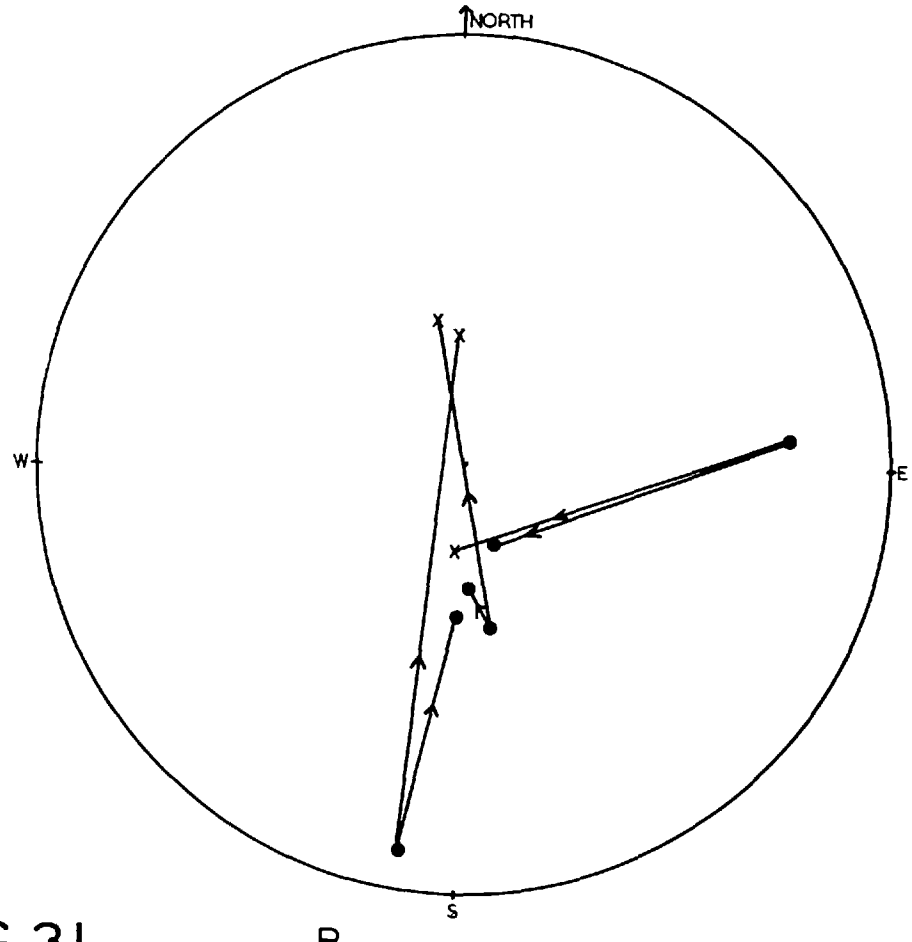
A number of cores were drilled vertically through a block of the grit. They were marked and sliced into two. The directions and specific intensities of the natural remanent magnetisations of these specimens were measured using an astatic magnetometer. The directions were plotted on a polar diagram, FIG 3.1(A) and were found to arrange themselves into two groups, one approximately being the direction of the earth's field in England and the other antiparallel to this direction. This confirmed Nairn's result. However the directions obtained from two specimens, 6C1 and 6A2, deviated considerably from each of these two groups. Repeating the measurements a few days later after storing in the earth's field gave a similar result which indicated a measure of stability and proved that the 2 scattered directions were not errors of measurement or calculation. The specific intensities of both these specimens were rather low compared with the average value of all the specimens. Both were sliced into two; 6C1α and 6C1β being produced from 6C1, 6A2α and 6A2β from 6A2. The directions and specific intensities of each was measured. The directions obtained are plotted in FIG 3.1 (B). In each respective case the directions of the natural remanence of the two daughter specimens were found to generally resolve, one into a normal group and the other to a

SOME N.R.M. DIRECTIONS PLOTTED ON POLAR DIAGRAM



A

N.R.M. DIRECTIONS BEFORE & AFTER SLICING



B

FIG 3.1

reversed group. An apparently reversed specimen, 6E, which was cored in situ very near to the specimens previously considered was also sliced. Of the two daughter specimens, 6E1 was found to be reversed and 6E2 normal. Table 1 shows the polarisation strengths of the specimens dealt with. The scalar sum of the strengths of the two daughter specimens in each of these cases is much greater than that of the original specimen. This obviously has a simple explanation since it is evident that the measured polarisation of each of the original specimens was in fact the vector sum of two oppositely directed polarisations. In the case of 6E the reversed polarisation was predominant and the specimen was considered to be reversed. There is good agreement between the polarisation strength of 6E and the difference between the polarisations of the two daughter specimens. In each of the cases of 6A2 and 6C1 the normal polarisation was probably almost equal to the reversed polarisation. Agreement between the polarisation value of the original specimen and the difference between the polarisation values of its two daughter specimens in each of these cases is not so striking as for 6E. In these two cases a vector agreement is required rather than scalar agreement since both the polarisations of 6A2 and 6C1 are scattered. Material lost in the saw cut on slicing probably accounts for the fact that in each of the cases of 6A2 and 6C1 the two daughter specimens produced by slicing do not have similar polarisation strengths. The lengths of the original specimens were about two to three cms, and their diameters were 2.2 cms.

TABLE 1.

SPECIMEN	POLARISATION STRENGTH Positive means Normal Negative means Reversed	
6A2	49 x 10^{-6} e.m.u.	
↓		
6A2α	-133 x 10^{-6} e.m.u.	Difference = 96 x 10^{-6} e.m.u
6A2β	+ 37 x 10^{-6} e.m.u.	Sum = 170 x 10^{-6} e.m.u
6C1	87 x 10^{-6} e.m.u.	
↓		
6C1α	+213 x 10^{-6} e.m.u.	Difference = 175 x 10^{-6} e.m.u.
6C1β	-388 x 10^{-6} e.m.u.	Sum = 601 x 10^{-6} e.m.u.
6E	-583 x 10^{-6} e.m.u.	
↓		
6E1	-1,200 x 10^{-6} e.m.u.	Difference = 535 x 10^{-6} e.m.u
6E2	+ 665 x 10^{-6} e.m.u.	Sum = 1,865 x 10^{-6} e.m.u

The results show that at least 3 specimens out of the 19 original spocimens contained both normal and reversed polarisations, and that reversals of the natural magnetisation were taking place in the grit over distances of about a cm, or possibly less. These results have been described because they had much bearing on future work and were constantly kept in mind. They made the following points clear :

1) They showed experimentally that intermediate and stable directions found between normal and reversed sections of a stratum may not necessarily represent intermediate directions of the earth's field during an alleged reversal.

2) They stressed the importance, in the case of the iron grit especially, of slicing cores as thin as was consistent with accurate measurement, and with the fragility of the core concerned.

3) They served a warning that even though the direction of the natural polarisation of a specimen might be close to either a mean normal or a mean reversed direction, the specimen might possibly still contain an appreciable amount of the opposite polarisation.

4) They showed that reversals of the natural polarisation were taking place in a very short space interval within the grit.

It was considered essential to investigate further into the spacial distribution of normal and reversed parts of the grit. Blocks, each representing the full thickness of the grit were collected at suitable

exposures along the 16 mile horizon. These exposures are described in Appendix 1.(a). The blocks were cast in plaster of paris in the laboratory and cores of diameter 2.2 cms were drilled vertically through. The position of each core with respect to the block of grit was recorded. The cores were then marked so that after slicing there would be no ambiguity in determining the correct orientation of each individual slice. As many horizontal slices as possible were cut from the core and the distance from the centre of each slice (hereafter called specimen) from the top of its core (i.e. the top surface of the grit) was recorded. The 'best' specimen thickness was about 0.8 cms but this varied a little due mainly to the changing fragility of the grit which sometimes broke very easily. A brief note on the method used to number each specimen according to its position in situ with respect to the grit is given in Appendix 1(b). The directions and specific intensities of the natural polarisations of about 190 specimens cut in the above manner were measured with an astatic magnetometer. The distance between the specimen and the lower magnet was such that a deflection of 2.62 cms was observed per 10^{-4} e.m.u. of dipole moment. At this sensitivity the centre of the specimen was about $1\frac{1}{2}$ times its diameter below the bottom magnet of the astatic system.

Chapter 4 deals with the directions of the natural remanences, and in Chapter 5 the spacial distribution of normal and reversed parts of the grit is considered.

Chapter 4

DIRECTIONS OF THE NATURAL REMANENCES

Table 2 gives the declination, inclination and specific intensity of the natural remanent magnetisation (N.R.M.) of each specimen measured. The directions are plotted on a polar diagram, FIG. 4.1 (A). There are two closely grouped sets of directions, one being directed approximately along the earth's present field (normal) and the other antiparallel to this direction (reversed). There are also a few scattered directions. The mean directions of each group, together with its standard deviation was calculated.

Normal Group: The mean direction has a declination of ($3^{\circ} \pm 7^{\circ}$) east of north and dips down by ($68.5^{\circ} \pm 2^{\circ}$)

Reversed Group: The mean direction has a declination of ($182^{\circ} \pm 6^{\circ}$) east of north inclined up by ($69^{\circ} \pm 2^{\circ}$).

Both normal and reversed groups of directions are seen to be spread about their respective mean directions by about the same amount.

At London the present day declination is 9° west of north inclined down by 66.3°. The average direction of the field over the past 500 years is given by a declination of 7° west of north inclined down by 70.4°. The direction of the field at London produced by an axial dipole at the centre of the earth has zero declination and is inclined by 68.5° down. These facts, together with the mean normal and mean reversed directions of magnetisation of the grit are shown in FIG. 4.1 (B).

TABLE 2

NATURAL REMANENT POLARISATIONS (N.R.M's)

Specimen	Declination East of true North	Inclination Positive means Down	Specific Intensity I(e.m.u./grm)
1A	-25°	$+60^{\circ}$	9×10^{-6}
2A	158°	-65°	12×10^{-6}
2C	154°	-81°	4×10^{-6}
3A	-8°	$+68^{\circ}$	16×10^{-6}
3D	-4°	$+70^{\circ}$	19×10^{-6}
3E	-10°	$+70^{\circ}$	27×10^{-6}
2D	173°	-78°	14×10^{-6}
2G1	190°	-68°	5×10^{-6}
2G2	186°	-73°	2×10^{-6}
2H	176°	-66°	10×10^{-6}
3F1	14°	$+69^{\circ}$	8×10^{-6}
3F2	9°	$+68^{\circ}$	46×10^{-6}
5B	164°	-78°	11×10^{-6}
5C	185°	-73°	14×10^{-6}
6A2	85°	-24°	-
6A1	182°	-68°	197×10^{-6}
6B1	170°	-57°	11×10^{-6}
6B2	189°	-52°	9×10^{-6}
6C1	188°	-10°	-
6C2	181°	-59°	26×10^{-6}
6E	168°	-58°	-
6F1	181°	-52°	24×10^{-6}
6F2	-19°	$+73^{\circ}$	20×10^{-6}
6G1	171°	-61°	66×10^{-6}

Continued.....

Table 2 -contd-

Specimen	Declination East of True North	Inclination Positive Means Down	Specific Intensity I (e.m.u./grm)
6G2	-6°	$+ 61^{\circ}$	24×10^{-6}
6A2α	154°	$- 74^{\circ}$	19×10^{-6}
6A2β	181°	$+ 74^{\circ}$	3×10^{-6}
6C1α	-1°	$+ 65^{\circ}$	19×10^{-6}
6C1β	180°	$- 61^{\circ}$	27×10^{-6}
6E1	175°	$- 66^{\circ}$	63×10^{-6}
6E2	-9°	$+ 62^{\circ}$	33×10^{-6}
3A	4°	$+ 69^{\circ}$	8×10^{-6}
3Aα	-16°	$+ 71^{\circ}$	6×10^{-6}
3Aβ	-2°	$+ 73^{\circ}$	14×10^{-6}
2C1	3°	$+ 74^{\circ}$	16×10^{-6}
2C2	198°	$- 69^{\circ}$	4×10^{-6}
2C3	207°	$- 70^{\circ}$	14×10^{-6}
2C4	95°	$- 81^{\circ}$	8×10^{-6}
3D1	-1°	$+ 75^{\circ}$	6×10^{-6}
3D2	-2°	$+ 67^{\circ}$	22×10^{-6}
3D3	20°	$+ 70^{\circ}$	25×10^{-6}
3D4	81°	$+ 69^{\circ}$	4×10^{-6}
5C1	158°	$- 79^{\circ}$	6×10^{-6}
5C2	185°	$- 76^{\circ}$	43×10^{-6}
5C3	-10°	$+ 68^{\circ}$	51×10^{-6}
5C4	-12°	$+ 63^{\circ}$	12×10^{-6}
5B1	-2°	$+ 72^{\circ}$	45×10^{-6}
5B2	220°	$- 37^{\circ}$	15×10^{-6}
5B3	188°	$- 75^{\circ}$	47×10^{-6}
5B4	30°	$- 63^{\circ}$	3×10^{-6}

Continued.....

Table 2 -contd-

Specimen	Declination East of True North	Inclination positive means Down	Specific Intensity I (e.m.u./grm)
5E1	200°	- 71°	6×10^{-6}
5E2	199°	- 69°	44×10^{-6}
5E3	-25°	- 29°	4×10^{-6}
5E4	3°	+ 68°	69×10^{-6}
5E5	6°	+ 75°	51×10^{-6}
6J1	182°	- 69°	7×10^{-6}
6J2	177°	- 68°	70×10^{-6}
6J3	11°	+ 62°	28×10^{-6}
6J4	-2°	+ 70°	17×10^{-6}
6J5	-52°	+ 59°	3×10^{-6}
6J6	-55°	+ 78°	8×10^{-6}
6L1	184°	- 74°	14×10^{-6}
6L2	12°	- 82°	3×10^{-6}
6L3	175°	- 67°	228×10^{-6}
6L4	-13°	+ 66°	62×10^{-6}
6L5	-5°	+ 68°	19×10^{-6}
6Q1	-42°	+ 67°	10×10^{-6}
6Q2	155°	- 73°	19×10^{-6}
6Q3	201°	- 60°	24×10^{-6}
6Q4	170°	- 66°	201×10^{-6}
6Q5	-4 °	+ 63°	53×10^{-6}
6Q6	206°	- 69°	22×10^{-6}
5D1	-16°	+ 72°	5×10^{-6}
5D2	192°	- 63°	5×10^{-6}
5D3	+7 °	- 79°	3×10^{-6}
5D4	196°	- 76°	128×10^{-6}

Continued .....

Table 2 - contd -

Specimen	Declination East of True North	Inclination positive means Down	Specific Intensity I (e.m.u./grm)
5D5	154°	- 71°	135 x 10^{-6}
5D6	- 9°	+ 78°	90 x 10^{-6}
6N1	195°	- 41°	18 x 10^{-6}
6N2	204°	+ 7°	11 x 10^{-6}
6N3	194°	- 65°	115 x 10^{-6}
6N4	180°	- 66°	99 x 10^{-6}
6N5	5°	+ 72°	33 x 10^{-6}
6N6	15°	+ 69°	8 x 10^{-6}
6M1	50°	- 45°	13 x 10^{-6}
6M2	145°	- 66°	6 x 10^{-6}
6M3	183°	- 66°	198 x 10^{-6}
6M4	8°	+ 67°	56 x 10^{-6}
6M5	4°	+ 69°	9 x 10^{-6}
22A1	13°	+ 75°	6 x 10^{-6}
22A2	212°	- 69°	40 x 10^{-6}
22A3	22°	+ 68°	40 x 10^{-6}
22A4	195°	- 69°	76 x 10^{-6}
22A5	36°	+ 65°	43 x 10^{-6}
22A6	185°	- 68°	60 x 10^{-6}
22C1	30°	+ 53°	10 x 10^{-6}
22C2	87°	- 69°	10 x 10^{-6}
22C3	105°	- 54°	11 x 10^{-6}
22C4	75°	- 65°	64 x 10^{-6}
22C5	231°	- 59°	30 x 10^{-6}
22D1	20°	+ 72°	6 x 10^{-6}

Continued.....

Table 2 -contd-

Specimen	Declination East of True North	Inclination Positive means Down	Specific Intensity I (e.m.u./grm)
22D2	181°	- 66°	15×10^{-6}
22D3	210°	- 67°	32×10^{-6}
22D4	10°	+ 68°	15×10^{-6}
22D5	-57°	+ 18°	3×10^{-6}
22D6	204°	- 72°	23×10^{-6}
17A1	148°	- 4°	33×10^{-6}
17A2	162°	- 64°	19×10^{-6}
17A3	21°	+ 69°	11×10^{-6}
17A4	23°	+ 63°	4×10^{-6}
17A5	-34°	+ 64°	3×10^{-6}
17C1	282°	- 56°	6×10^{-6}
17C2	277°	- 53°	13×10^{-6}
17C3	36°	+ 68°	4×10^{-6}
17C4	26°	+ 22°	7×10^{-6}
21A1	192°	- 73°	84×10^{-6}
21A2	200°	- 68°	29×10^{-6}
21A3	187°	- 73°	49×10^{-6}
21A4	0°	+ 72°	31×10^{-6}
21B1	221°	- 22°	1×10^{-6}
21B2	187°	- 64°	36×10^{-6}
21B3	14°	+ 60°	41×10^{-6}
21B4	6°	+ 67°	72×10^{-6}
21B5	11°	+ 72°	50×10^{-6}
21C1	172°	- 63°	17×10^{-6}
21C2	183°	- 64°	40×10^{-6}
21C3	194°	- 73°	50×10^{-6}

Continued....

Table 2 -contd-

Specimen	Declination East of true North	Inclination Positive means Down	Specific Intensity I(e.m.u./grm)
21C4	16°	+ 70°	47×10^{-6}
21C5	186°	- 68°	102×10^{-6}
21C6	60°	+ 17°	3×10^{-6}
21D1	217°	- 72°	9×10^{-6}
21D2	283°	- 65°	4×10^{-6}
21D3	23°	+ 68°	18×10^{-6}
21D4	192°	- 64°	39×10^{-6}
21D5	196°	- 67°	67×10^{-6}
21D6	39°	+ 70°	33×10^{-6}
23B1	-15°	+ 73°	4×10^{-6}
23B2	15°	+ 71°	6×10^{-6}
23B3	-2°	+ 71°	12×10^{-6}
23B4	-2°	+ 72°	33×10^{-6}
23B5	0°	+ 76°	37×10^{-6}
23B6	49°	+ 43°	4×10^{-6}
23C1	-7°	+ 69°	6×10^{-6}
23C2	18°	+ 65°	6×10^{-6}
23C3	20°	+ 53°	8×10^{-6}
23C4	-62°	+ 62°	8×10^{-6}
23C5	22°	+ 80°	26×10^{-6}
23C6	88°	- 33°	3×10^{-6}
23F1	65°	+ 44°	4×10^{-6}
23F2	11°	+ 67°	9×10^{-6}
23F3	9°	+ 68°	23×10^{-6}
23F4	6°	+ 66°	34×10^{-6}

Continued.....

Table 2 -contd-

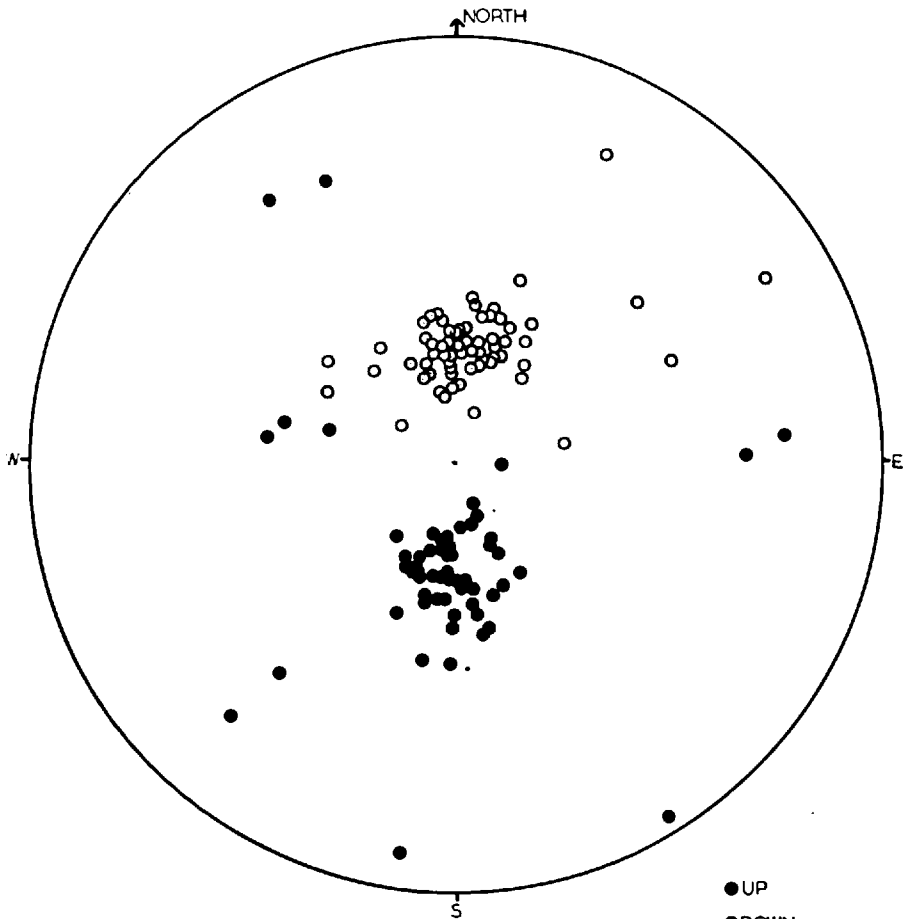
Specimen	Declination East of True North	Inclination positive means Down	Specific Intensity I(e.m.u./grm)
26A1	206°	-50°	1×10^{-6}
26A2	170°	-69°	2×10^{-6}
26A3	146°	-70°	7×10^{-6}
26A4	53°	+32°	1×10^{-6}
26A5	-42°	-34°	1×10^{-6}
26A6	61°	-78°	3×10^{-6}
26B1	183°	-58°	4×10^{-6}
26B2	-17°	-37°	4×10^{-6}
26B3	-31°	-21°	142×10^{-6}
26B4	254°	-47°	2×10^{-6}
26B5	-56°	-60°	13×10^{-6}
26B6	55°	0°	1×10^{-6}
26B7	126°	+61°	5×10^{-6}
26B8	11°	-36°	5×10^{-6}
26B9	44°	-54°	2×10^{-6}
26C1	209°	-75°	3×10^{-6}
26C2	224°	-27°	$10x 10^{-6}$
26C3	192°	-60°	5×10^{-6}
26C4	225°	-62°	1×10^{-6}
26C5	77°	+19°	7×10^{-6}
26C6	119°	-37°	6×10^{-6}
29A1	23°	+66°	7×10^{-6}
29A2	14°	+61°	31×10^{-6}
29A3	8°	+60°	31×10^{-6}

Continued.....

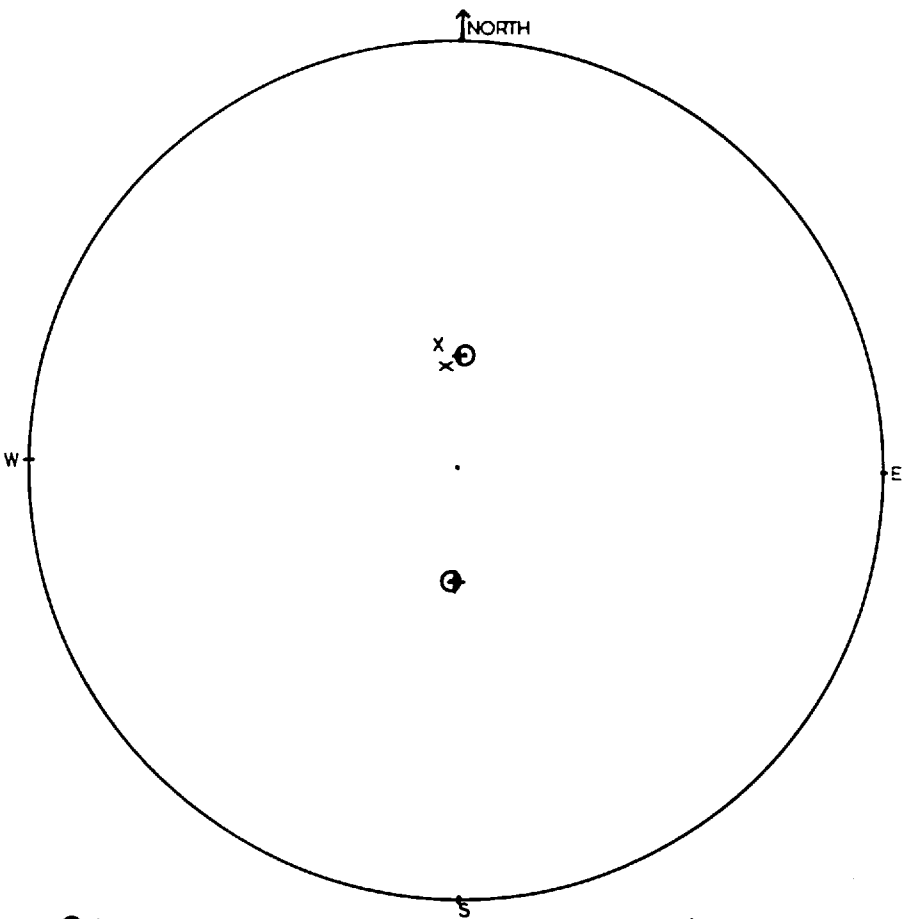
Table 2 - contd-

Specimen	Declination East of True North	Inclination Positive Means Down	Specific Intensity I(e.m.u/grm
29B1	- 36°	- 27°	2×10^{-6}
29B2	29°	+ 60°	8×10^{-6}
29B3	31°	+ 64°	34×10^{-6}
29C1	20°	+ 66°	14×10^{-6}
29C2	18°	+ 61°	19×10^{-6}
29C3	6°	+ 64°	29×10^{-6}
29C4	7°	+ 59°	27×10^{-6}
29D1	148°	- 66°	1×10^{-6}
29D2	2°	+ 65°	16×10^{-6}
29D3	3°	+ 65°	26×10^{-6}

N.R.M. DIRECTIONS PLOTTED ON POLAR DIAGRAM. MEAN NORMAL & MEAN REVERSED DIRECTIONS



A



B

FIG 41.

The angle between mean normal and mean reversed directions is less than a degree away from 180° apart : within the limits of their standard deviations they may be considered to form a straight line whose direction is parallel to the field direction in Sussex produced by an axial dipole. It has been found (Blackett et al 1960)[15] that rocks of ages up to 20 million years old are on the average magnetised roughly along or antiparallel to the direction of the field of an axial dipole: the remanences of rocks older than 20 million years often have directions which are inclined to the axial dipole field direction. Usually, the greater the age of the rock, the greater becomes this angle. Using results obtained from - 'An analysis of rock magnetic data'(Blackett et al 1960)[15] the direction of the remanence of a rock in Europe of age 100 million years might be expected to diverge from the axial dipole field direction by about 25°. This is not so for the grit. Although the grit probably had its origin about 100 million years ago the directions of both normal and reversed natural polarisations lie close to those directions given by the field of an axial dipole. As an explanation, it is tentatively suggested at this stage that the grit may not have acquired its present day magnetisation when it was originally laid down: the grit may have become magnetised subsequent to its formation and possibly within the last 20 million years. The magnetisation period will be further discussed in the discussion, Chapter 10.

Accordingly the mean directions of the natural remanences of normal and reversed groups have not been 'corrected' for the present day tilt of

the grit which is 3^{o} in a southerly direction. It is not possible to be sure whether the tilting has occurred before or after the natural magnetisation was acquired. However if one wishes to correct for tilt, the inclinations of both normal and reversed specimens are each increased by 3^{o} to 72^{o}. This is steeper than the present axial dipole field direction in Sussex. The palaeomagnetic record for Europe indicates shallower dips in previous times.

Chapter 5

VARIATION OF THE NATURAL REMANENT MAGNETISATION DOWN VERTICAL CORES OF IRON GRIT.

In Chapter 3 it was shown that reversals of the natural polarisation were taking place over distances of about a cm. or less. This chapter is concerned with the investigation of whether or not normal and reversed volumes have any definite spacial distribution.

FIGS. 5.1,5.2, 5.3, 5.4, 5.5, 5.6, 5.7 show how the natural specific intensity of specimens sliced from cores (in each case drilled vertically through the full thickness of the grit) varies with the specimen depth. The latter is the distance from the centre of the specimen to the top of its particular core. On the notation used, positive intensities signify normally polarised specimens and negative intensities are reversed polarisations. In the case of a scattered direction, an upward inclination was taken by convention to be a reversed specimen and a downward dip was considered a normal specimen: the corresponding point on the diagram was in this case marked by an S. On each diagram measurements of specimens cut from one particular block only of the grit are shown, and the map of FIG 2.1 shows the position along the horizon of the grit where each particular block was collected. The order of the diagrams is such that one proceeds from site to site from east to west along the horizon of grit.

N.R.M. PLOTTED AGAINST SPECIMEN DEPTH FOR CORES FROM ROCK SAMPLE 17

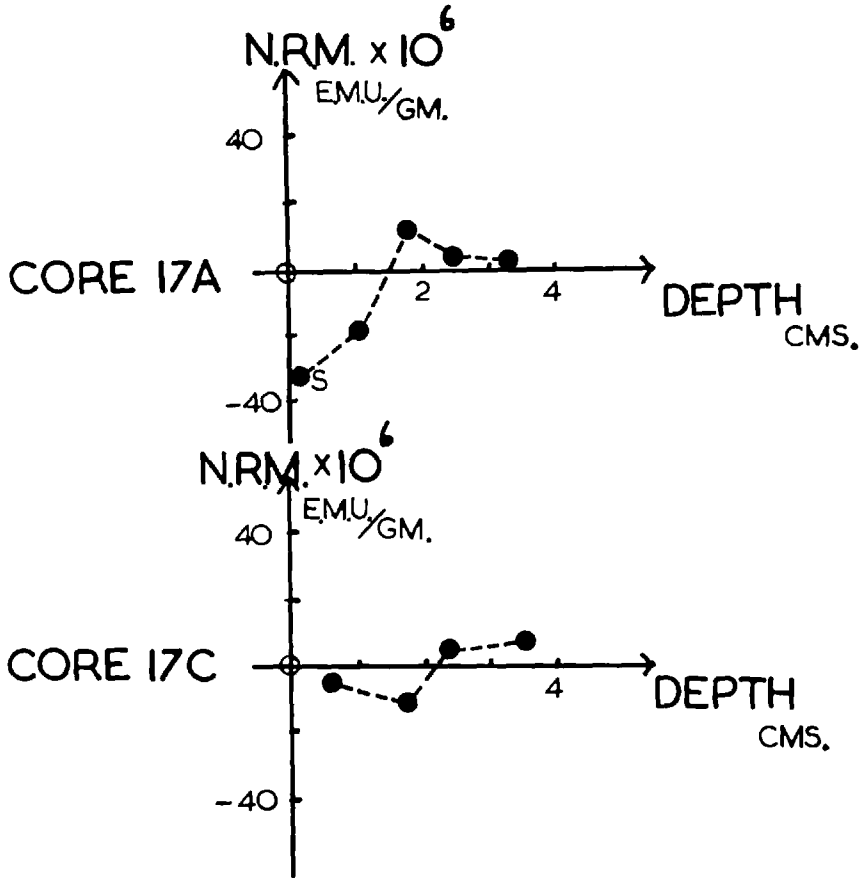


FIG 5.1

N.R.M.-v-SPECIMEN DEPTH. ROCK SAMPLE 5

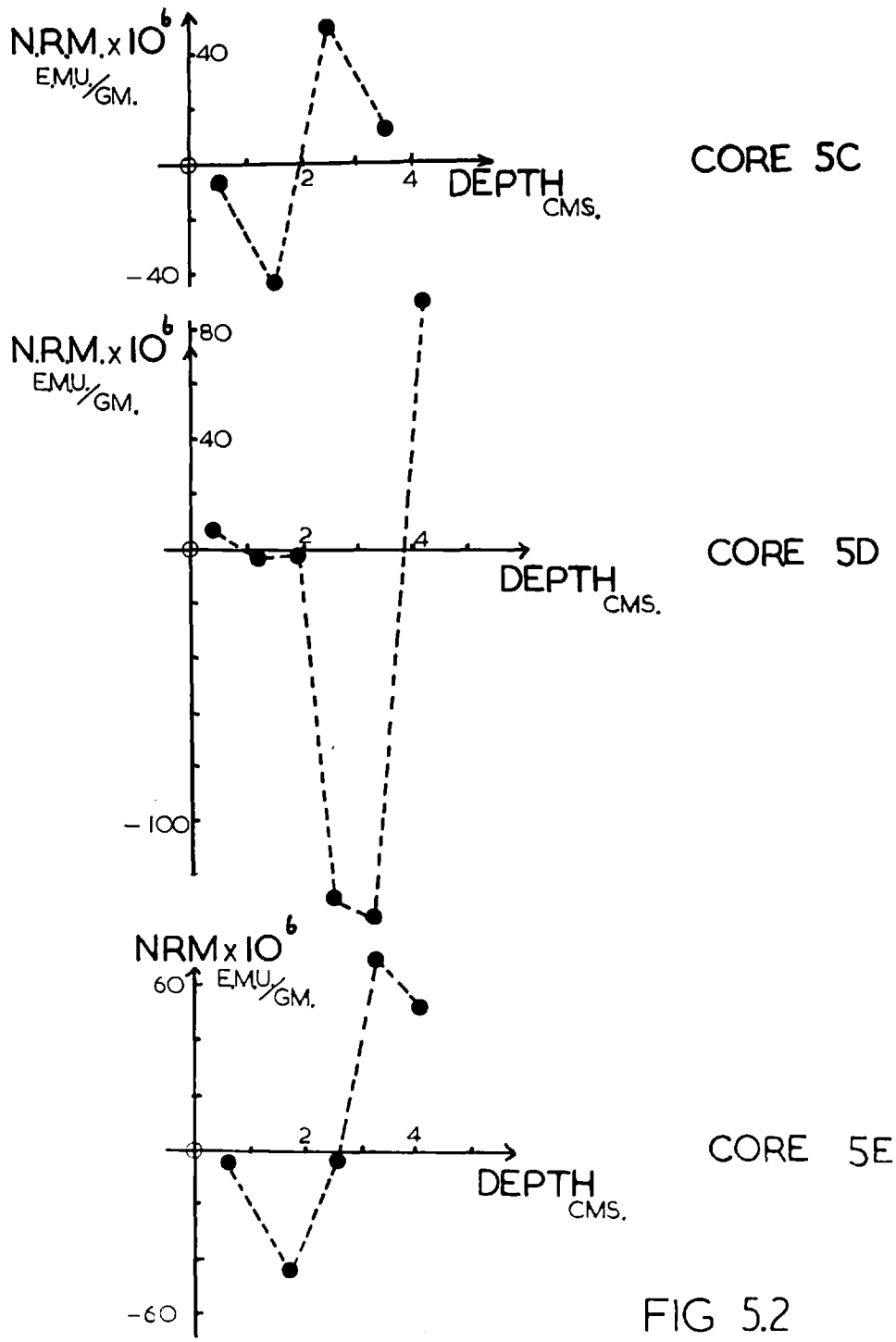


FIG 5.2

N.R.M.-v-SPECIMEN DEPTH. ROCK SAMPLE 6

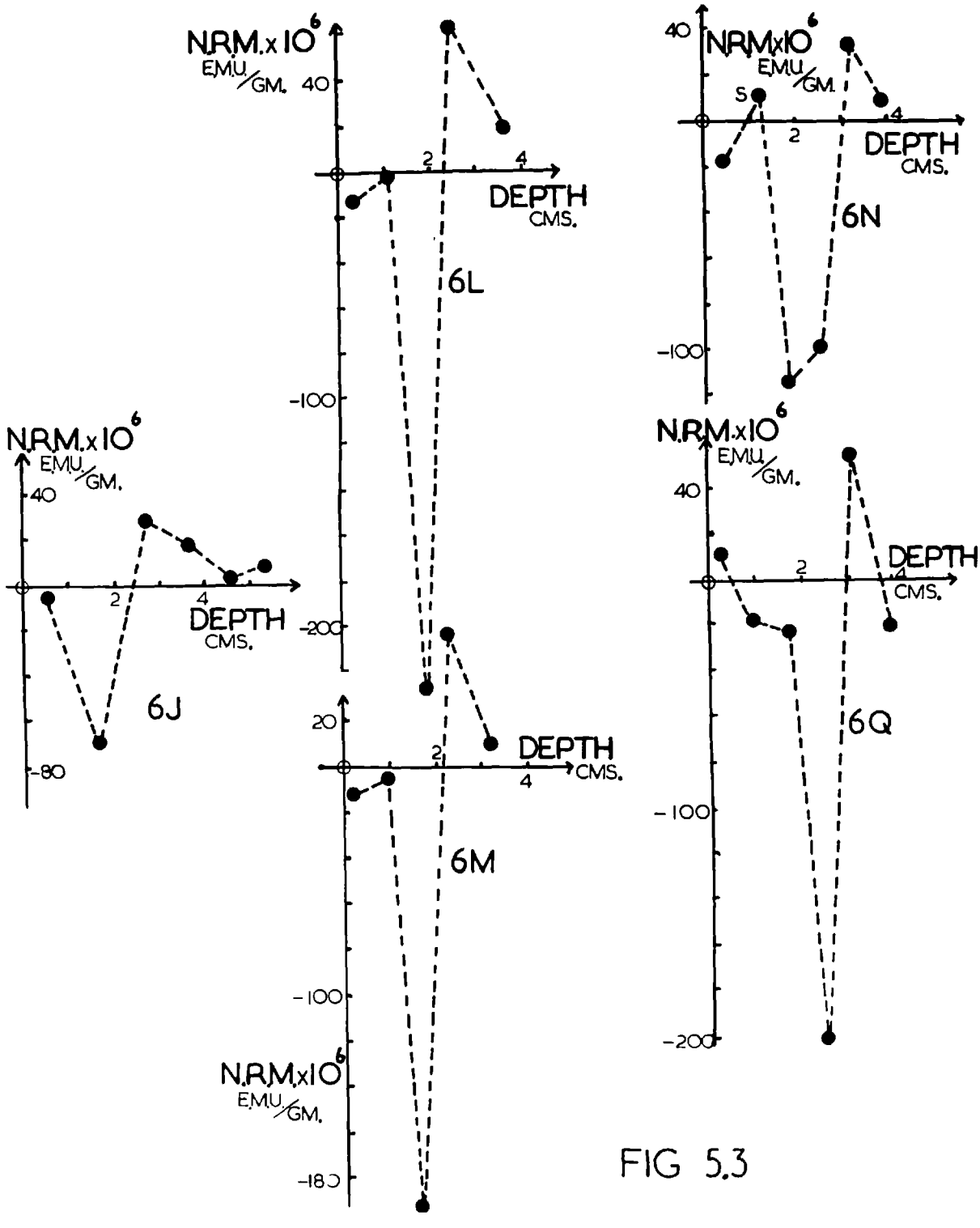


FIG 5.3

N.R.M.-v- SPECIMEN DEPTH. ROCK SAMPLE 21

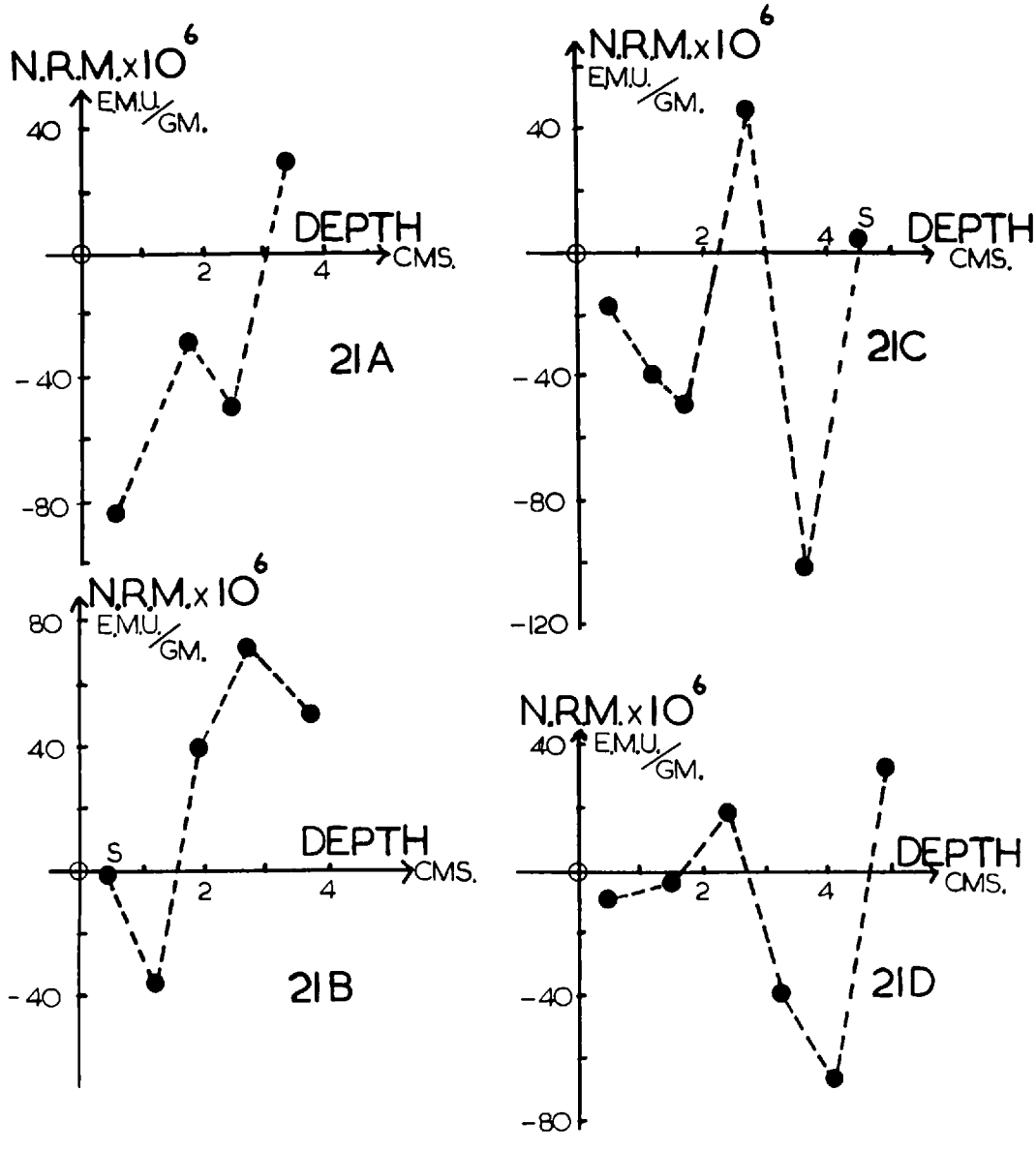


FIG 5.4

NRM v SPECIMEN DEPTH ROCK SAMPLE 22

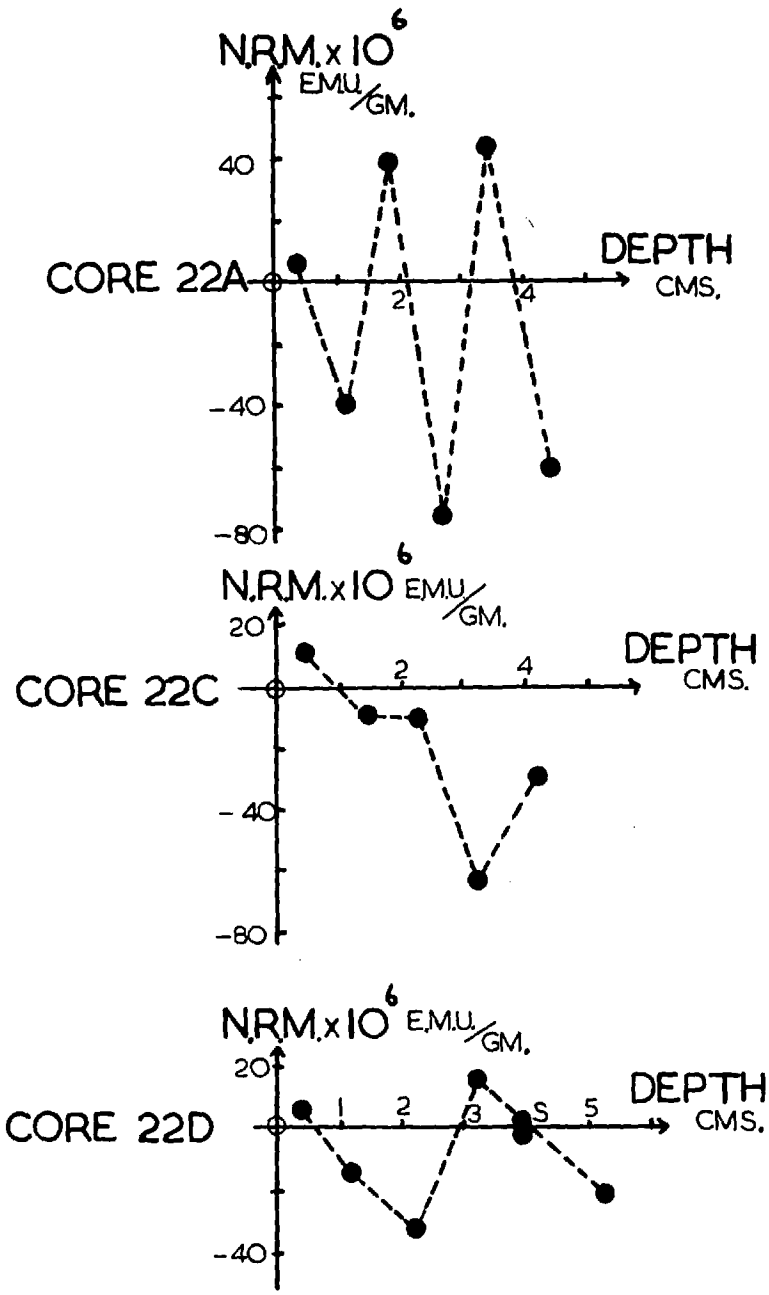


FIG 5.5

N.R.M.-v- SPECIMEN DEPTH. ROCK SAMPLE 23

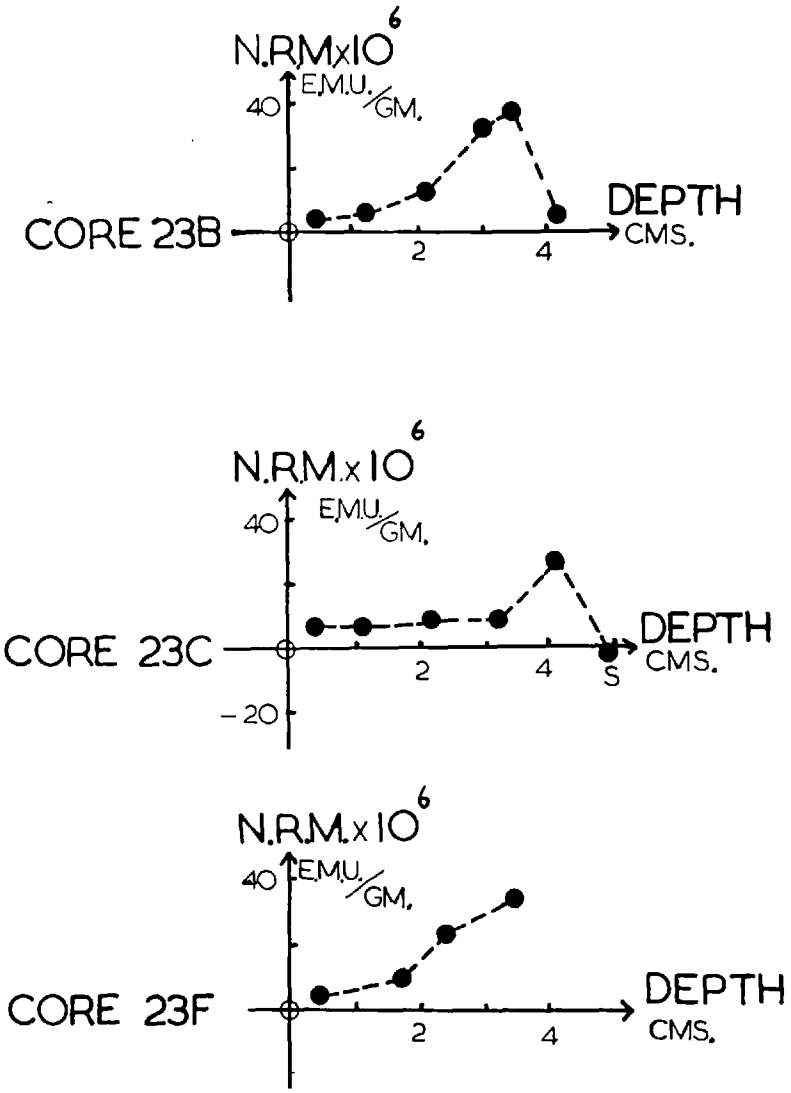


FIG 5.6

N.R.M.-v-SPECIMEN DEPTH. ROCK SAMPLE 29

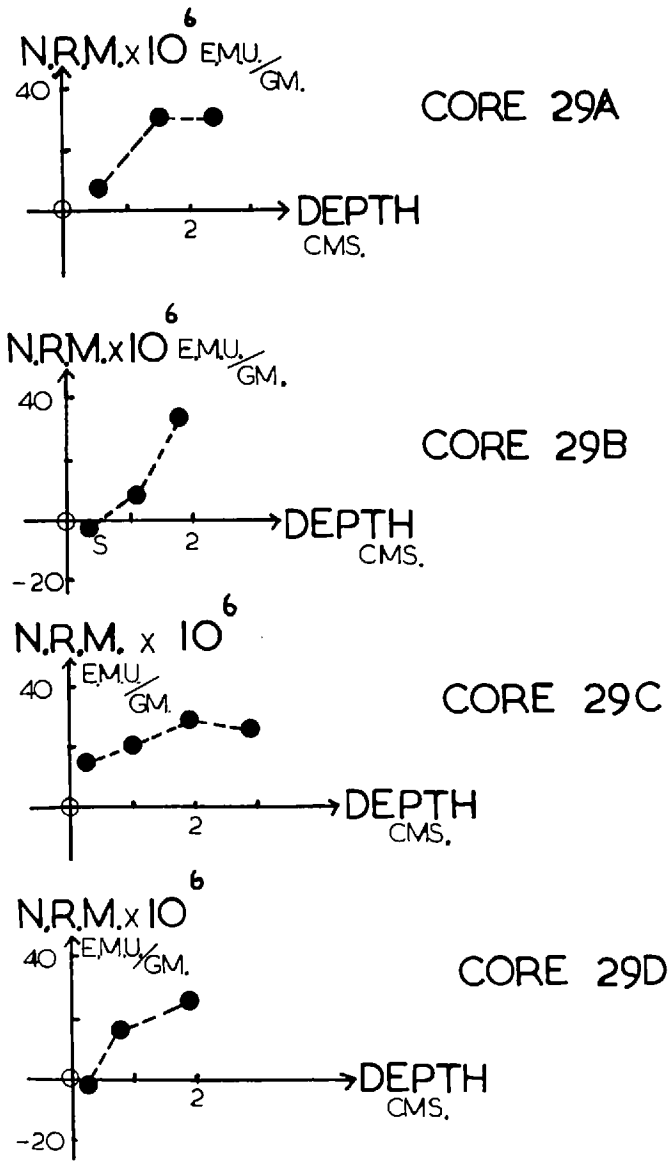


FIG 5.7

In general the diagrams reveal a rapid variation of the natural specific polarisation as one proceeds down through the grit. Sometimes an extremely large reversed polarisation is exchanged for a large normal polarisation over a depth of only a few mms.

Fig. 5.1 shows that both cores drilled from Block 17 (collected at the eastern extreme of the grit) apparently start off reversed at the top but become normal half way down. In situ the centres of these cores were separated by a horizontal distance of 4 cms.

Figs. 5.2 and 5.3 show measurements taken from Blocks 5 and 6 respectively, both of which were collected at the same site. The cores 6L, 6M and 6N (Fig. 5.3) in situ form a triangle, their centres being separated by a horizontal distance of about twice their diameter. The natural intensity varies rapidly from specimen to specimen in a rather complex manner down each of these cores. However the pattern of intensity plotted against depth is very similar for each of these three cores. Since the cores were drilled vertically through the grit this result indicates that over the volume represented by the cores 6L, 6M and 6N normal and reversed volumes are arranged in approximately horizontal layers. The specimen at a depth of about 1 cm. in each of these 3 cores is weakly polarised: two are reversed and the other is scattered. In Chapter 3 the possibility of apparently reversed specimens containing some normal polarisations and vice versa was considered and one might speculate in the present case that in the volume of grit

represented by cores 6L, 6M and 6N there is a thin horizontal seam of normal polarisation at a depth of about 1 cm. below the surface of the grit. In Chapter 6 the intensity versus depth pattern of three sections, each cut vertically through the grit a few cms. away from this trio of cores, is investigated by a more discriminating technique. Intensity versus depth patterns similar to the intensity versus depth patterns of cores 6L, 6M and 6N are obtained, and these show that over limited horizontal distances a seam of normal polarisation does in fact exist at a depth of one cm.

Cores 6J and 6Q which in situ were about 8 and 15 cms. respectively from the trio 6L, 6M and 6N, on opposite sides, each show intensity versus depth patterns which are fairly similar to those of cores 6L, 6M and 6N. It seems that horizontal seams of normal and reversed polarisations which exist over the volumes of grit represented by cores 6L, 6M and 6N run through about 10 to 15 cms. at least of this block with only slight modifications. The three cores drilled through rock sample 5 (Fig. 5.2) collected 5 feet to the east of rock sample 6 do not show very similar intensity versus depth patterns, but their 'general' pattern might possibly be vaguely similar to the general pattern shown by the cores drilled from rock sample (block) 6. It is possible that the horizontal seams of normal and reversed polarisations which exist over at least a large volume of rock sample 6 run with modifications over horizontal distances of a few feet.

The variation of the natural remanent magnetisation with depth 2 miles further to the west at Cootham, is given by cores from rock samples 21 and 22 (Figs. 5.4 and 5.5. respectively). No general intensity versus depth pattern could be discovered either for cores drilled from rock sample 21 or for cores drilled from sample 22, even though the cores from each of these blocks had been drilled only a few cms. away from each other. A more thorough attempt to investigate the intensity distribution of normal and reversed parts of rock sample 22 is described later in this Chapter. The complex pattern of magnetisation of core 22A (Fig. 5.5) is rather interesting. This core had been sliced such that each slice was magnetised in the opposite sense to its nearest neighbours, revealing 5 complete reversals of the natural magnetisation down its length of 5 cms.

Rock sample 23, collected further again to the west at Fittleworth station, is predominantly normally polarised, Fig. 5.6. The three cores drilled vertically through this sample show fairly similar intensity versus depth patterns. The natural intensity tends to increase as one proceeds down each core. However, towards the bottom specimen of each of the two cores 23B and 23C there is a swift decrease of polarisation strength. This possibly suggests the presence of a thin horizontal seam of reversed polarisation running through the base of these cores. Direct measurement of the magnetic pattern of a plane section (23I(a)) cut vertically from this sample about 9 cms. away from these three cores

shows a reversed polarisation along its lower surface (Fig. 6.3 Chapter 6).

Rock sample 29, collected at the western extreme of the grit is also generally normally magnetised (Fig. 5.7) Again, as for rock sample 23, there is a tendency for the intensity to increase as one proceeds down through the cores drilled vertically through the sample. A reversed polarisation running along the top surface of this sample is possibly indicated. This is found later in Chapter 6 in a vertical section 29E(a) cut from the same rock sample (Fig. 6.3).

It is concluded that for 3 of the rock samples considered, i.e., rock samples 6, 23 and 29 (Figs. 5.3, 5.6 and 5.7 respectively) and possibly rock samples 17 and 5 (Figs. 5.1 and 5.2) normal and reversed polarisations form approximately horizontal layers within each sample and are not distributed at random. The general intensity versus depth pattern observed in any one of these blocks of rock might possibly extend, with modifications, over horizontal distances of a few feet of the horizon of grit, but probably do not extend over distances of the order of miles between different exposures. However, the intensity versus depth patterns of cores drilled vertically from rock samples 21 and 22 show little similarity to one another. This might possibly indicate that there is no definite spacial distribution between normal and reversed parts within these two blocks. It was decided to investigate more thoroughly one of these blocks. Rock sample 22 was chosen for this investigation.

As many cores of diamter 2.2 cms. as possible were drilled vertically out of block 22, and these cores sliced into thin discs (specimens). The positions of the cores with respect to the block, and the positions of each specimen with respect to the top of the core from which it was cut were carefully recorded. The top surface of block 22 was not plane and the distance between the top of each core and a fixed plane (at a fixed height) was measured by sliding a bridge over the top of the oriented block. Hence the position of each specimen with respect to a fixed, but arbitrary horizontal level was known.

The inclination and declination of 16 specimens previously drilled from this rock sample had already been accurately measured. Their directions were closely grouped into either normal or reversed directions having dips of about $\pm$ 65°. For the present purpose it was necessary to know only the sense of the polarisation of each specimen and to have some measure of its strength if possible. To save time it was therefore decided to measure only the vertical component of the natural polarisation of each specimen on the assumption that the majority were magnetised at about 20° or 30° to the vertical.

The experimental procedure consisted of placing the specimen under the lower magnet of an astatic magnetometer at a distance roughly equal to its own diameter and in such a position that its vertical component could be measured by rotating through 180° about an axis

coincident with that of the astatic system. A second value for the vertical component was obtained by turning the specimen through 180° about its own (cylindrical) axis and repeating the procedure. The average of the two was taken to be the vertical component of magnetisation of the specimen. Occasionally the two readings for one specimen were of opposite sign. This was taken to indicate that a reversal was occurring within the specimen. This conclusion need not necessarily follow since it is possible that the geometry of the specimen and the lower magnet might cause this effect when both are close together. However when some of the specimens in which a reversal was suspected were later sliced into two, measurement of the two half specimens in most cases showed that reversals were in fact taking place within the original specimens (described later on in this chapter). Table 3(a) gives the vertical component (I_z) of the natural magnetisation (N.R.M.) of the specimens cut from rock sample 22. When I_z was directed down the specimen was considered normal. I_z up was taken to indicate a reversed specimen. These results are illustrated in Fig. 5.8. The row of cores QPODNCM in situ form a straight line. The row LKJIH in situ also form a straight line about 5 cms. away from and parallel to QPODNCM. Each core is shown in its correct position relative to the opposite line of cores. Similarly the row GFAE in situ forms a line parallel to LKJIH at a distance away of about 5 cms. The normal specimens are left unshaded whilst reversed specimens are shaded.

Table 3 (a)

VERTICAL COMPONENT OF NATURAL REMANENT MAGNETISATION (I_z) FOR SPECIMENS FROM SAMPLE 22

Specimen	Positive Means Down (Normal) I_z (e.m.u/grm)	Specimen	Positive Means Down (Normal) I_z (e.m.u./grm).
22E1	$+4 \times 10^{-6}$	22J1	-55×10^{-6}
22E2	-13×10^{-6}	22J2	-81×10^{-6}
22E3	$+2 \times 10^{-6}$	22J3	$+36 \times 10^{-6}$
22E4	-18×10^{-6}	22J4	-9×10^{-6}
22E5	-16×10^{-6}	22J5	-8×10^{-6}
22E6	-75×10^{-6}	22J6	$+75 \times 10^{-6}$
22F1	-53×10^{-6}	22I1	-21×10^{-6}
22F2	$+85 \times 10^{-6}$	22I2	-35×10^{-6}
22F3	$+10 \times 10^{-6}$	22I3	$+2 \times 10^{-6}$
22F4	-75×10^{-6}	22I4	$+57 \times 10^{-6}$
22F5	$+1 \times 10^{-6}$	22I5	-30×10^{-6}
22G1	-26×10^{-6}	22I6	-12×10^{-6}
22G2	-25×10^{-6}	22I7	$+15 \times 10^{-6}$
22G3	-10×10^{-6}	22K1	-25×10^{-6}
22G4	-9×10^{-6}	22K2	$+36 \times 10^{-6}$
22G5	$+15 \times 10^{-6}$	22K3	-51×10^{-6}
22H1	-28×10^{-6}	22K4	-112×10^{-6}
22H2	$+17 \times 10^{-6}$	22K5	$+35 \times 10^{-6}$
22H3	$+5 \times 10^{-6}$	22K6	-35×10^{-6}
22H4	$+5 \times 10^{-6}$	22L1	-34×10^{-6}
22H5	-32×10^{-6}	22L2	-44×10^{-6}

Continued.....

Table 3 (a) -contd-

Specimen	Positive Means Down (Normal) I_z (e.m.u./grm)	Specimen	Positive Means Down (Normal) I_z (e.m.u./grm)
22L3	$+3 \times 10^{-6}$	22P3	$+9 \times 10^{-6}$
22L4	-14×10^{-6}	22P4	-84×10^{-6}
22L6	$+18 \times 10^{-6}$	22P5	-61×10^{-6}
22M1	-27×10^{-6}	22P6	$+10 \times 10^{-6}$
22M2	-37×10^{-6}	22Q1	$+5 \times 10^{-6}$
22M3	$+3 \times 10^{-6}$	22Q2	$+1 \times 10^{-6}$
22N1	-11×10^{-6}	22Q3	-18×10^{-6}
22N2	-29×10^{-6}	22Q4	-18×10^{-6}
22N3	-4×10^{-6}	22Q5	0 x
22N4	$+52 \times 10^{-6}$	22R1	$+20 \times 10^{-6}$
22N5	-23×10^{-6}	22R2	-17×10^{-6}
2201	$+9 \times 10^{-6}$	22R3	-100×10^{-6}
2202	$+8 \times 10^{-6}$	22R4	0 x
2203	-9×10^{-6}	22R5	$+31 \times 10^{-6}$
2204	0.0 x	22S1	-18×10^{-6}
2205	-75×10^{-6}	22S2	$+20 \times 10^{-6}$
2206	-55×10^{-6}	22S3	-91×10^{-6}
22P1	-8×10^{-6}	22S4	-19×10^{-6}
22P2	-6×10^{-6}		

Table 3 (b)

VERTICAL COMPONENT OF NATURAL REMANENT MAGNETISATION OF HALF SPECIMENS AFTER SLICING.

Specimen	Positive Means Normal. Approximate Value I_z(e.m.u/grm)	Specimen	Positive Means Normal. Approximate Value I_z(e.m.u/grm).
22I1α	-38×10^{-6}	22J6α	$+93 \times 10^{-6}$
22I1β	-10×10^{-6}	22J6β	$+94 \times 10^{-6}$
22I2α	-41×10^{-6}	22H1α	-26×10^{-6}
22I2β	-35×10^{-6}	22H1β	-58×10^{-6}
22I3α	-13×10^{-6}	22H2α	-23×10^{-6}
22I3β	$+24 \times 10^{-6}$	22H2β	$+81 \times 10^{-6}$
22I4α	$+136 \times 10^{-6}$	22H3α	$+31 \times 10^{-6}$
22I4β	$+48 \times 10^{-6}$	22H3β	-2×10^{-6}
22I5α	-70×10^{-6}	22H4α	-35×10^{-6}
22I5β	-12×10^{-6}	22H4β	$+46 \times 10^{-6}$
22I6α	-39×10^{-6}	22H5α	-75×10^{-6}
22I6β	$+14 \times 10^{-6}$	22H5β	-15×10^{-6}
22J1	-89×10^{-6}		
22J2α	-131×10^{-6}		
22J2β	-99×10^{-6}		
22J3α	-16×10^{-6}		
22J3β	$+105 \times 10^{-6}$		
22J4α	$+33 \times 10^{-6}$		
22J4β	-52×10^{-6}		
22J5α	-42×10^{-6}		
22J5β	$+37 \times 10^{-6}$		

CORES FROM ROCK SAMPLE 22 ARRANGED AS IN SITU

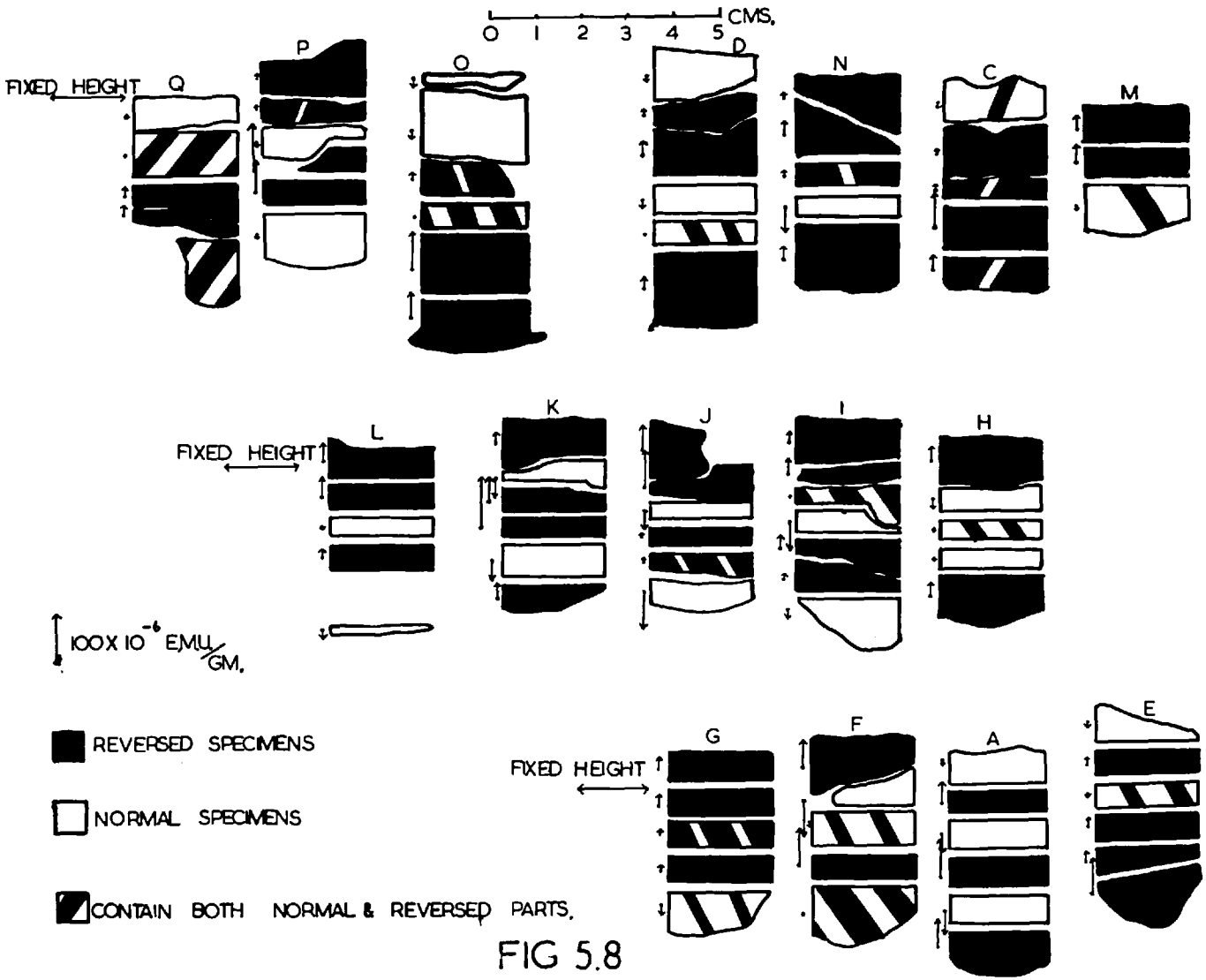


FIG 5.8

SPECIMENS FROM CORES 22J, 22I, 22H, AFTER FURTHER SLICING

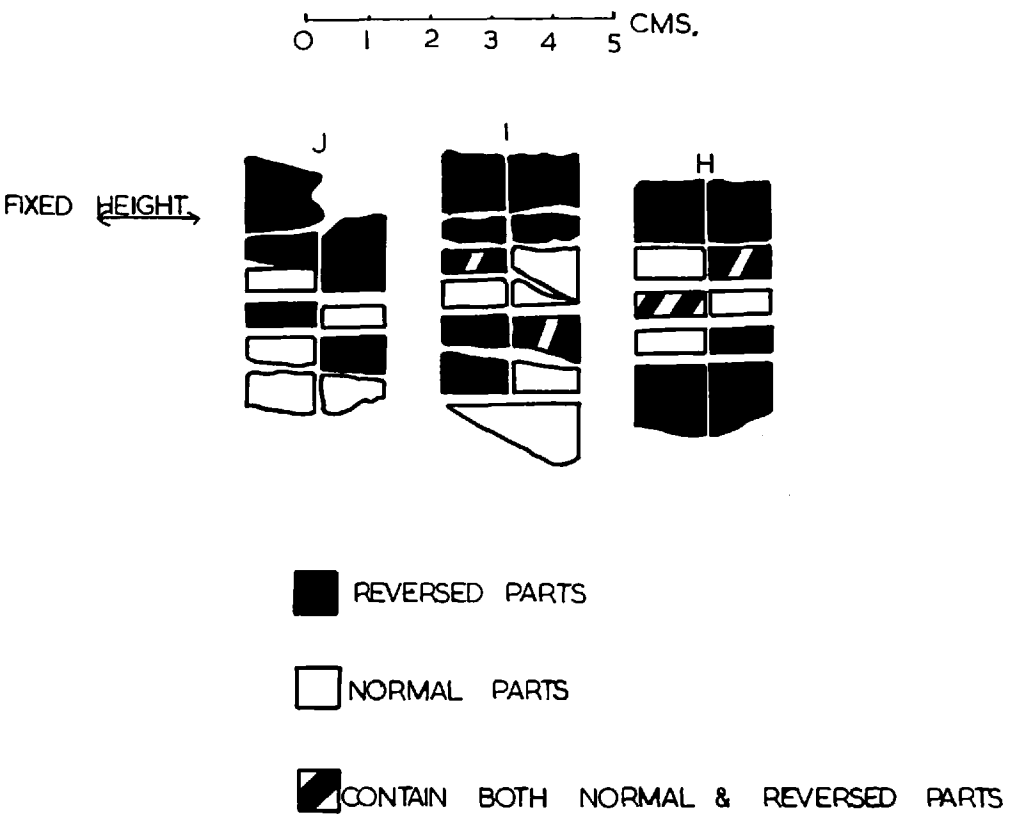


FIG 5.9

A specimen which is suspected of containing both normal and reversed polarisations is partly shaded. The arrow to the left of each specimen indicates by its length and direction the average specific intensity and sense of the vertical component of the natural polarisation.

Although it is possible in some cases to match up normal and reversed parts from core to core one can by no means conclude that normal and reversed parts have any definite spacial distribution within this block. Indeed the results obtained are such that the spacial distribution of normal and reversed parts within the block might possibly be randomly distributed. It was decided to go one step further in this method by cutting each of the cylindrical specimens from the cores J, I and H about a diameter. The vertical components of the natural polarisation of each piece was measured using the astatic magnetometer and the results are given in Table 3(b). (The absolute values of I_z for this particular set of measurements are probably unreliable owing to the irregular shapes of these half specimens which of necessity had to be close to the lower magnet of the astatic magnetometer for measurement: a good calibration was extremely difficult in this case. However the method is probably reliable as regards to determining the sense of the vertical component of these half specimens). Fig. 5.9 illustrates the results. The specimens 22J5 22I3 and 22H3 which were previously suspected of containing both normal and reversed polarisations each give two daughter specimens which contain opposite polarisations: this

justifies the suspicion. However, it is still not possible to trace with any confidence the continuation of normal or reversed parts over the volume represented by the cores 22H, 22I and 22J.

At this stage, the results seemed to indicate a rather strange conclusion. Whereas normal and reversed polarisations formed approximately horizontal layers over some parts of the horizon of the grit, along other parts of the same horizon no definite distribution of normal and reversed parts had been discovered. It was decided to investigate the spacial distribution of a part of rock sample 22 in finer detail using a more discriminating technique. Essentially this consisted of cutting a plane vertical section through from the block and studying its natural magnetic pattern directly at close quarters using a miniature astatic magnetometer system. The details of this method are given in Appendix II, and the results obtained are described in the following Chapter.

Chapter 6

DIRECT MEASUREMENT OF THE NATURAL MAGNETISATION PATTERN

Cores, 2.2 cms. diameter, were drilled vertically right through rock samples 6, 21, 23 and 29. They were each cut along their axis usually in the plane of the magnetic meridian (with respect to the rock sample in situ) to obtain plane vertical north-south sections of grit. Plane north-south vertical sections about 5 cms. squared were directly cut from rock samples 6 and 22. Each plane section was smoothed by polishing with a course abrasive and they are shown in colour in photograph P4. Reference axes were drawn on to these surfaces, one parallel to the vertical direction, and the other parallel to the horizontal direction. They were each in turn mounted on the turntable of a miniature astatic magnetometer (which is described in Appendix II) so that their plane surfaces were horizontal and 2 mms below the lower magnet. In each case the section's vertical direction was maintained normal to the lower magnet. To obtain a measure of the natural remanent magnetisation (N.R.M.) of that particular part of the section just below the lower magnet, the turntable was rotated through 180°, the deflection noted, and then the table brought back to its original position and a check made to ensure the light spot returned to its original position. It is estimated (see Appendix II) that the deflection obtained by turning

the table through 180° is proportional to the vertical component of the N.R.M of that part of the section below the lower magnet. A complete traverse of the section was then carried out by sliding the section horizontally along the turntable in a direction parallel to its vertical axis and taking measurements every 0.25 cms. When a vertical traverse over the full depth of the section had been completed, the section was moved laterally, parallel to its horizontal axis, by 0.5 cms, (the length of the lower magnet) and then another vertical traverse carried out. This procedure was continued until the whole of the plane section had been encompassed. Figs. 6.1 and 6.2 show some of the results obtained. Each of the curves shows how the field 2 mms. above the surface of the section due to the vertical component of the N.R.M. varies along the particular path being traversed. Their rapid variation with depth indicates that the N.R.M. fluctuates swiftly within the section. The sense of the magnetisation of the lower astatic magnetometer magnet was known and consequently the sense of the vertical component of the N.R.M. being measured was simply established. In Figs. 6.1 and 6.2, positive N.R.M.'s are normal parts and negative N.R.M.'s are reversed parts of the sections considered.

Five vertical traverses were required to cover the area of section 6M2 (cut from rock sample 6). The curves obtained were similar to one another, and the two shown in Fig. 6.1 (a) are typical. Since the traverses had been carried out along a vertical path (with respect to the section in situ), the similarity between curves indicated that normal and reversed

VARIATION OF N.R.M. WITH DEPTH FOR SOME PLANE SECTIONS CUT VERTICALLY THROUGH GRIT

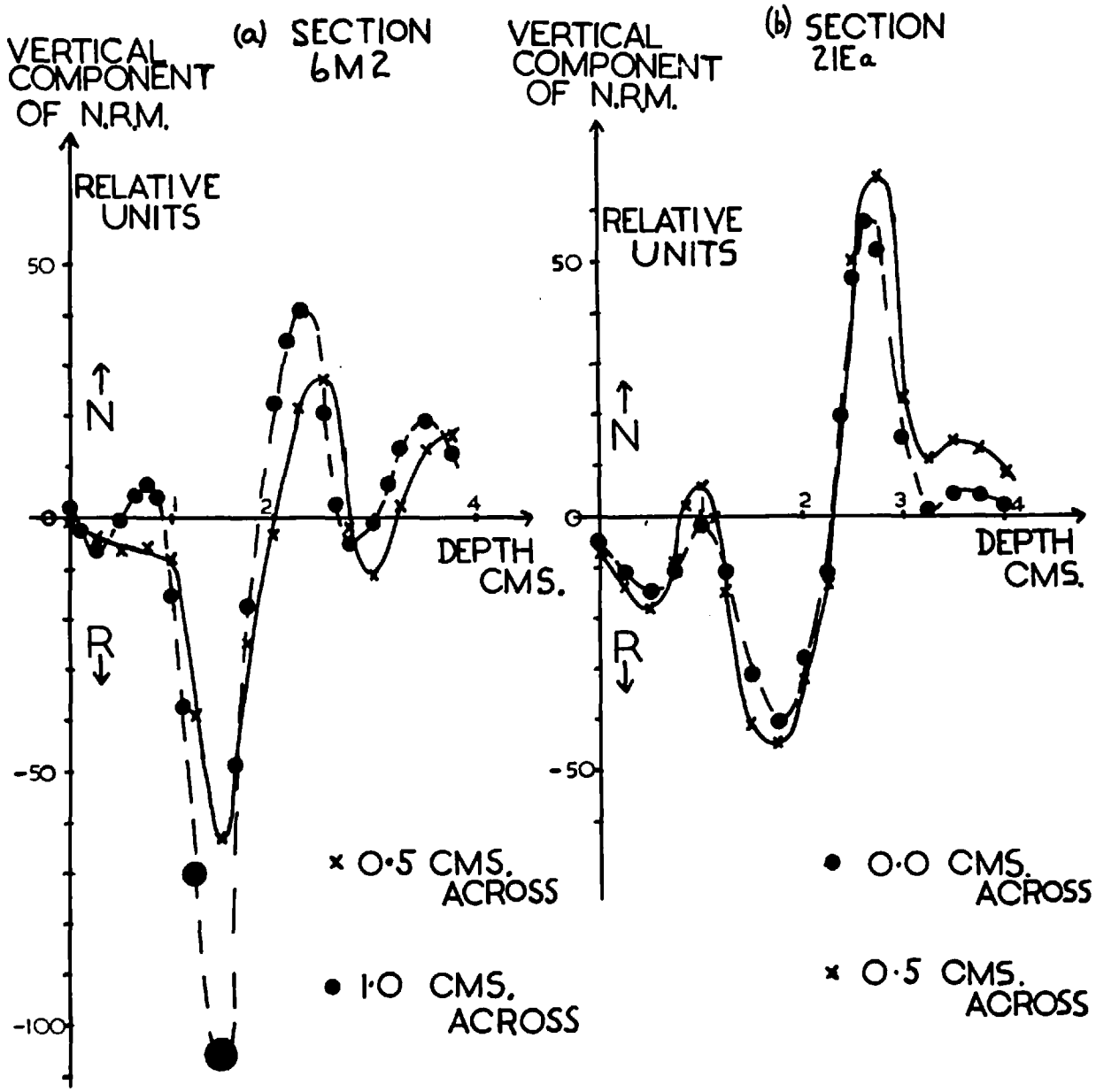


FIG 6.1

VARIATION OF N.R.M. WITH DEPTH FOR SOME PLANE SECTIONS CUT VERTICALLY FROM GRIT

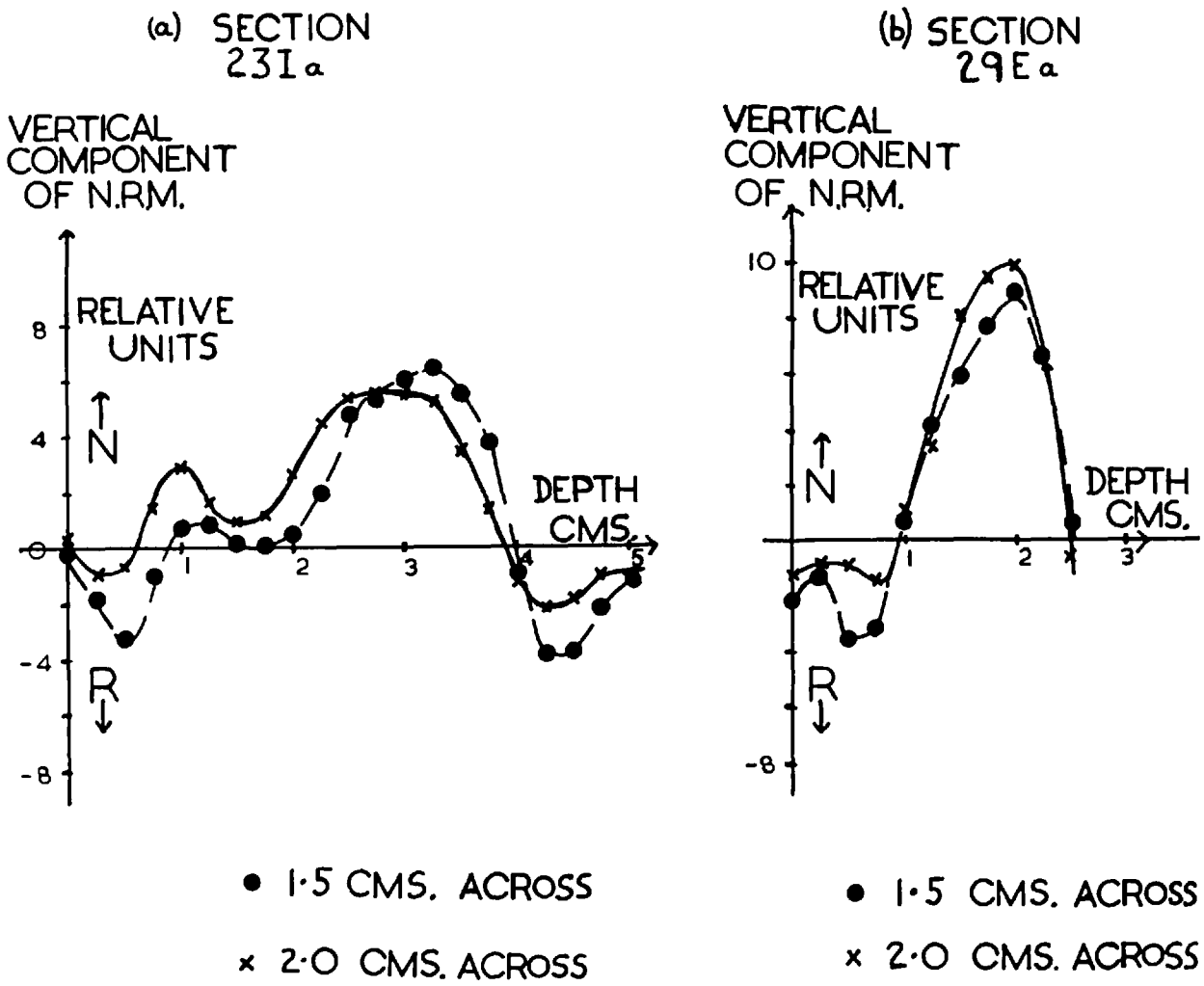


FIG 6.2

parts of this section were arranged in approximately horizontal strips. This agreed with the finding in Chapter 5 that normal and reversed parts of rock sample 6 arranged themselves into approximately horizontal layers. Moreover, the intensity versus depth patterns shown by the two curves in Fig. 6.1(a) are fairly similar to the intensity versus depth patterns given by cores drilled vertically from the same rock sample, (6), which were previously obtained by slicing (compare with Fig. 5.3). Both methods indicate that over much of the volume of this rock sample there is a large reversed polarisation at a depth of about 1.5 to 2 cms., followed by a not quite so large normal polarisation lower down.

The 5 vertical traverses carried out on section 21 H(a) cut from sample 21 also gave rather similar curves of N.R.M. plotted against depth. Two typical curves for traverses carried out 0.5 cms. apart are shown in Fig. 6.1(b). This result was the first indication that normal and reversed parts of this particular sample might have a definite spacial distribution. By the previous method of slicing, the cores from this sample did not appear to have any general intensity versus depth pattern.

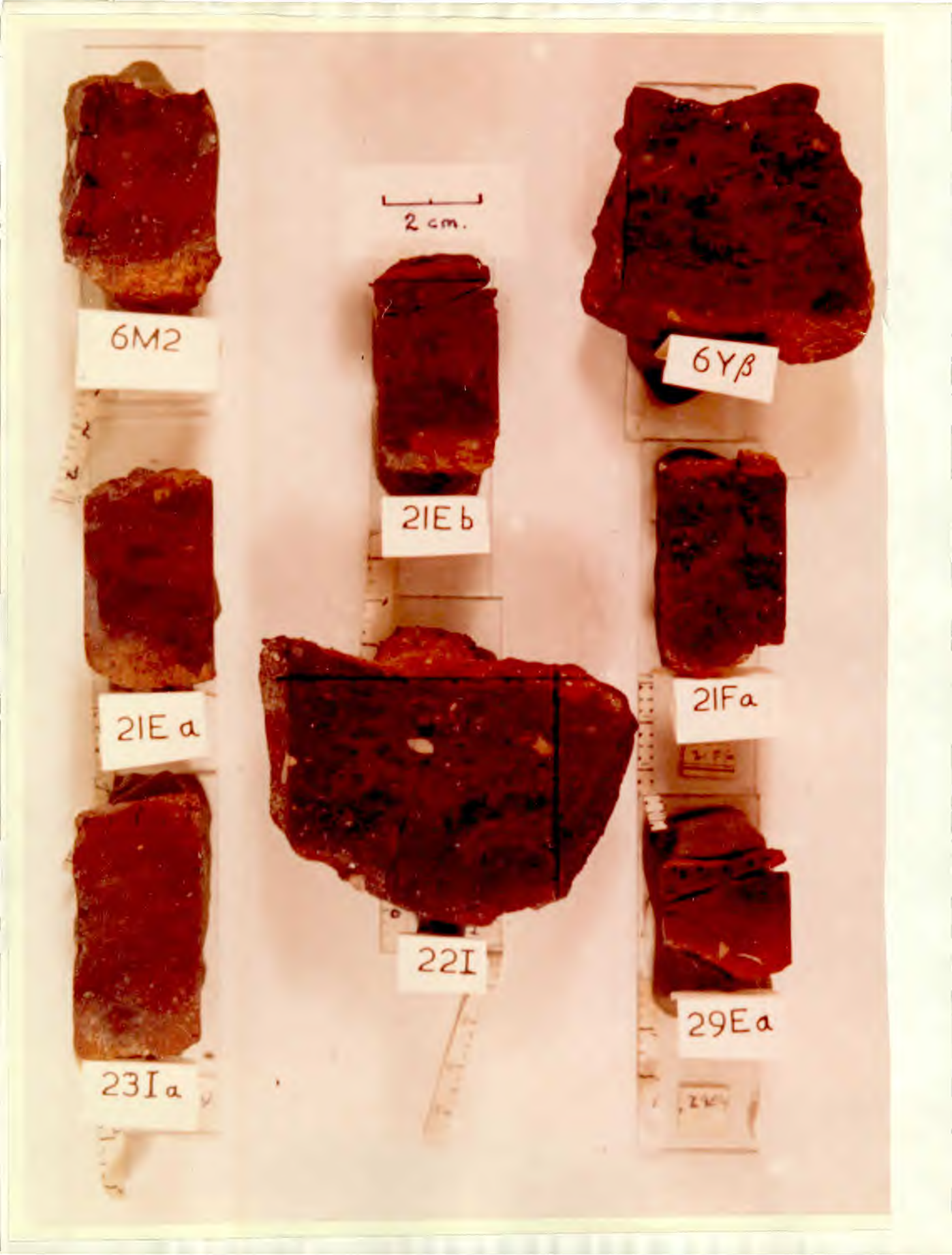
Two typical curves obtained by vertically traversing section 23I(a) (cut from sample 23) are shown in Fig. 6.2(a). Their general pattern should be compared to that obtained by the previous method of slicing cores drilled through this rock sample (Fig. 5.6). There is a fairly good resemblance, both patterns indicating that the N.R.M. increases towards higher normal intensities as one proceeds down through the sample,

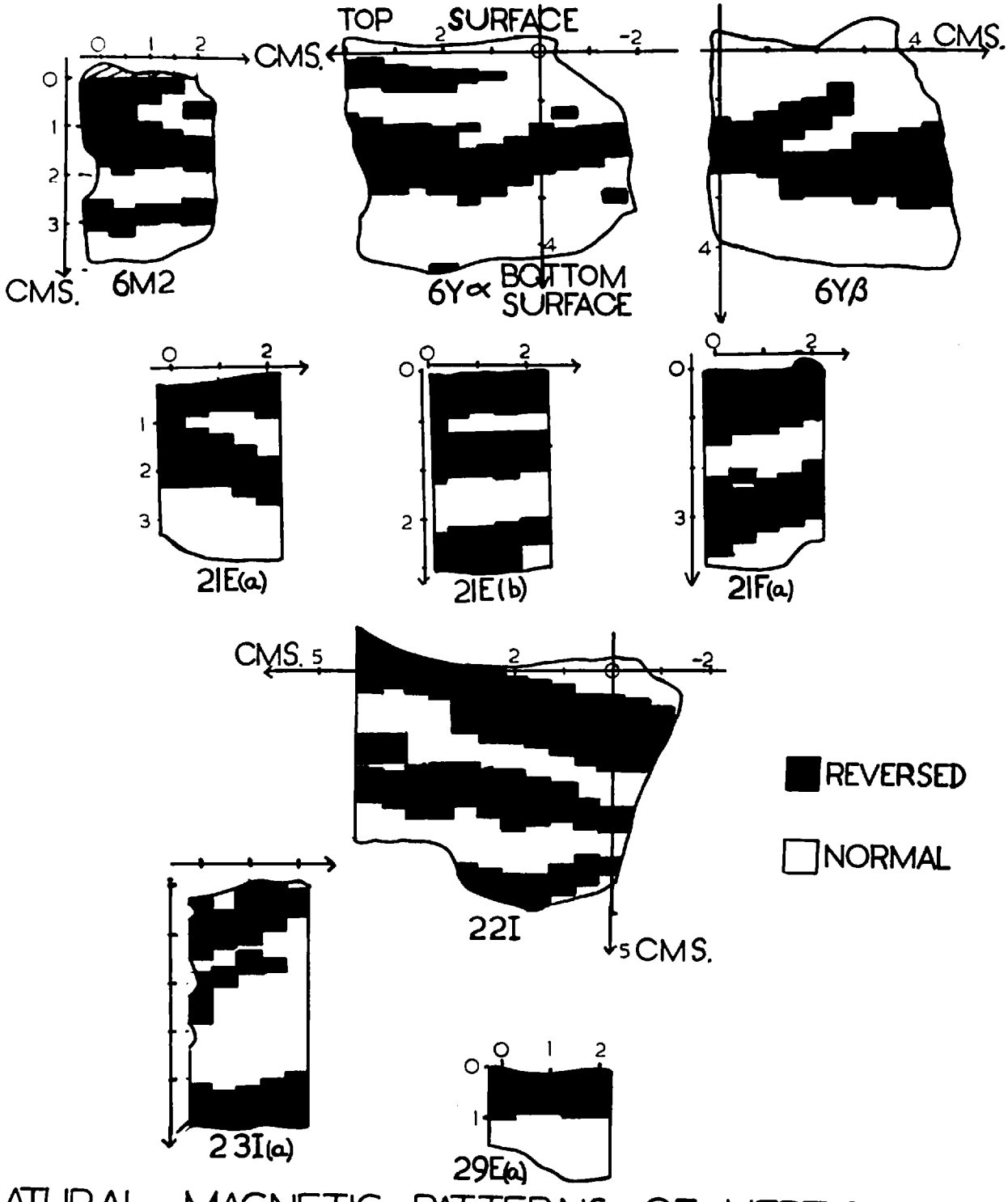
with a sharp decrease towards reversed intensities at its base.

Fig. 6.2(b) shows two typical curves obtained by vertically traversing section 29(a) cut from rock sample 29. Again there is good general agreement between the patterns of intensity versus depth obtained by the two methods (compare with the patterns shown in Fig.5.7). Both methods indicate that the N.R.M. increases towards higher normal values as one proceeds down through rock sample 29, although a sharp decrease towards reversed polarisations at the base of this sample is indicated only by the vertical traversing method.

The agreement between intensity versus depth patterns obtained by the method of traversing and those obtained by slicing cores for each of the rock samples 6, 23, and 29 (in which such a definite pattern had already been established by the latter method), both confirm the presence of a definite intensity versus depth pattern within these samples and also is a good check of the validity of the close range traversing technique for use with the iron grit. This technique was originally intended to investigate the spacial distribution of normal and reversed parts of rock sample 22, in which no definite spacial distribution of normal and reversed parts could be previously detected. A plane vertical section, about 5 cms. squared, had been cut in the plane of the magnetic meridian from this sample, and the whole of its area was investigated by the miniature magnetometer. This required 13 vertical traverses, each 0.5. cms apart. The results are illustrated in

Fig. 6.3 (see section 22I) together with the results obtained by traversing other sections. In this diagram, the natural magnetic patterns of the sections shown are indicated by shading in reversed parts but leaving the normal areas unshaded. For each section the top surface of the grit is shown uppermost. The colour patterns of most of these sections are shown in photograph P.4. Normal and reversed areas of section 22I do indeed arrange themselves in approximately horizontal layers, the top reversed layer being inclined to the horizontal by about 14°, the middle reversed layer by about 9°, and the bottom reversed layer is approximately level. The sections cut from rock sample 21 (sections 21E(a), 21E(b) and 21F(a), fig. 6.3) also have normal and reversed areas arranged into approximately horizontal layers. The previous method of slicing cores which had been drilled vertically through this sample had not detected any particular spacial distribution of normal and reversed parts. Sections 21E(a) and 21E(b) show the plane surfaces obtained by slicing the core 21E and were therefore directly next to each other in situ. The absence of a reversed layer at the base of section 21E(a) which is present in section 21E(b) suggests that there is probably a slanting of the magnetic layers in a direction perpendicular to these plane sections at the base of this core. The form of the layering of normal and reversed parts, whose horizontal pattern was established for the rock samples 6, 23 and 29 in Chapter 5 by the previous method of slicing vertical cores, is clearly revealed in Fig. 6.3 by the sections 6M2,6Yα and 6Yβ (cut from rock sample 6), 23I(a) (cut from rock sample 23) and 29E(a) (rock sample 29). Although both normal and reversed parts do


2 cm.
6M2
21E b
6Yβ
21E a
21F a
22I
29E a
23I a



NATURAL MAGNETIC PATTERNS OF VERTICAL SECTIONS. FIG 6.3

indeed exist in approximately horizontal layers, these layers sometimes branch, and sometimes get thin and die away in mid section.

The fact that a definite ordering of normal and reversed parts had previously remained undetected in rock sample 22 may possibly have been due to the slanting of the magnetic layers. It is perhaps a little surprising however that a definite spacial distribution was previously established for rock samples 6, 23 and 29 by the method of slicing vertical cores. However the intensity versus depth pattern of two of these samples (namely 23 and 29) was relatively simple, both being predominantly normally magnetised and having small fluctuations of the natural intensity. The intensity versus depth pattern of cores from rock sample 6 was rather complex, but the presence of a seam of reversed polarisation of high intensity at a depth of about 1.5 to 2.0 cms. within this sample acted as a "landmark' and simplified the analysis.

The sections shown in Fig. 6.3 were cut from rock samples 6,21, 22, 23 and 29 which were collected from exposures right along the 16 mile horizon of grit. These sections therefore constitute a good cross section of the grit. Although normal and reversed parts are arranged in approximately horizontal layers, an intensity versus depth pattern observed for sections cut from one exposure is not observed again in sections taken from another exposure a few miles away.

Discussion of Part I:

The results obtained so far show that reversals of the natural magnetisation of the iron grit take place over distances of a few mms., usually in a vertical direction. Sometimes 5 complete reversals take place over a depth of less than 5 cms. There are at least three theories which might each account for the observed reversals of the natural magnetisation. They are (1) that the earth's field has reversed at least once, and possibly five times over the period during which the grit has acquired its magnetisation; (2) that the earth's field was in a reversed sense when the grit was magnetised but that some parts of the grit are magnetically unstable. It is possible that since the last reversal of the earth's field to a normal sense, the unstable sections have become remangetised along the direction of the present field, the more stable parts remaining reversely polarised; (3) that the earth's field was in either a normal or a reversed sense when the grit was magnetised. Polarisations of the opposite sense might in this case be self reversed.

These theories are considered in the discussion (Chapter 10) in the light of further results, and will not be rigorously persued at present. The results described so far, however, make it difficult to believe that reversals of the earth's field, the period between which is though to be of the order of 10^6 years, (Cox et al (1963)[10] and Hospers (1954)[9]) can possibly account for the reversals of the natural magnetisation in the grit which are separated by only a few mms. Each of

the theories (2) and (3) were therefore held to be more likely to be true than theory (1). However theory (2) requires that a physical difference exists between normal and reversed parts of the grit, and theory (3) requires that a physical, chemical or petrological difference exists, or used to exist, between normal and reversed parts. Accordingly, it was decided to investigate the physical, chemical and petrological properties of the grit and to search for a significant difference between normal and reversed parts. Since there will, no doubt, be differences in a particular property between any two rocks taken from the same stratum, the search for a significant difference between normal and reversed specimens has to be of a statistical nature and include a large number of individual specimens for each test. The search for a possible physical chemical or petrological difference between normal and reversed parts of the grit is described in Part II of this thesis.

PART II

PHYSICAL, CHEMICAL AND PETROLOGICAL PROPERTIES OF THE IRON GRIT.

Chapter 7

PHYSICAL PROPERTIES

This chapter is mainly concerned with comparing the physical properties of normal and reversed specimens.

1) Directions and scatter of the natural polarisations:

The directions of the natural polarisations have already been studied in Chapter 4, and are shown plotted on a polar diagram in Fig. 4.1(a). They arrange themselves into two groups, one normal and the other reversed. The mean normal direction is; declination ($3^{\circ}\pm7^{\circ}$) east of north, inclination ($68.5^{\circ}\pm 2^{\circ}$) down. The mean reversed direction is; declination ($182^{\circ}\pm6^{\circ}$) east of north, inclination ($69^{\circ}\pm2^{\circ}$) up. These two mean directions are, to within a degree, 180° apart. The spreads of each group about their mean direction are similar.

2) Specific intensities:

Fig. 7.1 is a histogram showing natural intensity plotted against frequency of occurence for each individual specimen, (including those specimens from rock sample 22 whose vertical component of natural magnetisation only was measured). For direct comparison of normal and reversed specific intensities, normal frequencies were plotted on the top half, and reversed frequencies on the lower half of the diagram. The histogram for normal intensities includes 103 specimens, and that for reversed intensities includes 120 specimens. Both histograms show

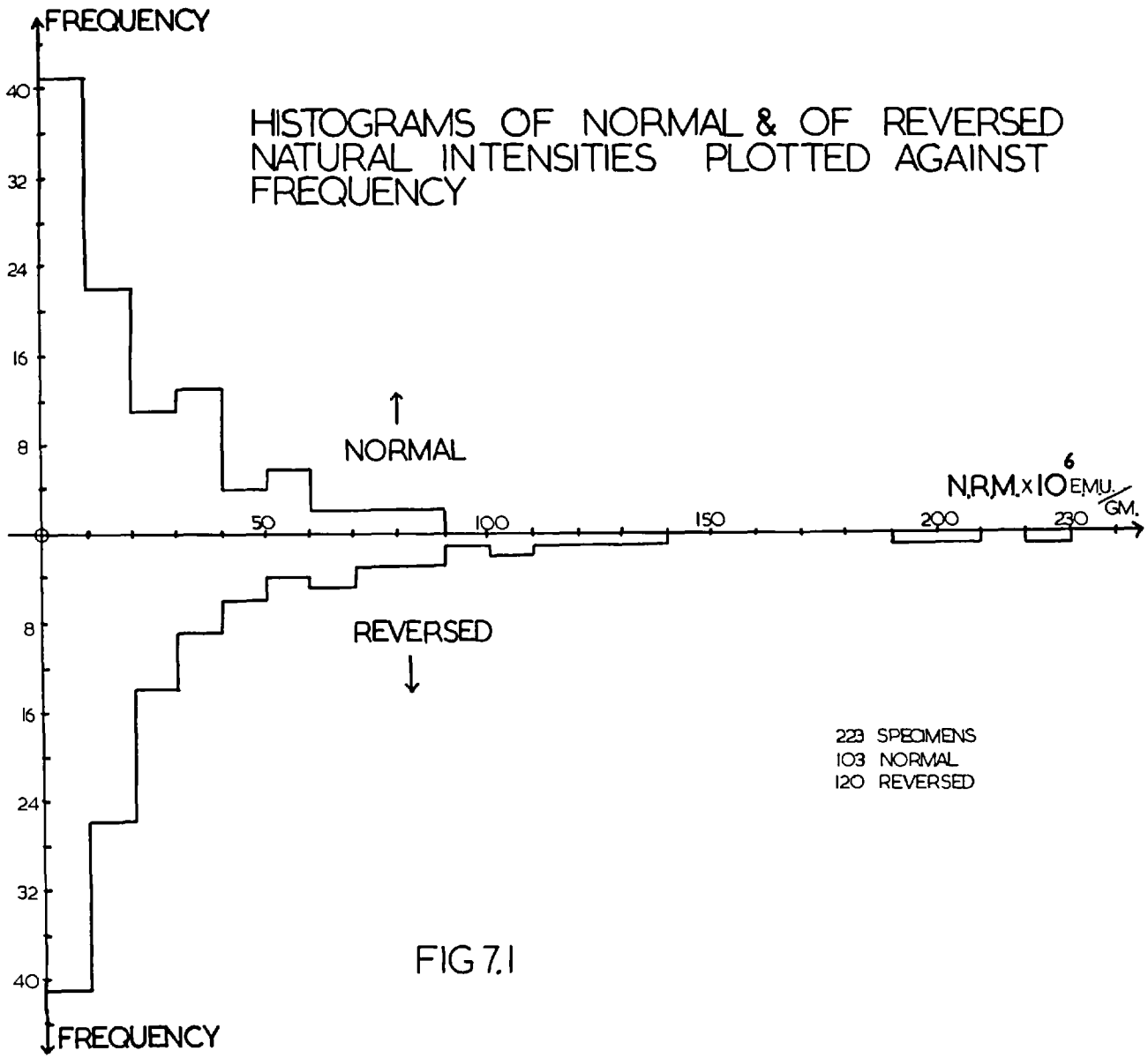

FREQUENCY
40
32
24
16
8
HISTOGRAMS OF NORMAL & OF REVERSED NATURAL INTENSITIES PLOTTED AGAINST FREQUENCY
NORMAL
N.R.M. x 10⁶ E.M.U./GM.
50
100
150
200
230
REVERSED
8
16
24
32
40
FREQUENCY
223 SPECIMENS
103 NORMAL
120 REVERSED

FIG 7.1

a similar distribution of intensities up to 90 x 10^{-6} e.m.u./grm, but no normal intensity was found to exceed this value whereas 8% of the reversed polarisations were greater than 90 x 10^{-6} e.m.u/grm, some ranging as high as 230 x 10^{-6} e.m.u./grm. This is possibly a difference between normal and reversed specimens and its significance must be considered. The mean value of the normal intensities is 22 x 10^{-6} e.m.u./grm and has a standard deviation of 2 x 10^{-6} e.m.u./grm. The mean value of the reversed intensities is 32 x 10^{-6} e.m.u./grm with a standard deviation of 4 x 10^{-6} e.m.u./grm. Discounting all intensities above 90 x 10^{-6} e.m.u./grm the mean normal value remains (22 $\pm$ 2) x 10^{-6} e.m.u./grm but the mean reversed value now becomes (23 $\pm$ 2) x 10^{-6} e.m.u/grm. It therefore seems reasonable to suppose that the possible difference between normal and reversed specimens is shown by the 8% reversed polarisations above 90 x 10^{-6} e.m.u./grm. This result might be of considerable significance if each of these reversed polarisations were independent of one and other. However this is not strictly the case. In Part I of this thesis the experimental results showed that normal and reversed polarisations within the grit usually consisted of approximately horizontal layers whose general pattern was maintained over distances of the order of the dimensions of a block of the grit (one foot). Over distances greater than this the general pattern, if still existing, appeared to have considerably changed and no general pattern appeared to exist over distances between exposures (of the order of miles).

If it is reasonably assumed on the basis of this evidence, (1) that within any one block normal and reversed polarisations keep to a definite pattern and exist in approximately horizontal layers and (2) that any such definite pattern completely breaks down over distances of a few feet and a completely new and independent pattern is formed, then the true significance of the difference observed in Fig. 7.1 will not be as great as it seems. For example, three of the nine reversed intensities above 90 x 10^{-6} e.m.u./grm shown in Fig. 7.1 represent specimens each cut at a depth of 1.5 to 2.5 cms. in rock sample 6 where the presence of a continuous horizontal seam of high reversed polarisation has been established in Part I. Another two were cut from rock sample 5 (which was collected 5 feet to the east of rock sample 6) at a depth of 2.5 to 3.5 cms. It appears then that 3, and possibly 5 of the nine reversed intensities above 90 x 10^{-6} e.m.u./grm represent but one seam of polarisation which possibly extends for but a few feet of the 16 mile horizon of the grit. The other reversed polarisations above 90 x 10^{-6} e.m.u./grm arise, one from rock sample 21, two from rock sample 22 (collected near to sample 21 at the same exposure) and one from rock sample 26. It is therefore estimated on the basis of assumptions (1) and (2) that the nine reversed intensities above 90 x 10^{-6} e.m.u./grm shown in Fig. 7.1 are likely to represent more than 3 but less than 6 individual seams of high reversed polarisations each of which possibly exist for no more than a few feet of the 16 mile horizon of grit.

Furthermore, the standard deviations of the mean values of the specific natural intensities for normal and reversed specimens were calculated by dividing the standard deviation of each distribution (Fig. 7.1) by $\sqrt{N}$ where N is the number of individual specimens in each distribution. However, assumptions (1) and (2) state that for any one rock sample, the specimen polarisation values are not completely independent, and so to obtain the standard deviation of the mean of each distribution it now becomes reasonable to divide the standard deviation of each distribution by $\sqrt{n}$ instead of $\sqrt{N}$, where n is the total number of rock samples (blocks) used. In this case, the mean normal specific intensity and standard deviation is $(22 \pm 7) \times 10^{-6}$ e.m.u./grm, and the mean reversed specific intensity and standard deviations is (32 ± 14) e.m.u./grm. Within the limits of their standard deviations, the difference between mean normal and mean reversed specific intensities is not significant.

Summing up, the apparent tendency for specimens with high natural polarisations greater than 90×10^{-6} e.m.u./grm. to be reversed might possibly be significant, but is not significant to the extent indicated by Fig. 7.1.

Of 223 specimens shown in the histogram of Fig.7.1, 46% are normal and the remaining 54% reversed. Intermediate directions were not considered for this histogram.

3) Colour Estimates.

Coloured photographs of a number of sections are shown in photograph P.4. Their magnetic patterns, obtained by the method of traversing, are shown in Fig. 6.3. The sections show quartz pebbles and sand grains set in a red matrix which is occasionally speckled with darker areas giving a mottled appearance. Sometimes a vein of the brighter red cement interupts and runs for a few cms. through the general pattern.

Careful inspection of the sections reveal that these veins often run, (as do the natural magnetic layers), in an approximately horizontal sense, although this is not always the case. Accordingly it was decided to investigate a possible correlation between the magnetic pattern and colour pattern of some plane sections. For example, section 6M2 (see photograph P.4) showed two rather thick red veins of cement, each of about the same redness, running in an approximately horizontal sense, one at a depth of 1.3 cms, and the other at 2.2 cms. depth. However on looking at the magnetic pattern for section 6M2, the horizontal strip at a depth of 1.3 cms. is reversely polarised, whilst the horizontal strip at 2.2. cms. depth is normally polarised. Two veins of the same colour and less than a cm. apart within the same section were thus measured to be oppositely polarised. This result suggests that there is no colour correlation between normal and reversed parts of the grit. However, a more extensive colour test was

carried out. Two sections, 6M2 and 21E(a) were chosen. A square 0.5 cms.^{2} was cut in a piece of paper. Using the same section reference axes used for the magnetic traverse experiments (described in the last chapter), areas of the section 0.5 cms. square were systematically observed using the 'window' of the paper. The redness of each area was estimated by eye and recorded as a percentage, 100% being the redness of a bright red reference vein in another section. The natural remanent magnetisation of each area (obtained from the magnetic traverse experiments described in the last chapter) was then plotted against its redness.

In this plot, (Fig. 7.2) positive N.R.M.'s denote normally polarised areas, and negative N.R.M.'s are reversely polarised areas. There is no correlation between redness and the natural intensity.

Previous colour tests, using whole specimens had also previously been carried out. For these tests the general redness of each specimen, as estimated by eye, was plotted against its measured polarisation. These tests also failed to show any colour correlation between normal and reversed specimens.

4) A.C. Demagnetisation:

Nine virgin specimens, 4 normal and 5 reversed were subjected to alternating field demagnetisation in the usual manner. For alternating fields with peak values up to 750 Oe., the natural polarisations were not observed to undergo any consistent change of direction. Their strengths

N.R.M. OF AREA 0·5 CMS. SQUARE PLOTTED AGAINST ESTIMATED REDNESS

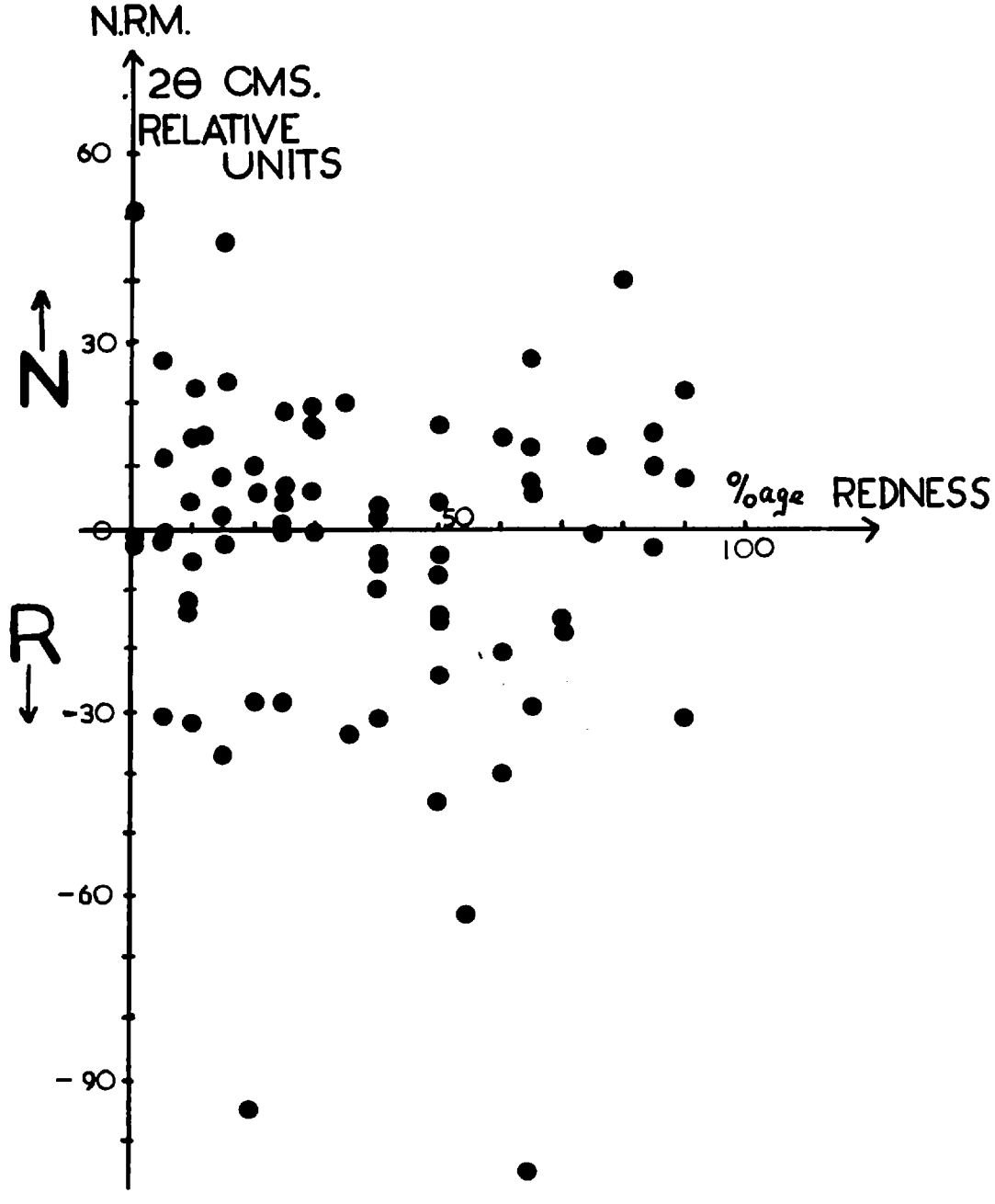


FIG 7.2

ALTERNATING FIELD DEMAGNETISATION APPLIED TO N.R.M.

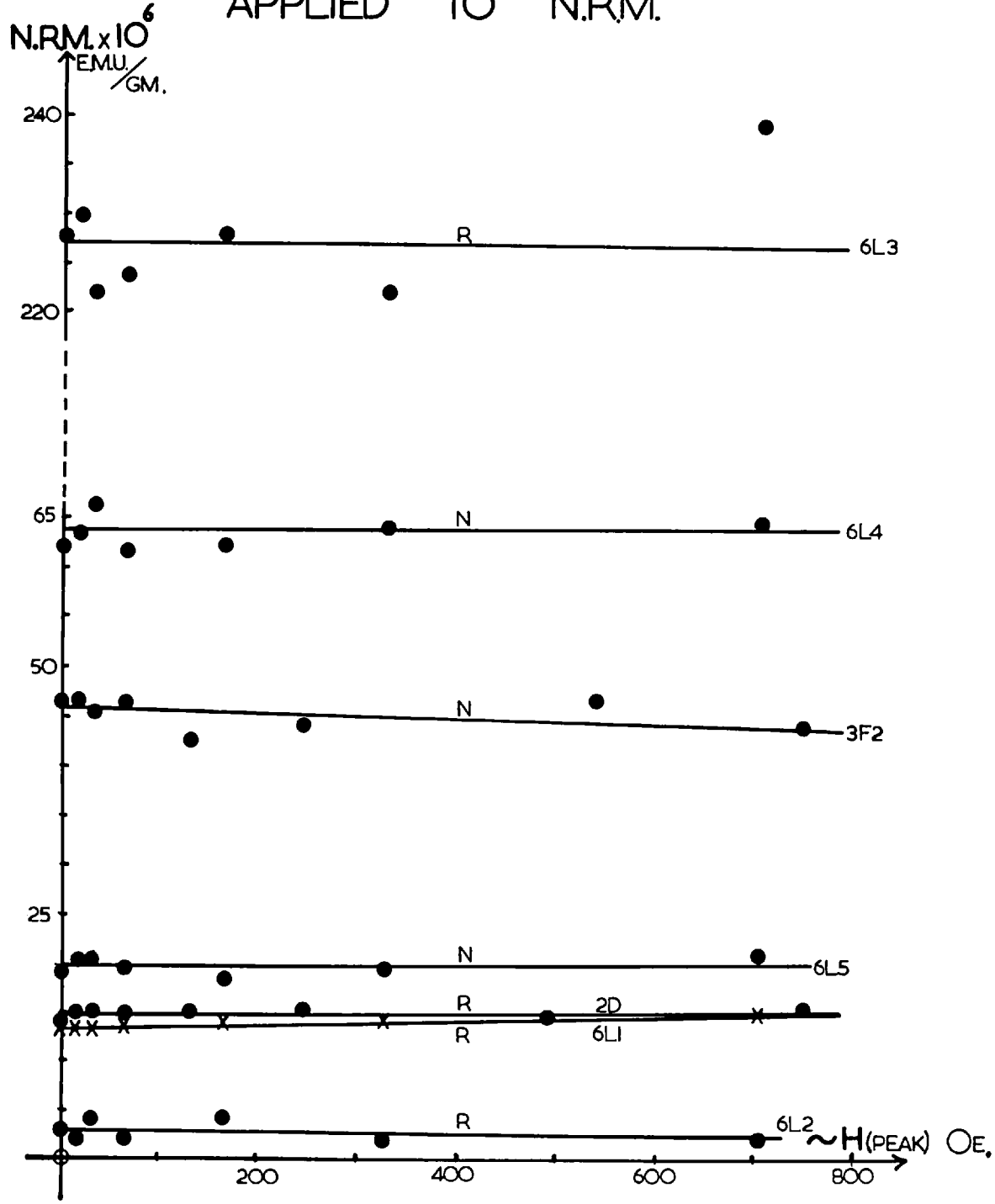


FIG 7.3

ALTERNATING FIELD DEMAGNETISATION APPLIED TO HIGH FIELD REMANENCES

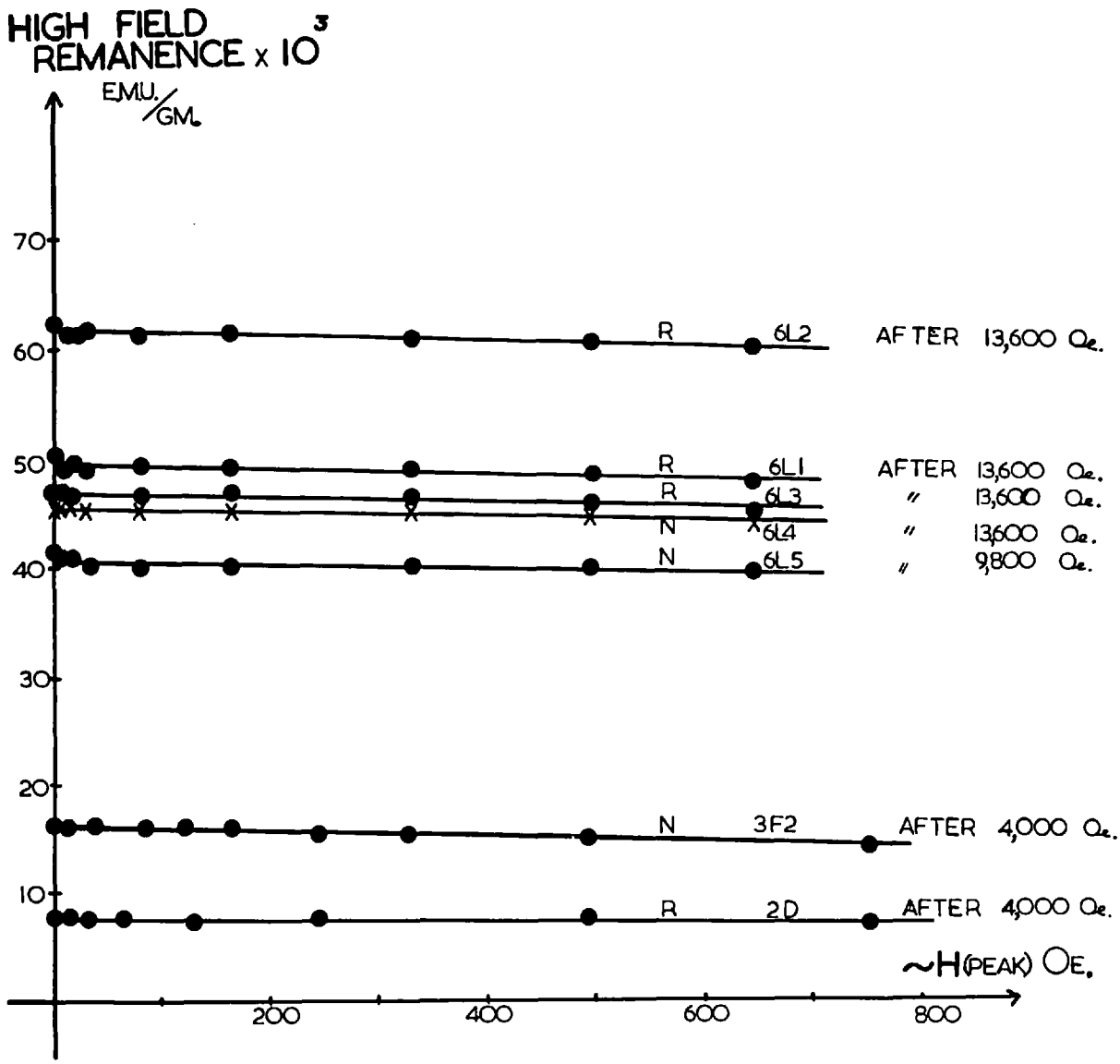


FIG 7.4

remained fairly constant (Fig. 7.3). Some of these specimens were then placed into steady high fields (4 to 14 k. Oe) and the remanence acquired was subjected to alternating field demagnetisation. The effect of alternating fields up to 750 Oe is to reduce these remanences by only a few percent (Fig. 7.4). The reluctance of the N.R.M. of the grit to be demagnetised by rather high demagnetising fields is also shared by the N.R.M. of pale red Triassic sandstones, and Blackett[16](1956) has described how alternating fields of up to 1000 Oe is not sufficient to to reduce the magnetisation of a saturated specimen of hematite by more than a few percent; for an artificial magnetite specimen the saturation magnetisation is demagnetised rapdily and disappears for alternating demagnetisation fields of 500 Oe.

Both normal and reversed natural polarisations together with their remanences in high steady fields react similarly to A.C. demagnetisation which has little effect.

5. Thermal demagnetisation of Natural Polarisations:

Several virgin specimens were heated in a non magnetic furnace directly below an astatic magnetometer. The variation of the natural polarisation vector with temperature was observed in each case in two dimensions (the vertical direction, and that horizontal direction in which the polarisation component was greatest). Fig. 7.5 illustrates vectorially how a typically normal and a typically reversed polarisation both reduce to zero when their curie temperature is reached. Neither

TWO-DIMENSIONAL VECTOR DIAGRAM SHOWING THERMAL DEMAGNETISATION OF A NORMAL & A REVERSED SPECIMEN.

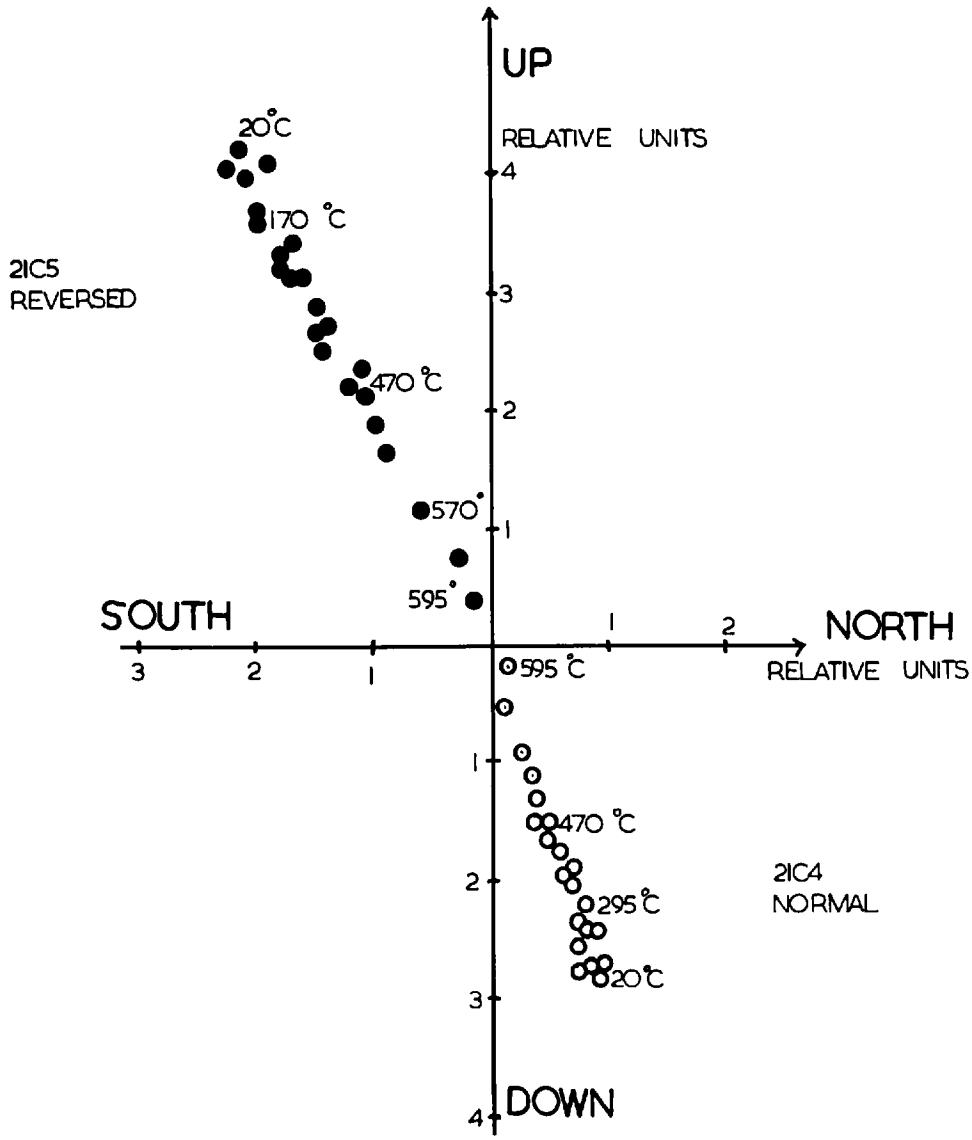


FIG 7.5

THERMAL DEMAGNETISATION

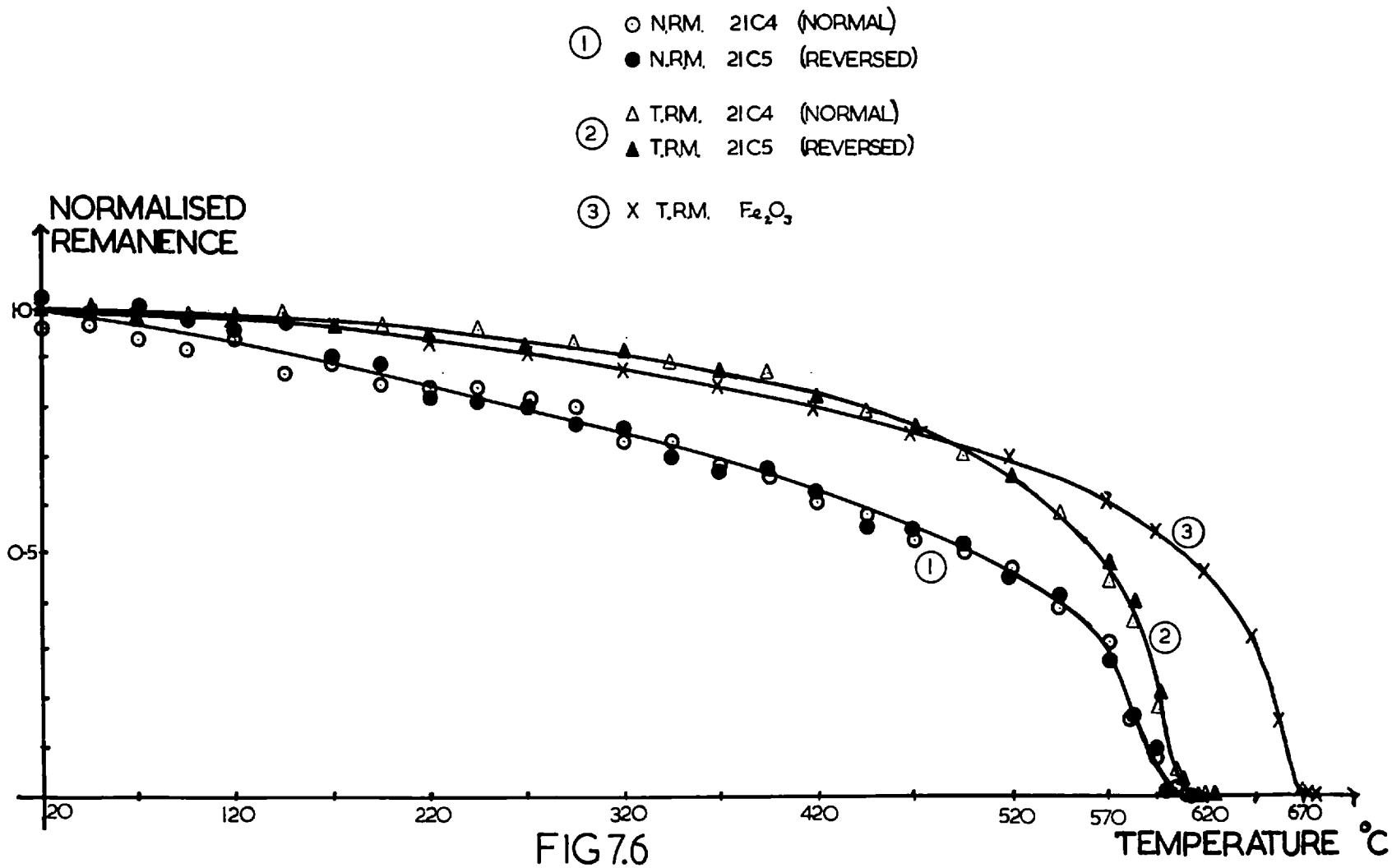


FIG 7.6

CURIE TEMPERATURE -v- N.R.M.

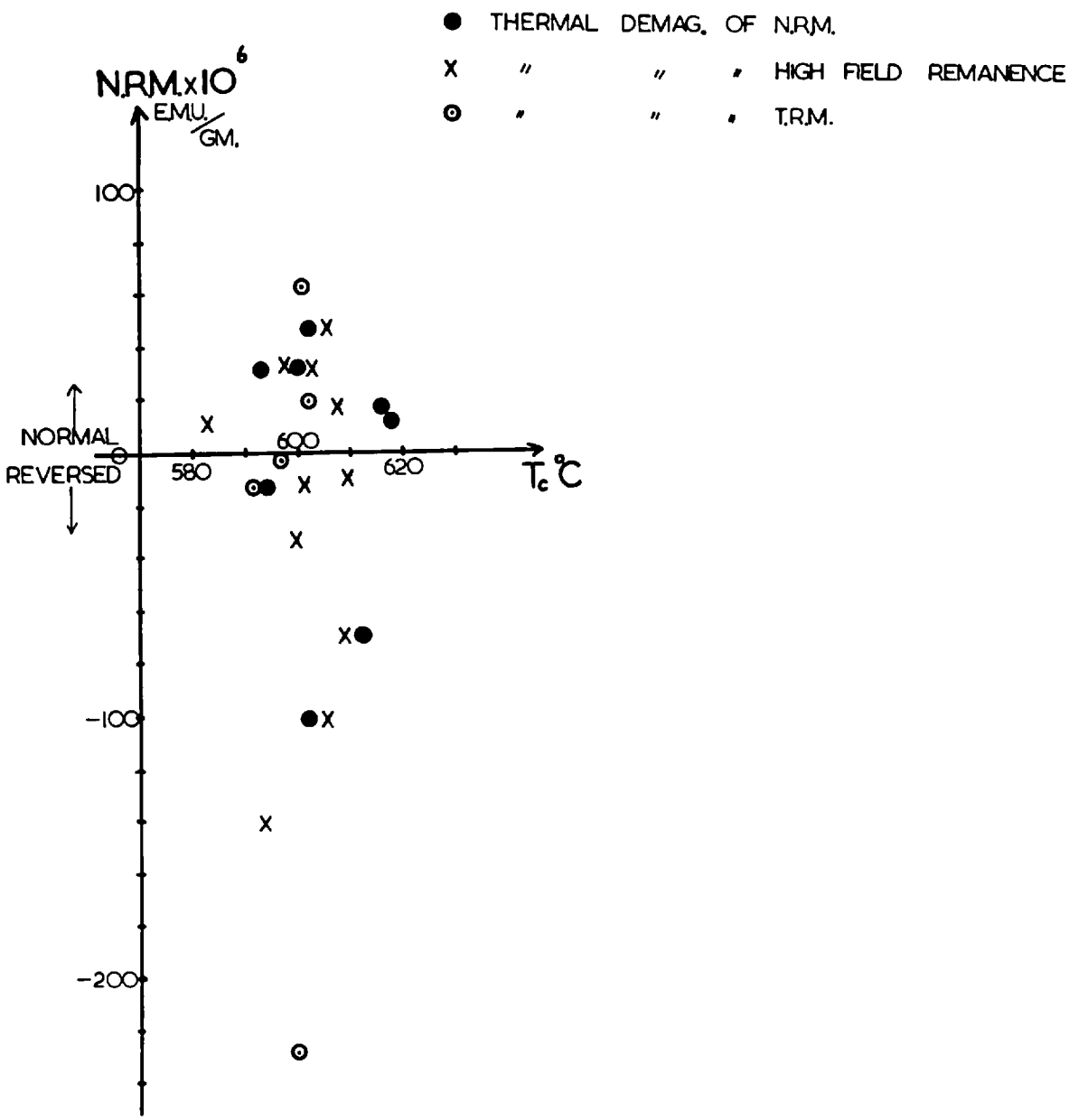


FIG 7.7

show any notable change in direction during thermal demagnetisation. Curve (1) of Fig. 7.6 shows how the magnitude of both these vectors varies with temperature. They are normalised and one curve is adequate to describe both. In each case half the natural polarisation is stable for temperatures up to 470°C and one third remains to a temperature only 50°C below its Curie point. There is only one curie point at (602° ± 5°)C which indicates that the natural polarisation is carried by one magnetic component only. No sign of a partial reversal is observed.

6) Thermal demagnetisation of T.R.M.

A number of specimens were heated to about 640°C and then cooled in a field of 0.5 Oe. The thermo-remanent magnetisations (T.R.M.'s) produced were usually an order of magnitude greater than the average N.R.M. Curve (2) of Fig. 7.6. shows how the magnitude of two of these T.R.M.'s vary with temperature on heating in zero field. One of these T.R.M.'s was acquired in a specimen which originally had a normal N.R.M. and the other in a specimen which originally had a reversed N.R.M. Both T.R.M.'s were directed in the same sense as the magnetising field. Both are normalised and one curve is adequate to describe them. The shape of this curve is rather rectangular and it sweeps quickly down to its only curie point at (606±5) °C. No partial reversal is indicated.

Curve (3) of Fig. 7.6 represents the thermal demagnetisation of a

specimen of pure, finely divided hematite which had acquired a T.R.M. by cooling in a field of 0.5. Oe from 720°C. This experiment was carried out on the same instrument and under similar conditions to the previous experiments (curves (1) and (2) of this diagram). The thermal demagnetisation curve of the T.R.M. of pure hematite (curve 3) is normalised and is rather similar to that of the T.R.M. of normal and reversed specimens (curve (2)). It has a curie temperature of 660°C.

The general shape of the thermal demagnetisation curve for the N.R.M.'s shown in Fig. 7.6. (Curve 1) is less rectangular, but fairly similar to the shape of the thermal demagnetisation curve of the T.R.M.'s for the same two specimens (Curve (2)). Haigh (1958)[17] has produced experimental evidence and considered theoretical arguments both indicating that the thermal stability of a chemically acquired magnetisation resembles, to a considerable degree that of a thermoremanent magnetisation for the same magnetic mineral. Haigh compares the thermal demagnetisation curve of a magnetisation acquired chemically (C.R.M.) with that of a magnetisation acquired thermally (T.R.M.). The general shape of both are rather similar but the thermal demagnetisation curve of the C.R.M. is less rectangular than that of the T.R.M. In the case of the grit the general similarity between curves (1) and (2) of Fig. 7.6. makes it possible that the natural polarisation of the grit might have been acquired by thermal processes or by chemical processes.

Curves (1) and (2) of Fig. 7.6. are typical of several thermal demagnetisation curves of the natural polarisations and T.R.M.'s (acquired in 0.5 Oe) carried out in zero field on normal and reversed specimens. The rather precise similarity between the heating curves of normal and reversed specimens is indeed impressive.

7) Curie Temperature.

Thermal demagnetisations of some natural polarisations, of T.R.M.'s (acquired in 0.5 Oe) and of high field remanences (produced in previously unheated specimens in fields from between 10,000 to 15,000 Oe). had been previously carried out under similar conditions on the same instrument. The curie temperatures shown by each of these curves was plotted against the corresponding specimen N.R.M. (Fig. 7.7). There is a large spread of curie temperatures which vary from 580°C to 620°C. It was noticed that this large spread arose because specimens collected from sites a few miles apart had considerably different curie temperatures. On the contrary specimens cut from the same core and often adjacent to one and other, as for example 21C4 and 21C5 (Fig. 7.6), gave identical curie temperatures even though their N.R.M.'s were oppositely polarised. Normal and reversed specimens show similar distributions of curie temperatures.

The mean value of the curie temperatures shown in Fig.7.7. is 600°C. The curie temperature of a specimen of pure hematite obtained under similar conditions on the same instrument was 660°C. (Fig. 7.6 curve (3)).

The text book value for the curie temperature of hematite is 685°C. It is therefore considered likely that there was a systematic error in the measurement of temperature on the instrument used. The average curie temperature of the grit is therefore probably higher than 600°C and is possibly about 625°C.

8) Thermo-remanent magnetisations (T.R.M.'s)

A number of specimens were heated to about 640°C and cooled to room temperature in a field of 0.5 Oe. The T.R.M.'s acquired were measured on an astatic magnetometer. In Fig. 7.8 each T.R.M. is plotted against the corresponding N.R.M. In general the T.R.M.'s are less than 1000×10^{-6} e.m.u./grm although 4 out of 33 specimens have T.R.M.'s about 6 times this value. Normal andreversed specimens have similar distributions of T.R.M.'s.

The ratio, $I_{NAT}/I_{T.R.M}$ (0.5 Oe) was calculated for each specimen. It was less than unity in all cases but one, in which case the value was unity. Its average value for both normal and reversed specimens was about 0.1, and there was no correlation between this ratio and the N.R.M. (Fig. 7.9).

9) High Field Remanences:

Paragraph 4 describes how alternating fields of up to 750 Oe have little alternating demagnetising effect on either the natural or high field remanences. It was decided to investigate the effects of fields up to 30,000 Oe on the grit. Five virgin specimens, all cut from the same core, (21B)

N.R.M. PLOTTED AGAINST T.R.M. ($0{\cdot}5\,Q_e$)

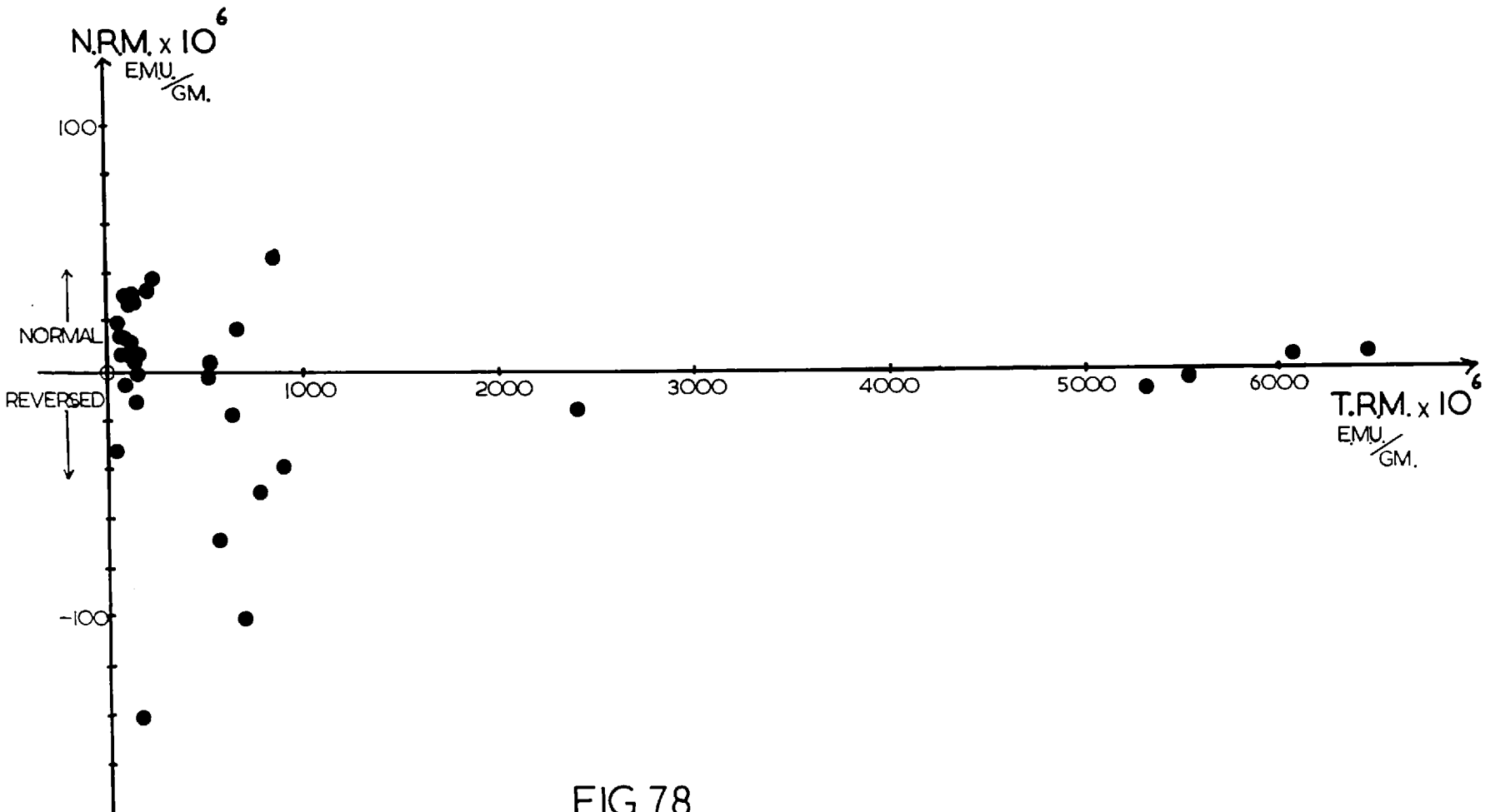


FIG 7.8

THE RATIO N.R.M./T.R.M. PLOTTED AGAINST N.R.M.

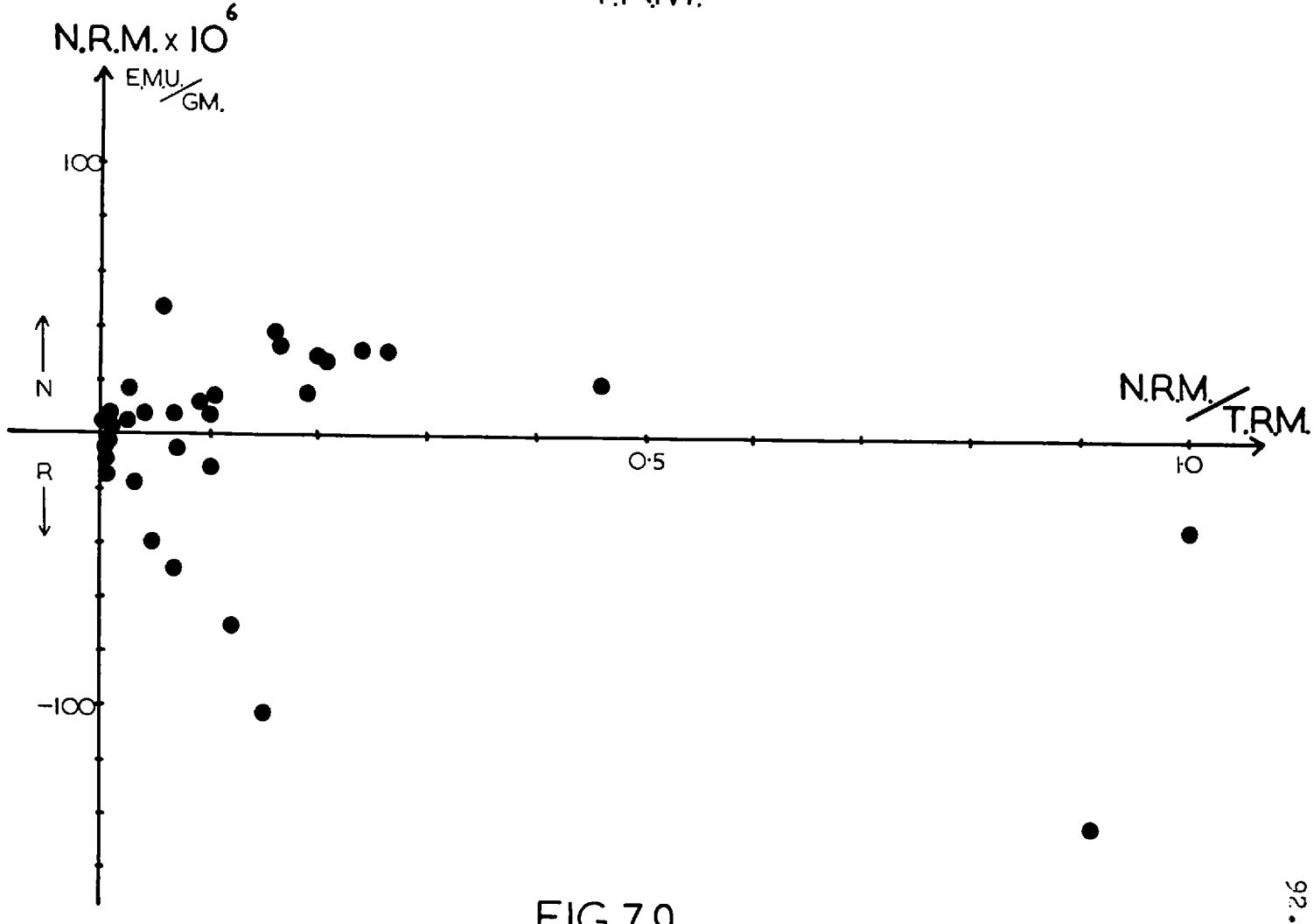


FIG 7.9

were chosen. Two of these specimens were reversed and three normal. They were each placed into a field of about 4,000 Oe directed along their axis, taken out, and the remanence acquired was measured. They were then each placed in a field of about 8,000 Oe directed in the same sense as before, taken out and the increased remanence measured. This procedure was repeated for fields up to nearly 30,000 Oe., and the results obtained are illustrated in the top right quadrant of Fig. 7.10. In this diagram, remanence is plotted against magnetising field. Each of these specimens was then placed into a field of 4,000 O_e. directed in the opposite sense to that of previous. The specimen was removed from the field and its altered remanence measured. This procedure was repeated for increasing reversed fields of up to nearly 30,000 Oe, and the variation of remanence with reversed field for each specimen is shown on the left side of Fig. 7.10. The value of the reversed field required to bring the remanence to zero is a measure of the remanent coercive force of the particular specimen. The horizontal dotted line in the top right quadrant of Fig. 7.10 is a consequence of the fact that the remanence produced by a high field is unaltered by fields of lower value directed in the same sense.

The remanence of these specimens is not completely saturated for magnetising fields up to 30,000 Oe, and some would possibly require fields of about 40,000 Oe or over to reach saturation remanence.

REMANENT HYSTERESIS CURVES

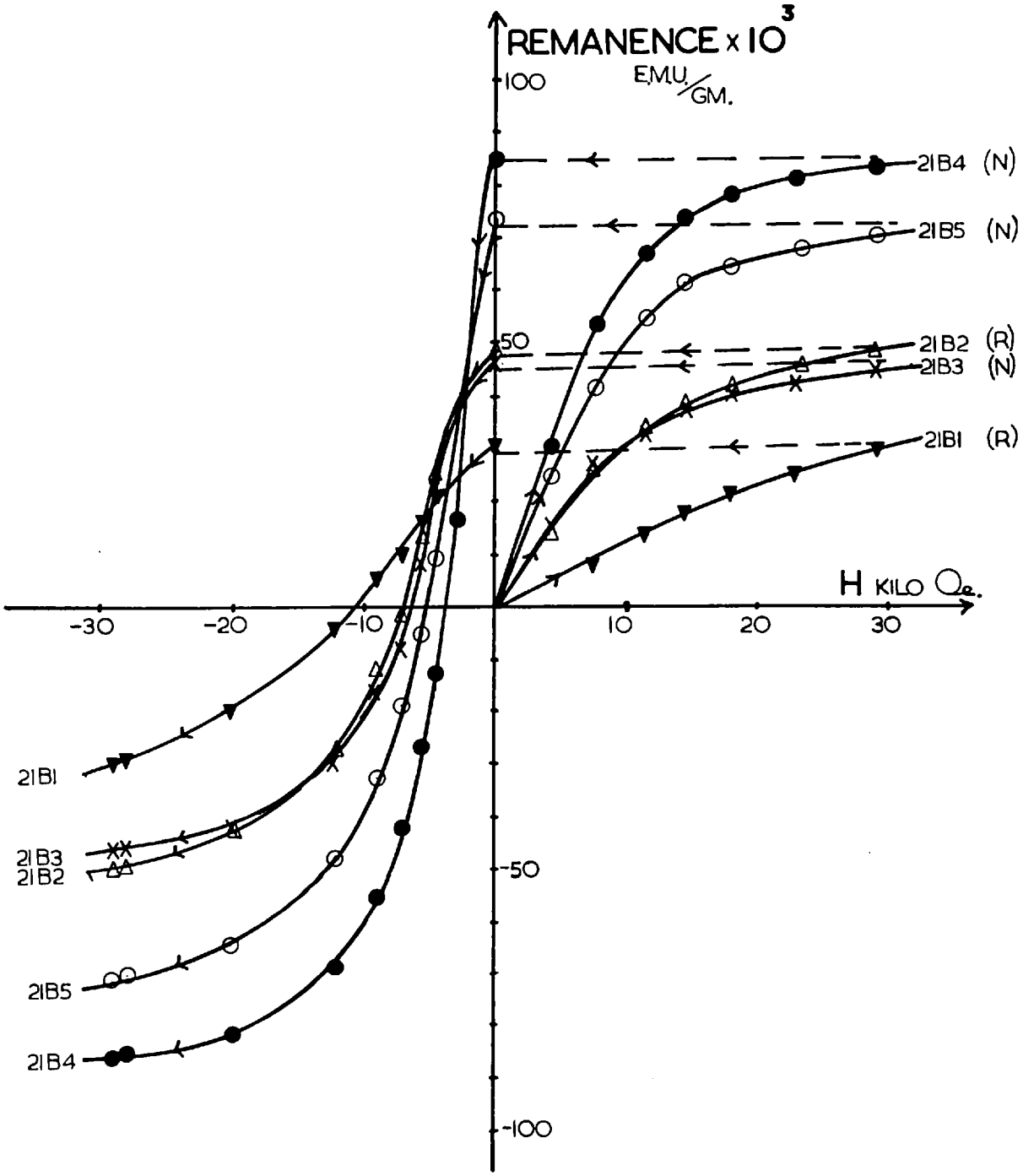


FIG 7.10

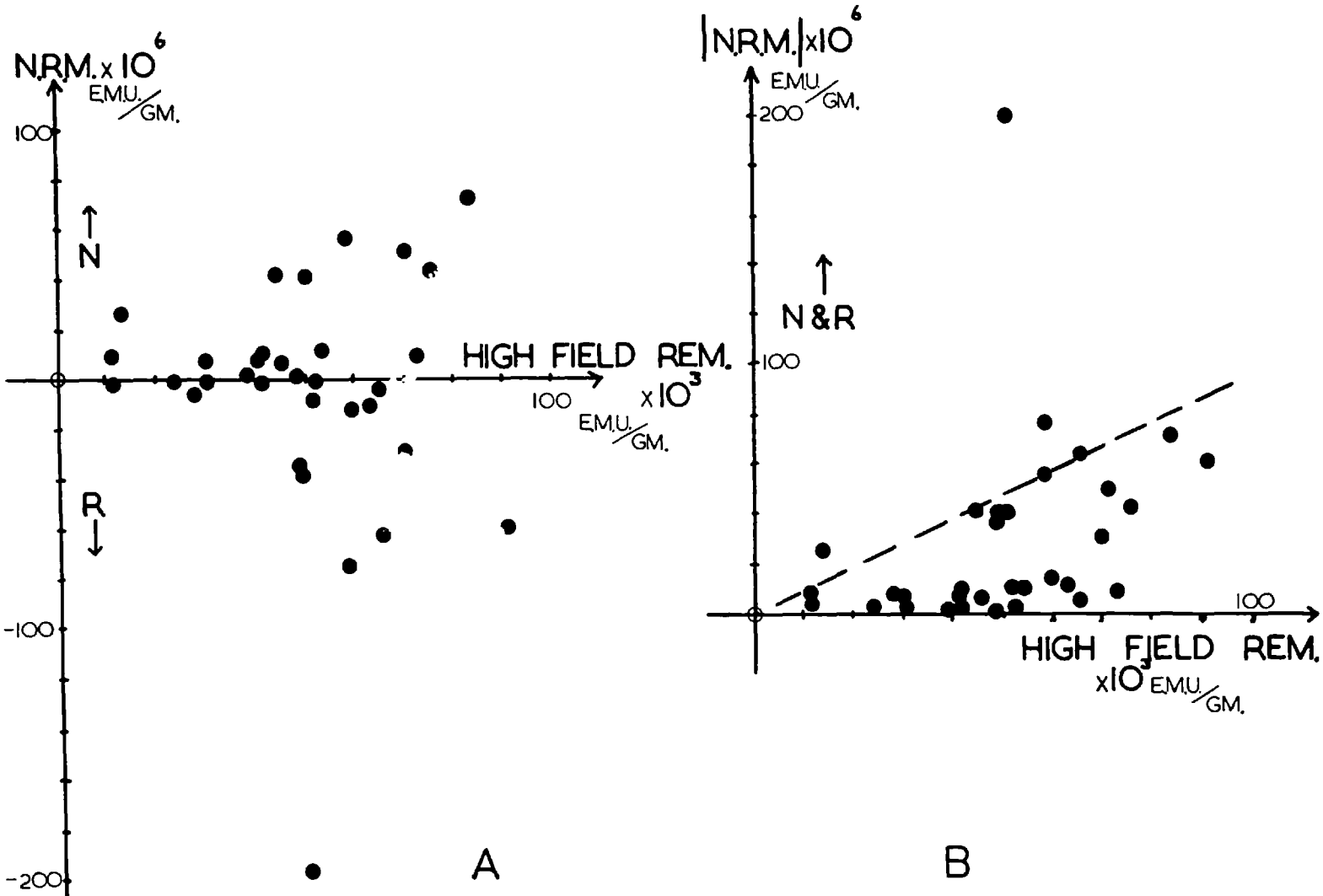

HIGH FIELD (29,000 Oe.) REMANENCE -V- N.R.M.
N.R.M. x 10^6 E.M.U./GM.
100
N
R
-100
-200
HIGH FIELD REM.
100 x 10^3 E.M.U./GM.
A
|N.R.M.| x 10^6 E.M.U./GM.
200
N&R
100
100
HIGH FIELD REM.
x 10^3 E.M.U./GM.
B

FIG 7.11

REMANENT COERCIVE FORCE -v- N.R.M.

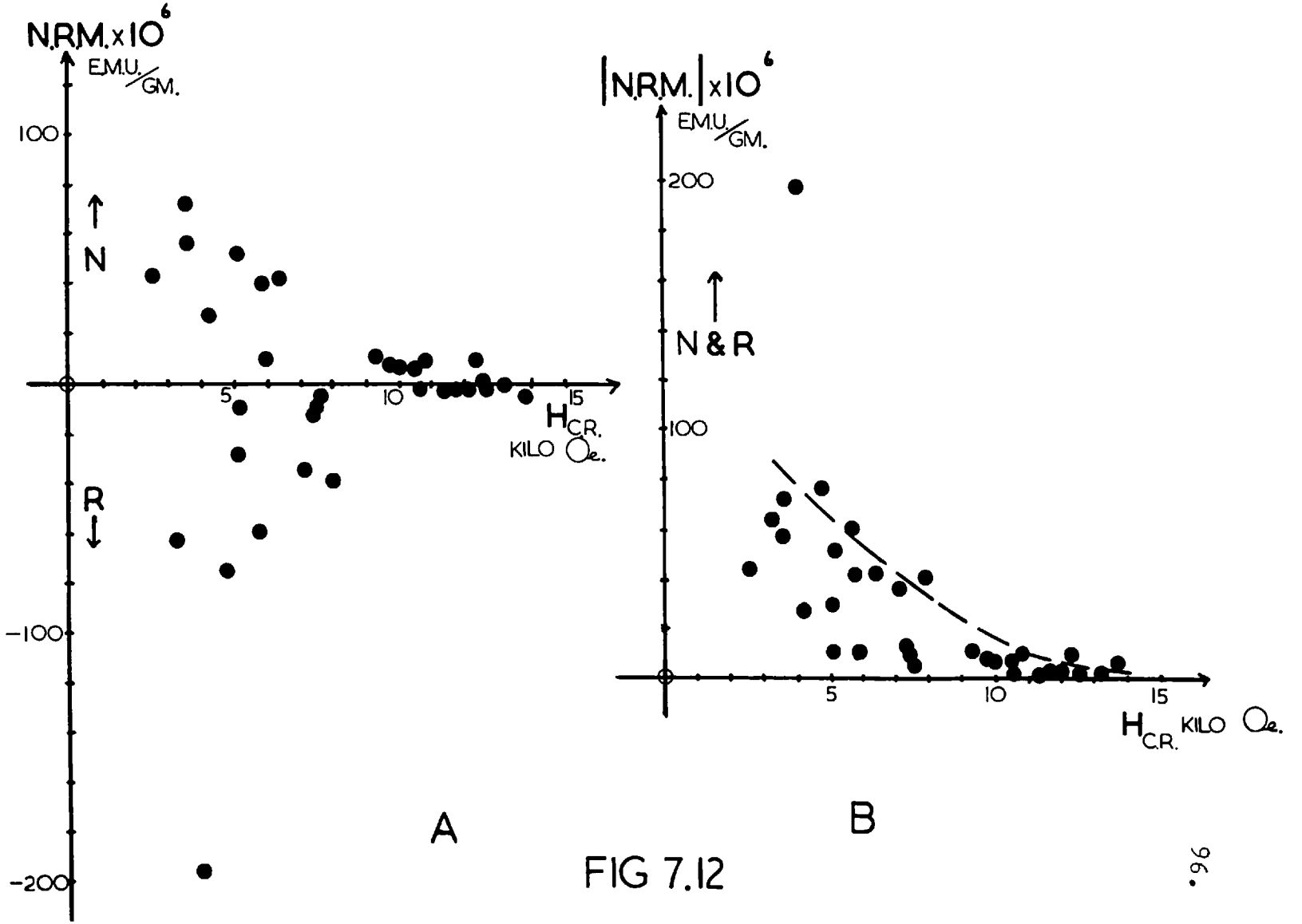
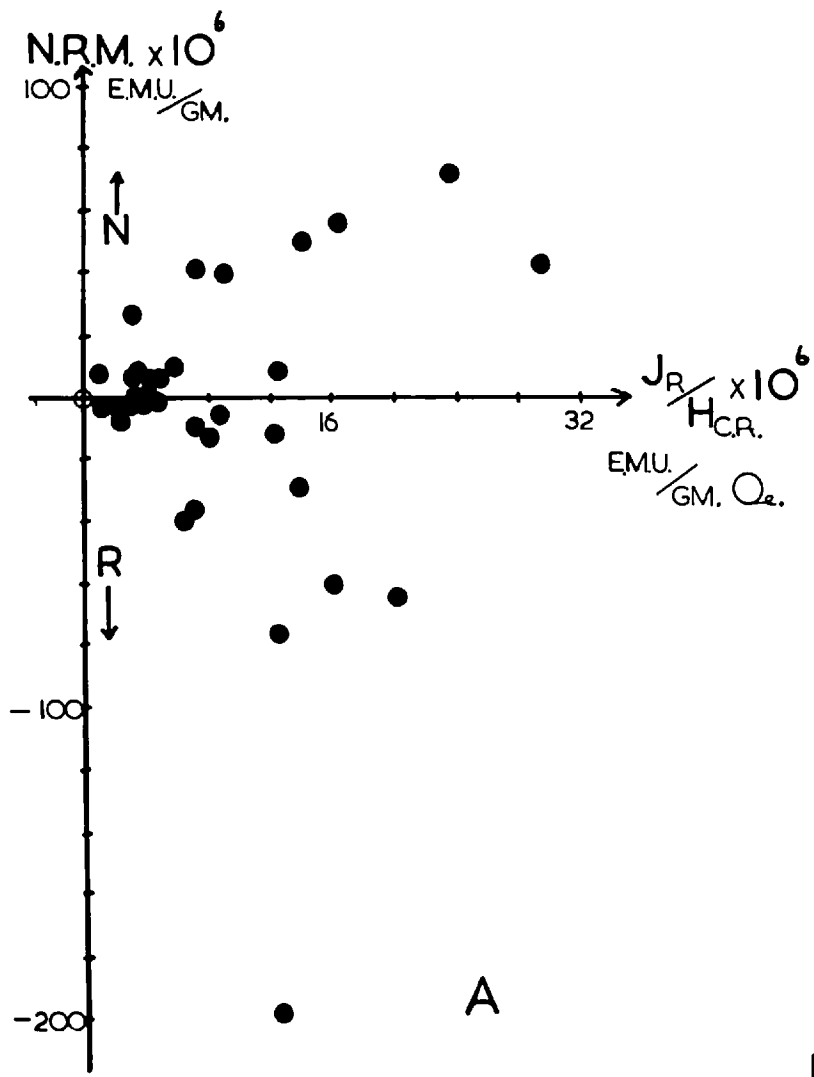


FIG 7.12


N.R.M. x 10^6
100
E.M.U./GM.
N
R
-100
-200
16
32
J_R/H_C.R. x 10^6
E.M.U./GM. Oe.
A

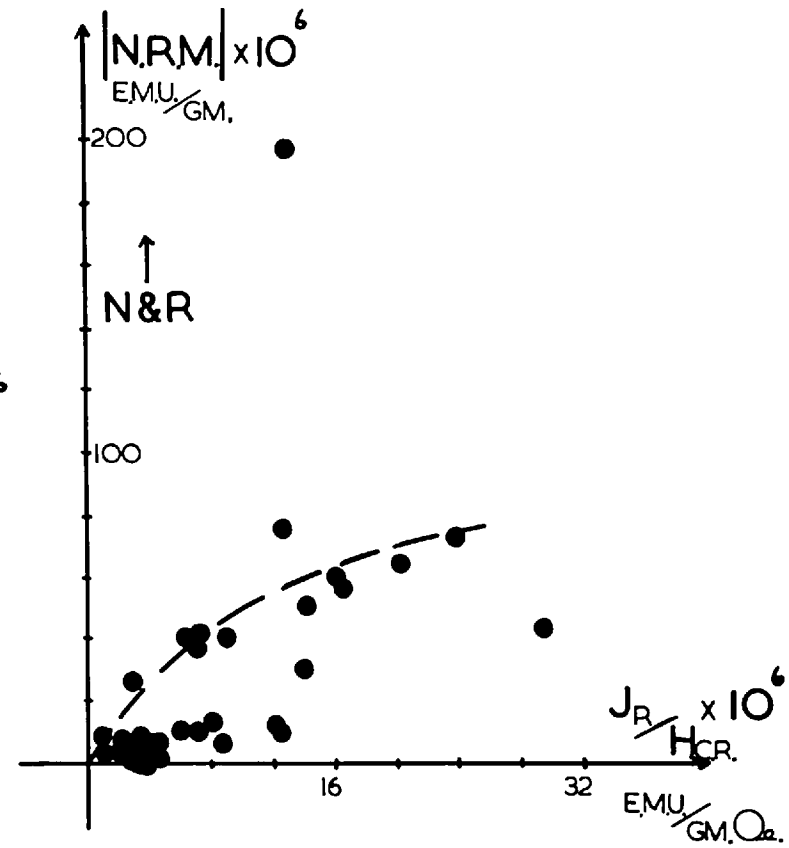

|N.R.M.| x 10^6
E.M.U./GM.
200
N&R
100
16
32
J_R/H_C.R. x 10^6
E.M.U./GM. Oe.
B

FIG 7.13

Several other virgin specimens were placed in a field of 29,000 Oe and their remanences were measured. Enough measurements were carried out to obtain the corresponding remanent coercive force in each case. Fig. 7.11 (A) shows high field remanence plotted against N.R.M. Normal and reversed specimens show similar distributions of high field remanence whose average value is about 50×10^{-3} e.m.u./grm. Fig. 7.11 (B) illustrates the same results, but in a different manner. Here high field remanence is plotted against the numerical value of the N.R.M. The majority of points assemble themselves to give a wedge-like appearance. It is suggested on the basis of this result that although there is no correlation between the measured N.R.M. of each specimen and its high field remanence, there might in fact exist a correlation between high field remanence and $\sum |I_{N.R.M.}|$ (where $\sum |I_{N.R.M.}|$ denotes the scalar sum of all the individual polarisations, irrespective of their directions, within a specimen). This suggestion implies that most normal specimens contain different amounts of reversed polarisations (and vice-versa for reversed specimens) with the results that the measured N.R.M. is always less than the total scalar sum of the N.R.M. ($\sum |I_{N.R.M.}|$) within each specimen. The limit occurs when a specimen contains all normal or all reversed polarisations and these cases probably correspond approximately to the dotted line in Fig. 7.11 (B) which possibly represents the correlation curve between $\sum |I_{N.R.M.}|$ and high field remanence. The implication that many normal specimens contain

different amounts of reversed polarisations, and vice-versa, is quite reasonable. Reference to Fig. 6.3 shows that many of the strips of normal and reversed polarisations present in the grit run horizontally and are less than 1 cm. wide. Since specimens were prepared by slicing vertical cores at approximately 1 cm. intervals it is quite likely that both normal and reversed polarisations are each present in different amounts in many specimens. The remanent coercive force, measured after the specimen had been placed in 29,000 Oe is plotted against N.R.M. in Fig. 7.12 (A). Normal and reversed specimens show a similar distribution. The average value of remanent coercive force is about 7,000 Oe but some range as high as 14,000 Oe. In Fig. 7.12 (B) remanent coercive force is plotted against the numerical value of the N.R.M. The majority of points form a wedge-like shape which has the thin part in the high remanent coercive force region. The argument that applied for the case of Fig. 7.11 (B) may be used again, and the results of Fig. 7.12 (B) possibly suggest that there is in fact a definite correlation between remanent coercive force and $\sum |I_{N.R.M.}|$ (as previously defined). This correlation possibly takes the approximate form of the dotted line shown in the Figure (Fig. 7.12(B)).

Fig. 7.13 shows in a different form the same results as Figs. 7.11 and 7.12. In Fig. 7.13 (A) the ratio, $J_R/H_{R.C.}$ for each specimen is plotted against the corresponding N.R.M. (J_R is the remanence in 29,000 Oe and $H_{R.C.}$ the remanent coercive force). Both normal and reversed

specimens show similar distributions of this ratio, whose usual value is about 12 x 10^{-6} e.m.u./grm.Oe. In Fig. 7.13(B) the ratio $J_R/H_{R.c}$ is plotted against the value of the N.R.M. It seems likely that there is a correlation between the quantity $\sum |I_{N.R.M.}|$ and the ratio $J_R/H_{R.c.}$ (where $\sum |I_{N.R.M.}|$ is as previously defined, and is always greater than the measured N.R.M).

In general, it seems that there exist relations between the total amount of natural polarisation within a specimen and both the high field remanence and remanent coercive force. Specimens having high values of $\sum |I_{N.R.M.}|$ are possibly associated with large high-field remanences but relatively low remanent coercive forces: specimens having low values of $\sum |I_{N.R.M.}|$ are associated with low high-field remanences and relatively high remanent coercive forces. These relations appear to be independent of the sense of the natural polarisations.

10) Soft Component after heating.

It was discovered that when some specimens were heated to about 750°C and allowed to cool down to room temperature, a soft magnetic component with a remanent coercive force of about 700 Oe. had appeared. This component was not present before the heat treatment. This phenomenon was studied by remanence measurements which are illustrated in Fig. 7.14. Curve (1) shows remanence plotted against reversed field for an unheated specimen. The initial magnetising field was 11,000 Oe. It is a smooth curve,

REMANENCE -V- BACK FIELD

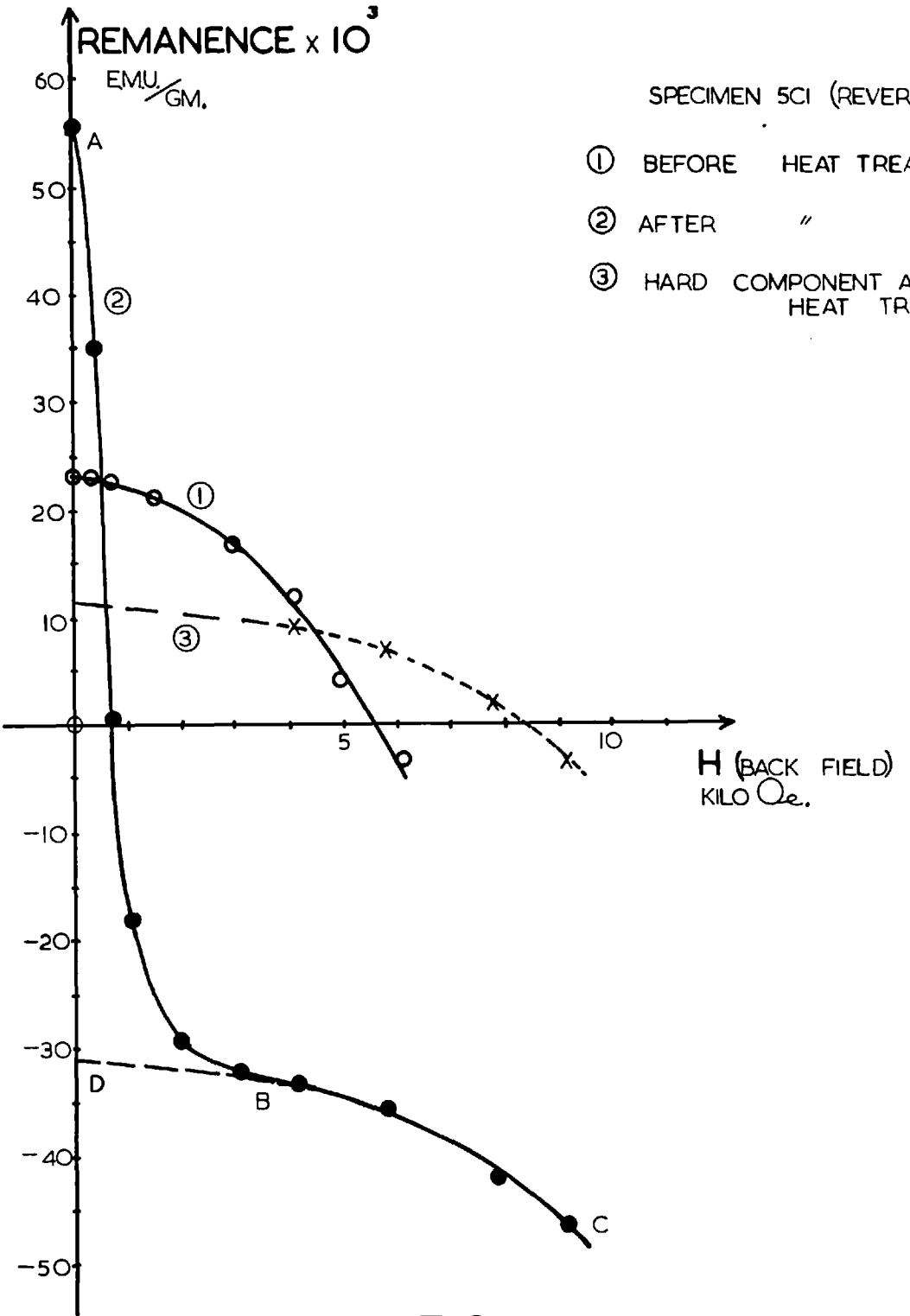


FIG. 7.14

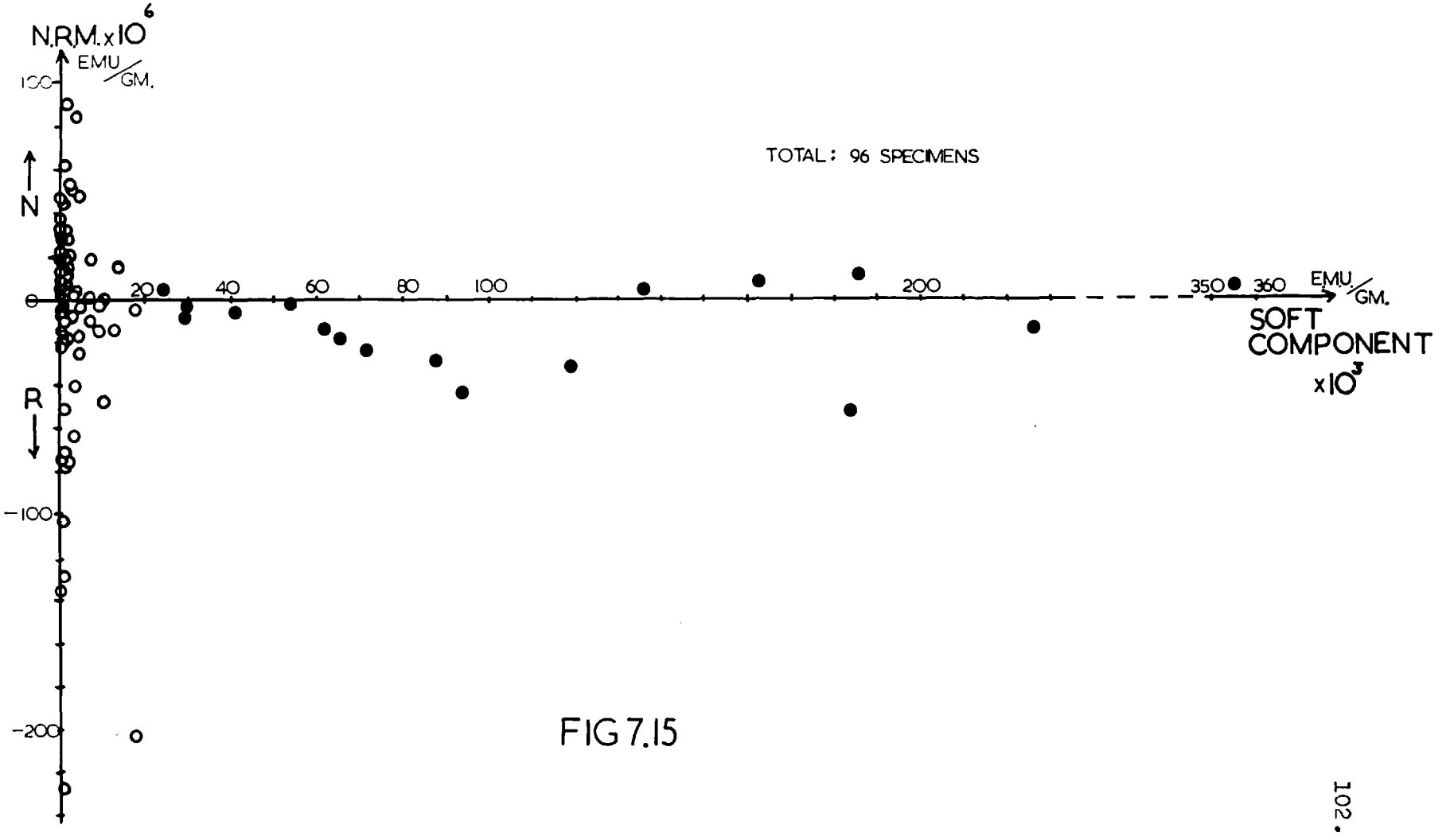

SOFT COMPONENT PRODUCED BY HEATING -v- N.R.M.
N.R.M. x 10^6 EMU/GM.
TOTAL: 96 SPECIMENS
N
R
100
-100
-200
20
40
60
80
100
200
350
360
EMU/GM.
SOFT COMPONENT x 10^3

FIG 7.15

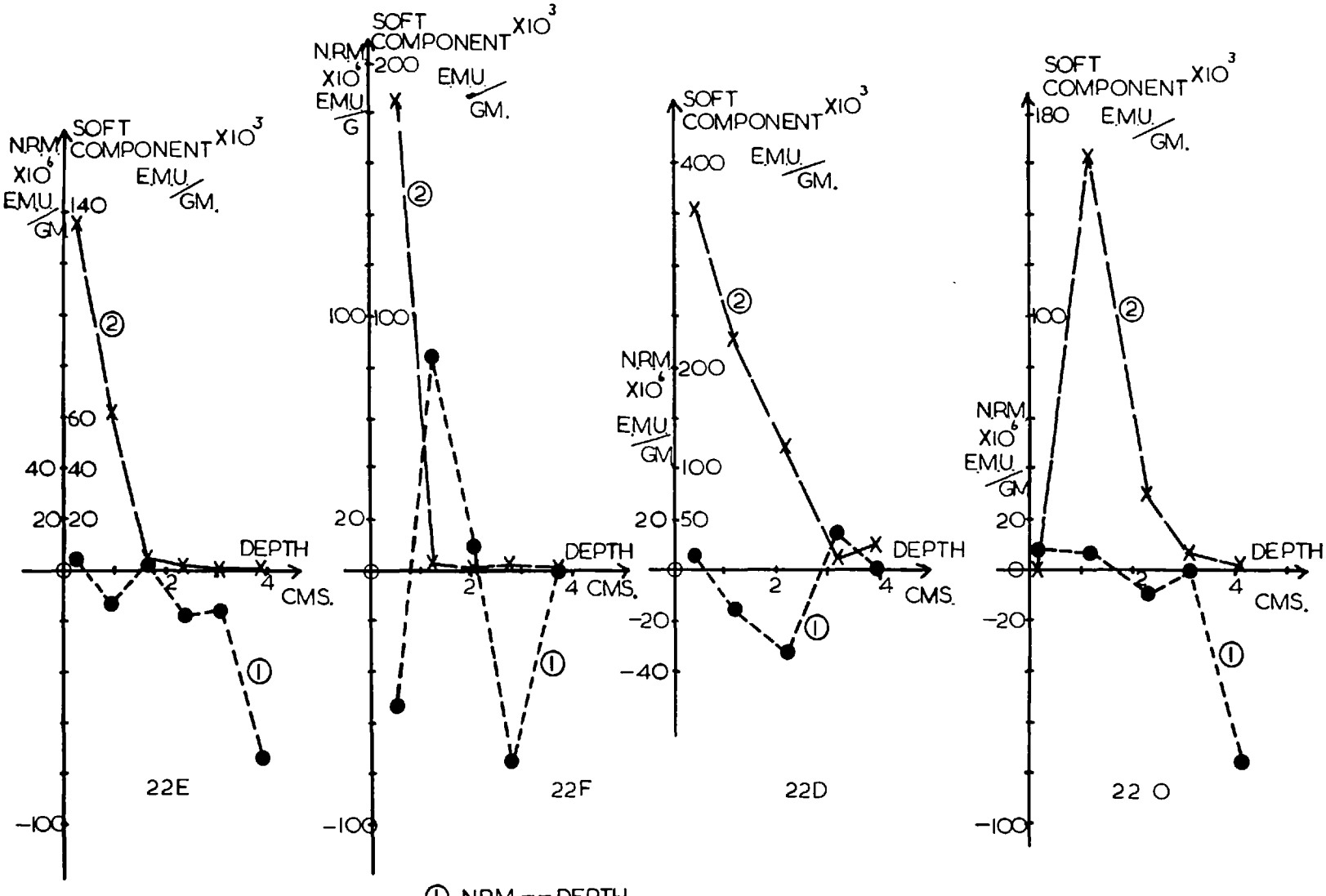
indicating one magnetic component only, and has a remanent coercive force of 5,600 Oe. The specimen was then heated to 750°C and kept at this temperature for 30 minutes. It was then allowed to cool to room temperature, and placed into 11,000 Oe. Increasing reversed fields were applied, and curve (2) shows how the remanence of the heat treated specimen varies with back field. There are clearly two different magnetic components now present; one is a magnetically soft component with a remanent coercive force of 700 Oe, and the other is magnetically hard having a remanent coercive force of about 8,500 Oe. A to B represents the demagnetisation and subsequent remagnetisation of the remanence of the soft component to saturation remanence. B to C represents the demagnetisation of a harder component. To obtain a measure of the saturation remanence of the soft component, curve CB was estimated back to D, and AD defined to be twice the soft component. Curve (3) was obtained from curve (2) by adding the soft component to CBD, and represents the variation of the remanence of the hard component with reversed field.

The production of the soft component was investigated as a function of the heating temperature for some specimens. It first begins to appear on cooling from about 630°C. Its production increases with increase of heating temperature and reaches a maximum for temperatures around 750°C. On cooling from a temperature of 850° C the amount of soft component was found to have decreased.

Preliminary experiments showed that the appropriate heat treatment produced only small amounts of the soft component in most specimens. However, those specimens in which considerable amounts of soft component had been produced by the heat treatment were usually reversed specimens. A more extensive investigation was therefore carried out to find whether this preliminary result led to a significant difference between normal and reversed specimens. A total of 96 specimens, 49 normal and 47 reversed were heated to 750°C and kept at this temperature for 30 minutes. They were then allowed to cool to room temperature. The amount of soft component produced by the heat treatment was measured using the technique described previously. In Fig. 7.15 the soft component is plotted against the corresponding N.R.M. The majority of these soft components are less than 20×10^{-3} e.m.u./grm., and are distributed fairly evenly between normal and reversed specimens. However soft components greater than 20×10^{-3} e.m.u./grm. had been produced by the heat treatment in 17 specimens. Of these, 5 specimens were normal and 12 were reversed. The mean value of the soft components above 20×10^{-3} e.m.u./grm. produced in the 5 normal specimens is $(170 \pm 50) \times 10^{-3}$ e.m.u./grm. The mean value of the soft components above 20×10^{-3} e.m.u./grm produced in the 12 reversed specimens is $(90 \pm 20) \times 10^{-3}$ e.m.u./grm. Owing to the large standard deviations of these mean values, not a great deal of significance can be attached to the difference between the mean values of

normal and reversed soft components above 20 x 10^{-3} e.m.u./grm. However, the fact that, in Fig. 7.15, soft components above 20 x 10^{-3} e.m.u./grm. occurred mainly in reversed specimens and also in specimens having weak normal N.R.M.'s, might be considered possibly significant. To analyse the possible significance of the fact that soft components above 20 x 10^{-3} e.m.u./grm. had been produced in specimens whose N.R.M. lay within the range + 10 x 10^{-6} e.m.u./grm to - 50 x 10^{-6} e.m.u./grm. soft component was plotted against depth for those cores containing one or more specimens in which a soft component above 20 x 10^{-3} e.m.u./grm. had been produced by the heat treatment. Figs. 7.16 and 7.17 show some of these diagrams. The corresponding plots of N.R.M. with depth are also shown in each. It was found by this analysis that the larger soft components (above 20 x 10^{-3} e.m.u./grm) were produced only in specimens cut from 3 particular rock samples. They were samples 5, 6 and 22. Specimens cut from other rock samples did not apparently produce large soft components on heat treatment and were mainly responsible for the mass of points in Fig. 7.15 representing low values of soft component.

The diagrams shown in Figs. 7.16 and 7.17 suggest that in those areas of the grit where it is possible to produce soft components greater than 20 x 10^{-3} e.m.u./grm. by heat treatment, this production is a function of depth rather than a function of the N.R.M. In general large amounts of soft component are formed near the top of these cores: soft



① N.R.M. -v- DEPTH

② SOFT COMPONENT PRODUCED BY HEATING -v- DEPTH

FIG 7.16

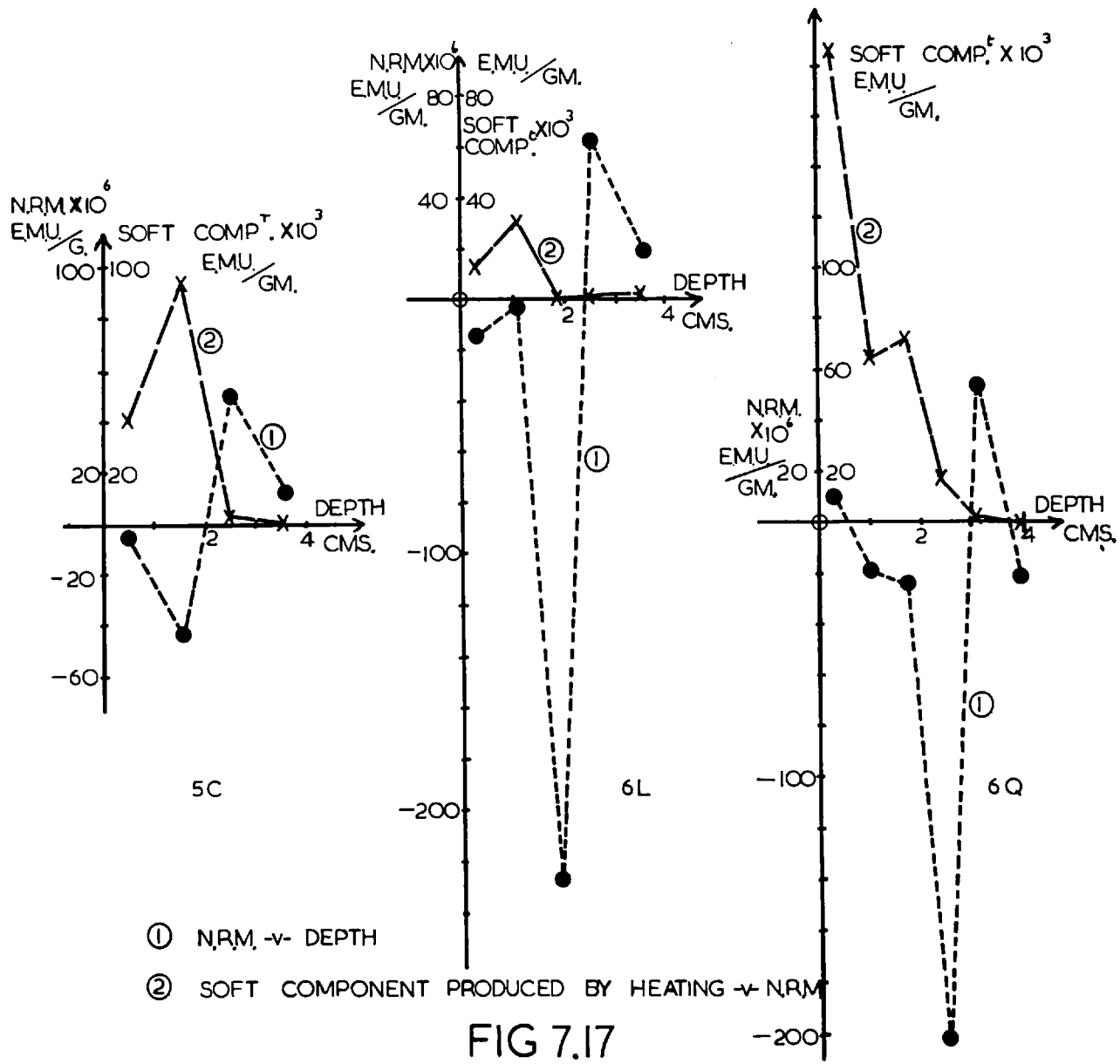

N.R.M. X10^6 E.M.U./G.
SOFT COMP^T. X10^3 E.M.U./GM.
100
20
-20
-60
2
4 CMS.
DEPTH
5C
N.R.M. X10^6 E.M.U./GM.
SOFT COMP^T. X10^3 E.M.U./GM.
80
40
-100
-200
2
4 CMS.
DEPTH
6L
SOFT COMP^T. X10^3 E.M.U./GM.
100
60
N.R.M. X10^6 E.M.U./GM.
20
-100
-200
2
4 CMS.
DEPTH
6Q
① N.R.M. -v- DEPTH
② SOFT COMPONENT PRODUCED BY HEATING -v- N.R.M.

FIG 7.17

component appears to drop rapidly with depth in the top half of each core and is usually negligible in the lower half. On the contrary the N.R.M. shows a different depth pattern from core to core. It was concluded that there was unlikely any relation between the N.R.M. of a specimen and the soft component after heating.

The possibly significant point now appears to lie in the fact that the N.R.M. of each of the top specimens of these cores lies within the range + 10 x 10^{-6} e.m.u./grm to -50 x 10^{-6} e.m.u./grm. Considering all cores drilled vertically from different exposures along the horizon of the grit, it is found that the N.R.M. of the top specimens lies within the range + 20 x 10^{-6} e.m.u./grm to -80 x 10^{-6} e.m.u./grm. This may possibly be significant, the both extremes of this range being respectively about one-quarter and one-third of the maximum values of normal and reversed natural polarisations (i.e. + 90 x 10^{-6} e.m.u./grm and - 230 x 10^{-6} e.m.u./grm, see paragraph 2 of this chapter). On the other hand the presence of this range does not indicate a physical difference between normal and reversed specimens. However the character of this range is probably responsible for biasing the production of soft components by heat treatment, (Fig. 7.15) towards reversed N.R.M.'s.

Conclusion of Paragraph 10.

Soft components above 20 x 10^{-3} e.m.u./grm. have been produced by heat treatment in some areas of the grit. It is concluded that the production of these large soft components within a specimen is probably

independent of the N.R.M., but depends rather on the depth of the specimen within the band of grit.

11) Susceptibility: The induced magnetisations of small pieces of grit were measured in fields up to 4,000 Oe. using a magnetic balance. The dark circles in Fig. 7.18 show how induced magnetisation increases with increasing field, while the light circles represent decreasing field. Within the limits of the errors involved, the hysteresis is small, and induced magnetisation varies linearly with field over the range 500 to 4,000 Oe. One is unable to measure the remanence in zero field using a magnetic balance, but it appears from Fig. 7.18 that the remanence after a field of 4,000 Oe has been applied is less than 15% of the polarisation in 4,000 Oe. From the slope of the line the susceptibility in the range 500 to 4,000 Oe may be calculated. The N.R.M. of each piece of the grit was estimated using the intensity-depth pattern for the core from which it was taken, knowing the depth from which the piece was obtained. In Fig. 7.19 susceptibility is plotted against N.R.M. A typical value of the susceptibility is 60×10^{-6} e.m.u./grm.Oe. Normal and reversed pieces have similar distributions of susceptibility.

12) X-Rays.

Magnetic fractions of a normal and a reversed specimen were each obtained using a Franz separator and by using heavy liquids and centrifuging. An X-ray diffraction analysis was carried out on the non-magnetic and magnetic fractions of each specimen. The photographs of both

INDUCED MAGNETISATION -v- INDUCING FIELD

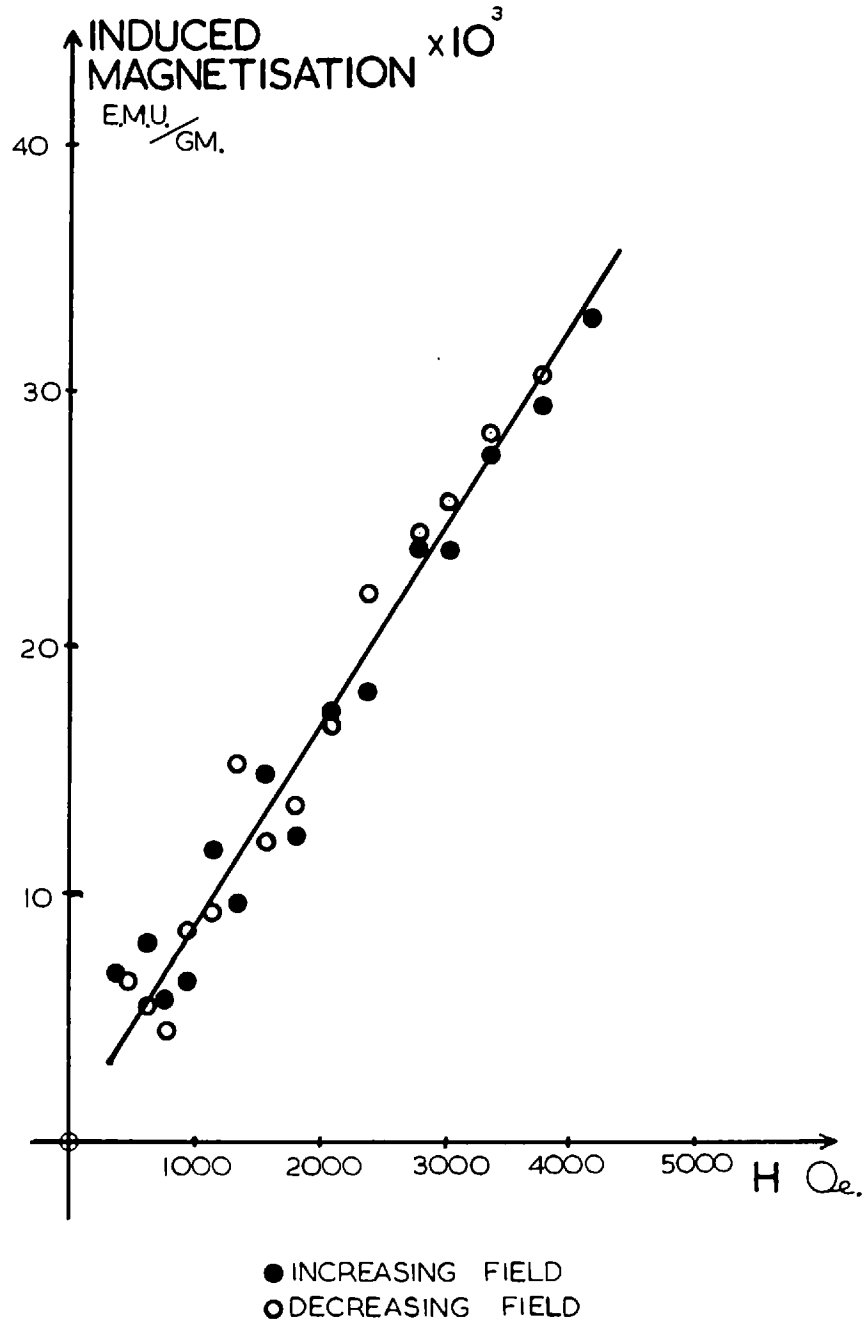


FIG 7.18

SUSCEPTIBILITY (IN RANGE 500 - 5000 Oe.) -v- N.R.M.

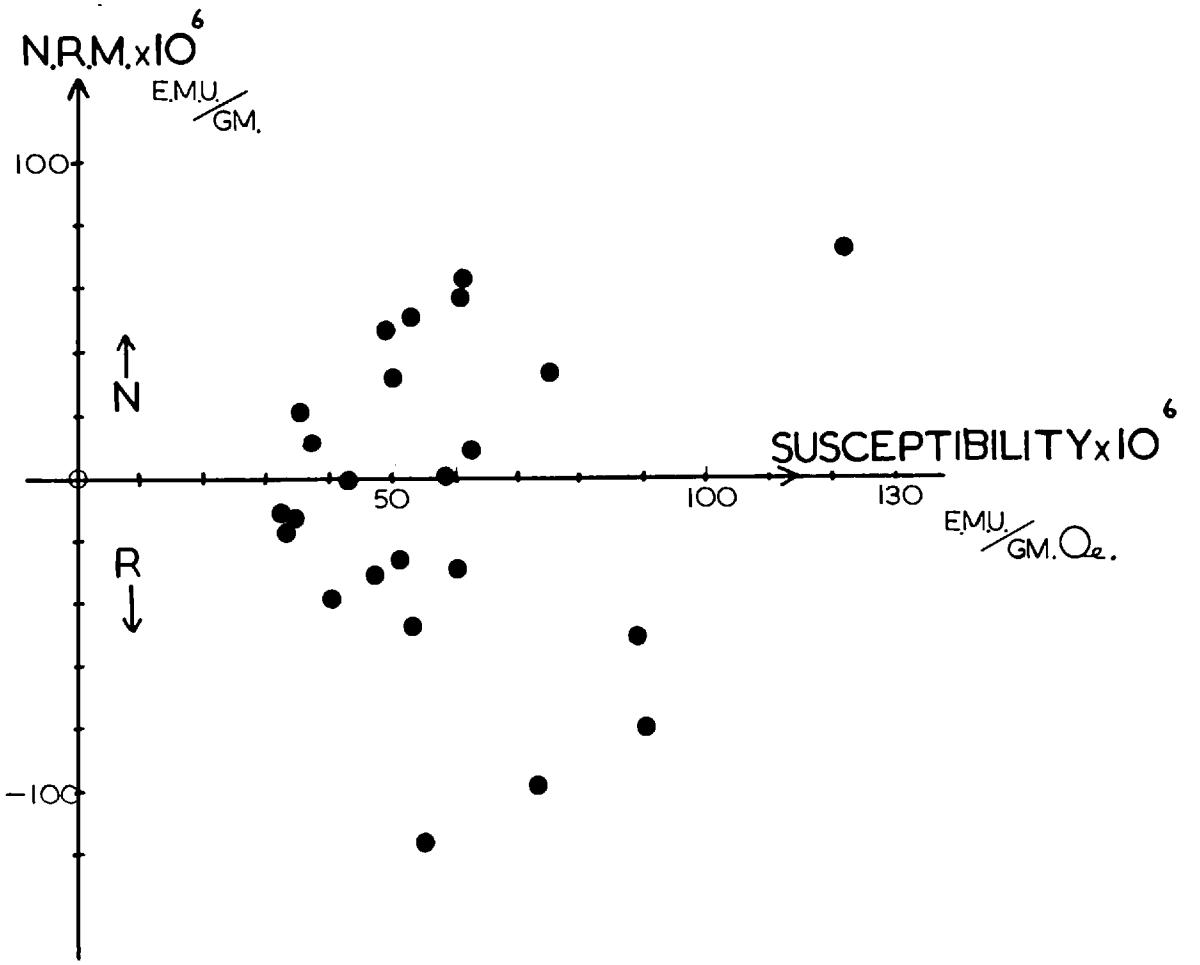


FIG 7.19

non-magnetic fractions gave lines consistent with those of a quartz standard X-ray.

The magnetic fractions of both specimens showed predominant quartz lines, but also present in each were extra lines which closely coincided with those of a pure hematite standard X-ray. No magnetite or maghemite lines were observed. It was concluded that the magnetic fractions of both specimens contain hematite.

13) Low temperature transitions

Morin (1950)[18] showed that the susceptibility of hematite, when cooled through - 15°C decreases rapidly to about one-ninth of the room temperature susceptibility. Haigh (1957)[19] was able to observe this transition in synthesised hematite containing up to 10% impurities, (TiO_2 and Al_2O_3). The X-ray analysis, paragraph 12, showed that the magnetic fraction of the grit included hematite. The results of a full chemical analysis given in Chapter 9 show that one-third by weight of the grit is Fe_2O_3. It was decided to find out whether the grit exhibited a low temperature transition. Some pure hematite was cooled to - 100°C in a magnetic balance and allowed to heat up to room temperature. The expected large increase of the induced magnetisation was observed at -15°C. A similar procedure was carried out on a few powdered specimens of the grit some of which had normal N.R.M.'s and others reversed N.R.M.'s. Each powder was heated from - 100°C to above room temperature in the magnetic balance, but for each the induced magnetisation remained constant

over all this temperature range. Any hematite which exists in the grit does not exhibit the Morin transition. The only naturally occuring hematites known to show the Morin transition are samples of massive hematite, which are mined as iron ore in Cumberland, and known as pencil ore (Haigh 1957)[19].

Summary of Chapter:

A number of different experiments have been carried out on the iron grit to determine some of its physical properties. The physical properties of normal specimens have been compared with those of reversed specimens. The most interesting comparison was described in paragraph 2. The histogram of Fig. 7.1. showed that 8% of all the reversed natural polarisations considered are greater than 90×10^{-6} e.m.u./grm, whereas no normal polarisations exceeded this value. The possibility of this difference being significant is considered in paragraph 2.

Otherwise to this, no significant physical difference has been detected between normal and reversed specimens. Chapter 9 describes the results of a chemical analysis which was carried out mainly for the purpose of detecting a chemical difference between normal and reversed specimens.

CHEMICAL PROPERTIES

1) Chemical Analysis:

A full quantitative chemical analysis was carried out on 15 specimens by Miss Jennifer Langbein, and a further 4 were analysed by Riley, Harford and Law[20] for Ferric Oxide, Titanium Dioxide and Alumina only. The results are shown in Table 4. Fe_2O_3 accounts for about one third by weight of the grit, and about half is composed of silica. There is about a half a percent of FeO, about 5% alumina and about 0.5% titanium oxide. Other minerals present in amounts less than 1% include Na_2O, K_2O, P_2O_5 MgO and CaO.

The minerals which can account for the magnetic properties of the grit are ferric oxide (Fe_2O_3) and ferrous oxide (FeO). The ferric oxide might be either in hematite or magnetite form, or both, whereas the ferrous oxide might indicate magnetite (any magnetite present would be detected and measured as FeO in this chemical analysis). The results were plotted in various ways. In Fig. 8.1 diagrams (A), (B) and (C) respectively show the weight precentages of Fe_2O_3, FeO, and TiO_2 plotted against N.R.M. Positive N.R.M.'s represent normal specimens and negative N.R.M.'s represent reversed specimens. The weight percentage of Al_2O_3 is plotted against N.R.M. in Fig. 8.2(a). In the discussion, Chapter 10, arguments are put forward to attribute the N.R.M. of the grit to hematite (Fe_2O_3).

TABLE 4

RESULTS OF CHEMICAL ANALYSIS.

	21D1	21D2	21D3	21D4	21D5
% by wt. of SiO_2	52.60	49.88	54.27	57.35	55.08
" " " " H_2O	5.19	5.05	4.20	3.49	3.44
" " " " Na_2O	0.38	0.34	0.30	0.38	0.30
" " " " K_2O	0.61	0.51	0.53	0.48	0.33
" " " " P_2O_5	0.79	1.24	1.09	1.26	1.38
" " " " TiO_2	0.49	0.89	0.49	0.36	0.29
" " " " Fe_2O_3	28.88	31.23	31.12	33.31	36.50
" " " " FeO	0.64	0.61	0.53	0.61	0.67
" " " " MnO	0.00	0.00	0.00	0.00	0.00
" " " " MgO	0.38	0.44	0.30	0.23	0.28
" " " " CaO	0.43	0.53	0.50	0.66	0.51
" " " " Al_2O_3	4.93	5.85	6.16	2.43	2.69
TOTAL	95.32%	96.57%	99.49%	100.58%	101.47%
N.R.M. c.m.u./grm x 10^6 + ive means Normal	- 9	-4	+18	-39	-67

CHEMICAL ANALYSIS CONTINUED

	21D6	6M1	6M2	6M3	6M4
% by wt of SiO_2	59.61	54.04	50.74	57.23	55.06
H_2O	3.94	4.61	4.44	3.81	3.29
Na_2O	0.30	0.21	0.82	0.38	0.20
K_2O	0.27	0.34	0.77	0.72	0.40
P_2O_5	1.24	0.47	1.83	0.52	0.00
TiO_2	0.31	0.31	0.41	0.41	0.34
Fe_2O_3	30.97	35.22	30.43	29.97	34.42
FeO	0.78	0.38	0.29	0.39	0.29
MnO	0.00	0.00	0.00	0.00	0.00
MgO	0.13	0.16	0.38	0.26	0.08
CaO	0.71	0.40	0,42	0.36	0.41
Al_2O_3	2.98	2.63	8.44	6.43	5.77
TOTAL	101.24%	98.77%	98.97%	100.48%	100.26%
N.R.M. e.m.u./grm x 10^6 + ive means Normal.	+33	-13	-6	-198	+56

CHEMICAL ANALYSIS CONTINUED.

	6M5	3F1	2G2	K231b1	K271C2
% by wt. of SiO_2	56.41	51.18	41.41	48.14	57.29
H_2O	3.82	3.88	5.89	3.26	3.63
Na_2O	0.24	0.11	0.11	0.12	0.13
K_2O	0.54	0.50	0.82	0.45	0.13
P_2O_5	0.02	0.27	1.19	0.17	0.26
TiO_2	0.41	0.41	0.61	0.30	0.25
Fe_2O_3	34.82	30.85	33.63	37.31	27.75
FeO	0.30	0.20	0.20	0.21	0.21
MnO	0.00	0.00	0.00	0.00	0.00
MgO	0.15	0.02	0.04	0.19	0.08
CaO	0.35	0.54	0.84	0.49	0.44
Al_2O_3	1.95	4.44	9.12	4.62	5.28
Total	99.01%	92.40%	93.86%	95.26%	95.46%
N.R.M. e.m.u/grm x 10^6 + ive means Normal	+9	+8	-2	+ 21	- 4

	5E2	5E3	5E4	5E5	
% by wt. Fe_2O_3	36.80	38.11	40.28	31.29	
TiO_2	0.10	0.10	0.60	0.30	
Al_2O_3	4.46	4.85	2.31	3.99	
N.R.M. e.m.u./grm x 10^6 +ive means Normal	-44	-4	+69	+51	

CHEMICAL ANALYSIS

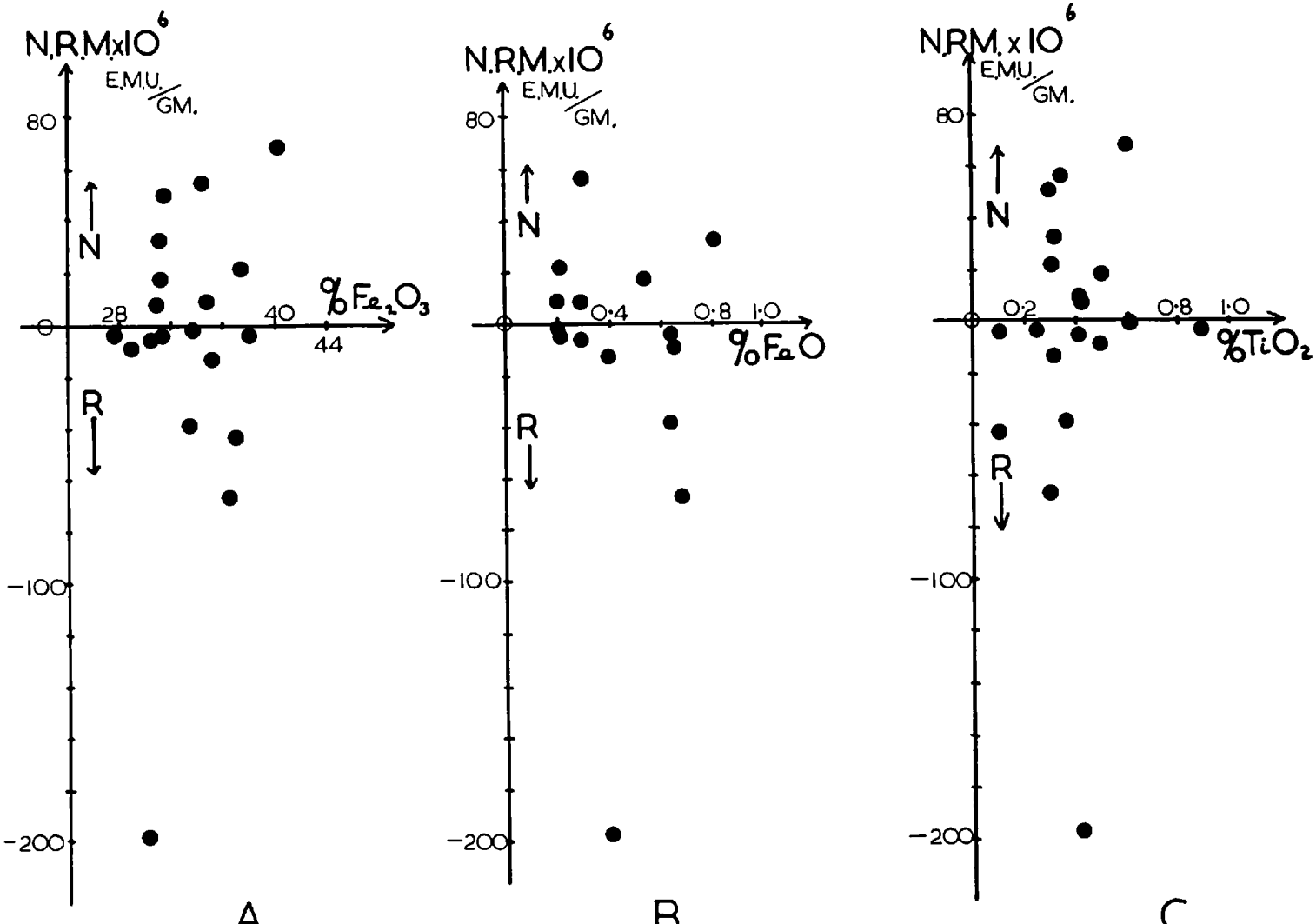


FIG 8.1

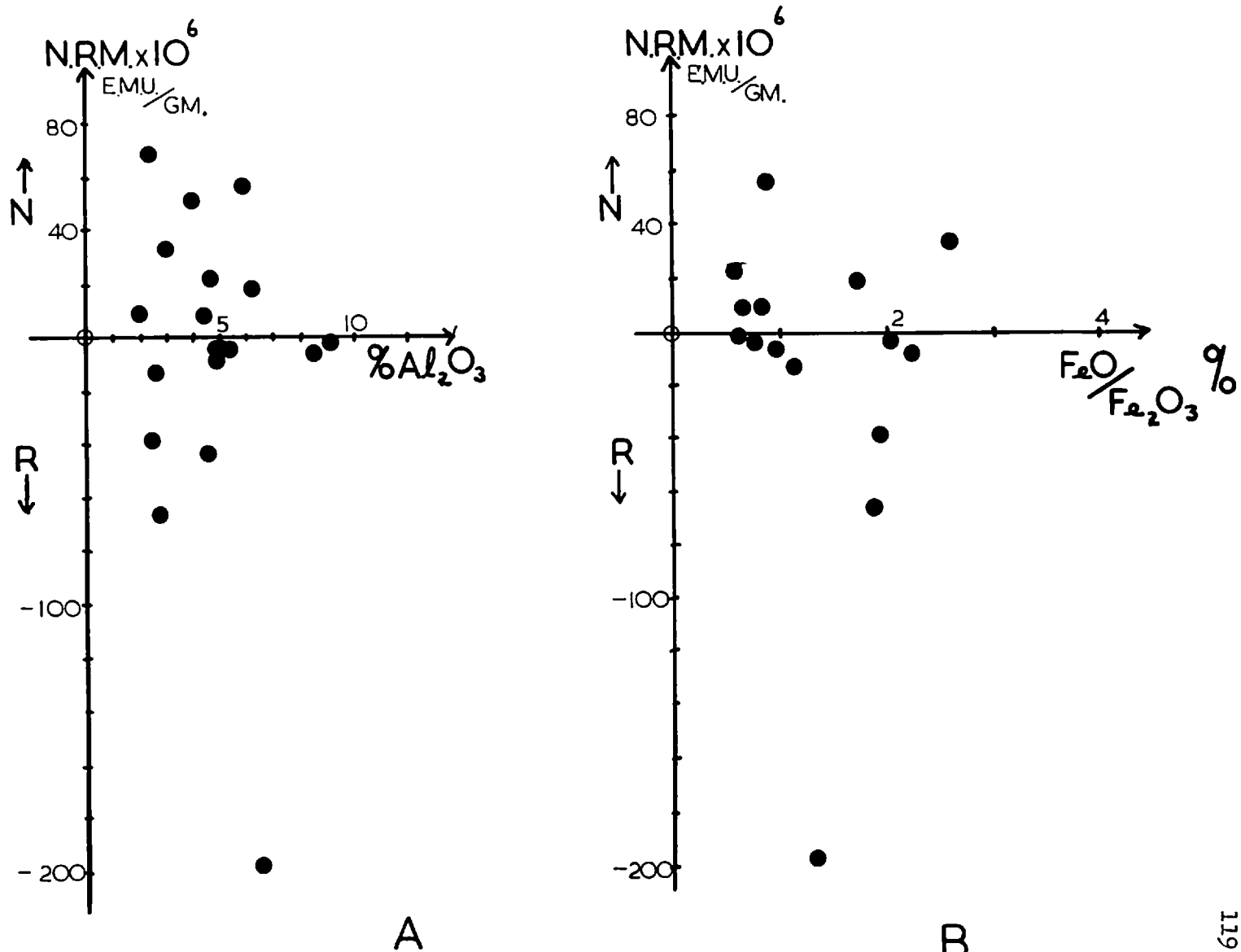

N.R.M.x10^6
E.M.U./GM.
80
40
N
R
-100
-200
5
10
%Al2O3
A
N.R.M.x10^6
E.M.U./GM.
80
40
N
R
-100
-200
2
4
FeO/Fe2O3 %
B

FIG 8.2

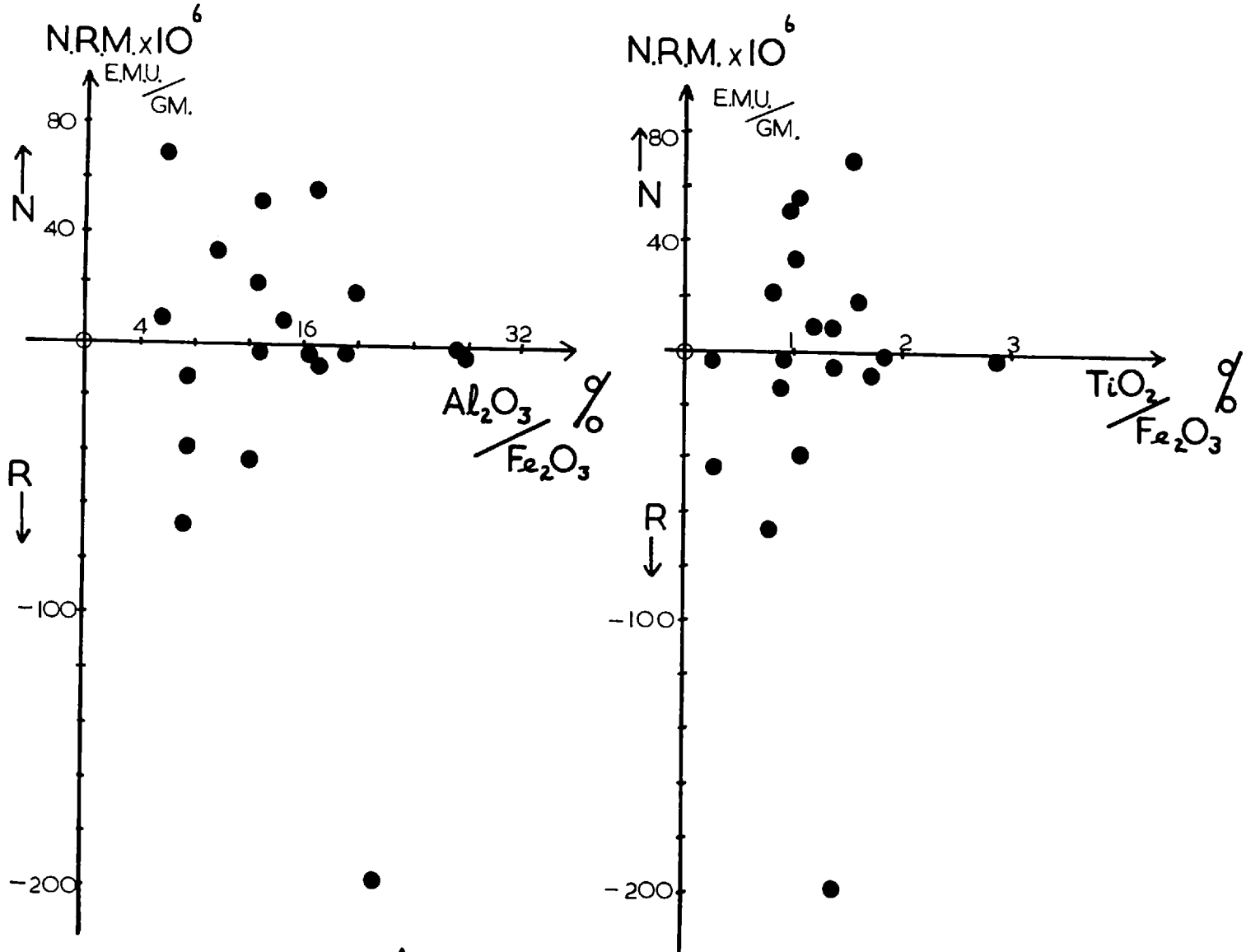

N.R.M. x 10^6
E.M.U. / GM.
80
N
40
4
16
32
Al2O3 / Fe2O3 %
R
-100
-200
A
N.R.M. x 10^6
E.M.U. / GM.
80
N
40
1
2
3
TiO2 / Fe2O3 %
R
-100
-200
B

FIG 8.3

Consequently the ratios of the weight of each mineral to that of hematite was calculated for each specimen. In Fig. 8.2(b) and Fig. 8.3 (a) and (b) the ratios FeO/Fe_2O_3, Al_2O_3/Fe_2O_3 and TiO_2/Fe_2O_3 respectively are plotted against N.R.M. Two of the diagrams shown in Figs. 8.1, 8.2 and 8.3 show a possible correlation between N.R.M. and the corresponding weight percentage or ratio. The rest do not. The possible correlations are those of Figs. 8.2(a) and 8.3(a) which plot the weight percentage of Al_2O_3 and the ratio Al_2O_3/Fe_2O_3 respectively against N.R.M. The mean value and standard deviation of the percentage weight of Al_2O_3 for normal specimens are 4 ± 1. Those values for reversed specimens are 5 ± 1. The mean value and standard deviation of the ratio Al_2O_3/Fe_2O_3 for normal specimens are $12\% \pm 2\%$ and those values for reversed specimens is $16\% \pm 2\%$.

Thus for both Figs. 8.2(a) and 8.3(a), normal and reversed standard deviations overlap each other and the slight difference between normal and reversed specimens observed in each case is, within the limits of this analysis, not significant. Other diagrams plotting the ratios SiO_2/Fe_2O_3, H_2O/Fe_2O_3, Na_2O/Fe_2O_3, K_2O/Fe_2O_3, P_2O_5/Fe_2O_3, MgO/Fe_2O_3 and CaO/Fe_2O_3 each against N.R.M. were plotted but are not shown. None of these diagrams indicate a significant difference between normal and reversed specimens.

Within the limits of this chemical analysis, there is no significant chemical difference between normal and reversed specimens.

2. Etching experiments with conc.HCl.

With the collaboration of Professor N. Kawai, a thin section of the grit was etched with concentrated hydrochloric acid for nearly 20 hours. The natural polarisations of normal and reversed areas were measured and colour changes observed at regular intervals during the etching process.

A thin section of area 3 x 3 cms was sliced from the vertical section 6Ya. This was ground with an abrasive until it was about 650μ thick. About 20 holes were drilled through a slab of perspex so that they covered an area just less than that of the thin section, and the thin section was made to adhere to this area using chloroform which dissolves perspex. For the purpose of etching, a small tower was mounted over the thin section and was filled with acid. Acid constantly circulated around the thin section and escaped via the holes below. The level of acid within the tower was kept constant during the process.

When it was required to measure the natural polarisation of different areas of the specimen the tank was removed and the perspex slab and thin section were mounted together on the turn-table beneath the small astatic magnetometer system which is described in appendix II. The top surface of the thin section was arranged to be 2 mms. away from the lower magnet. The axis of rotation of the turntable coincided with that of the magnetometer system within limits less than 1 mm. , and a measure of the N.R.M. of the area immediately below the lower magnet was obtained by

rotating the turn-table through 180° and noting the deflection of the magnetometer system.

The thin section was etched with concentrated hydrochloric acid for 19.75 hours. At zero, 0.75, 3.75, 6.75 9.75 and 19.75 hours, the process was interrupted, the section washed with water and dried, and the natural polarisation pattern was measured by six traverses in a vertical direction. An effort was made at each of these intervals to mount the section on the turntable so that it was the same distance (2 mms) away from the lower magnet. Three of the six traverses are shown in Fig.8.4. The three diagrams of Fig. 8.4.(a) represent vertical traverses carried out at zero time of etching and are a horizontal distance of 0.5. cms. away from each other (vertical and horizontal refer to the section when in situ). The three diagrams of 8.4(b) represent the same traverses as those of (A) and are in the same order, but they represent 3.75 hours of etching. The results of the same three traverses, shown in the same order, after 6.75 hours of etching are represented by Fig. 8.4(c). In these diagrams D is the vertical distance, in cms., of the particular area of the section from an arbitrary axis. Similar diagrams for 0.75, 9.75 and 19.75 hours of etching were also studied but are not shown. In general, although the N.R.M.'s of normal and reversed polarisations decrease with total etching time, the shape of the intensity versus depth pattern given by each traverse changes very little. It appears then that the acid destroys normal and reversed N.R.M.'s at similar rates and in a similar

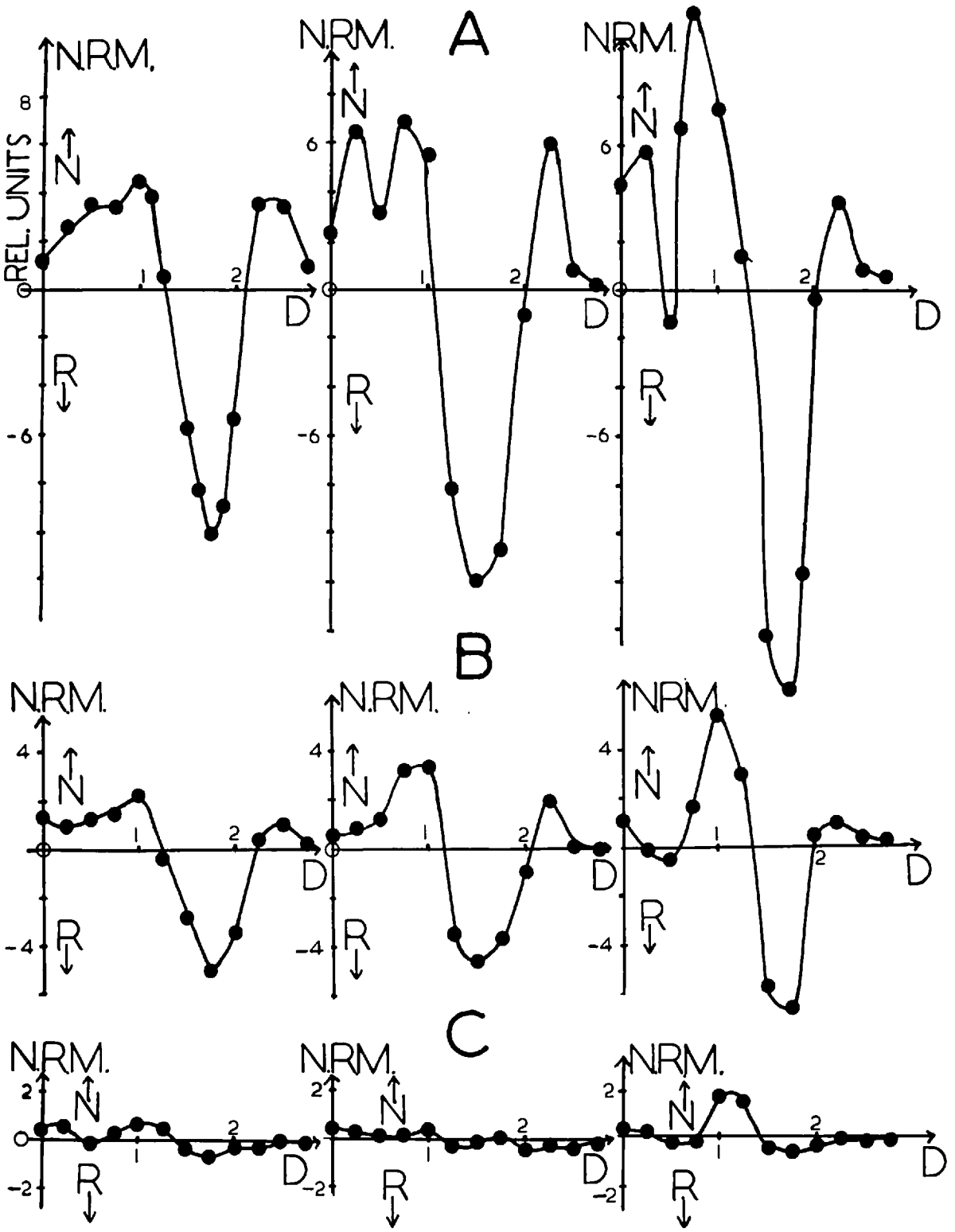


FIG 8.4

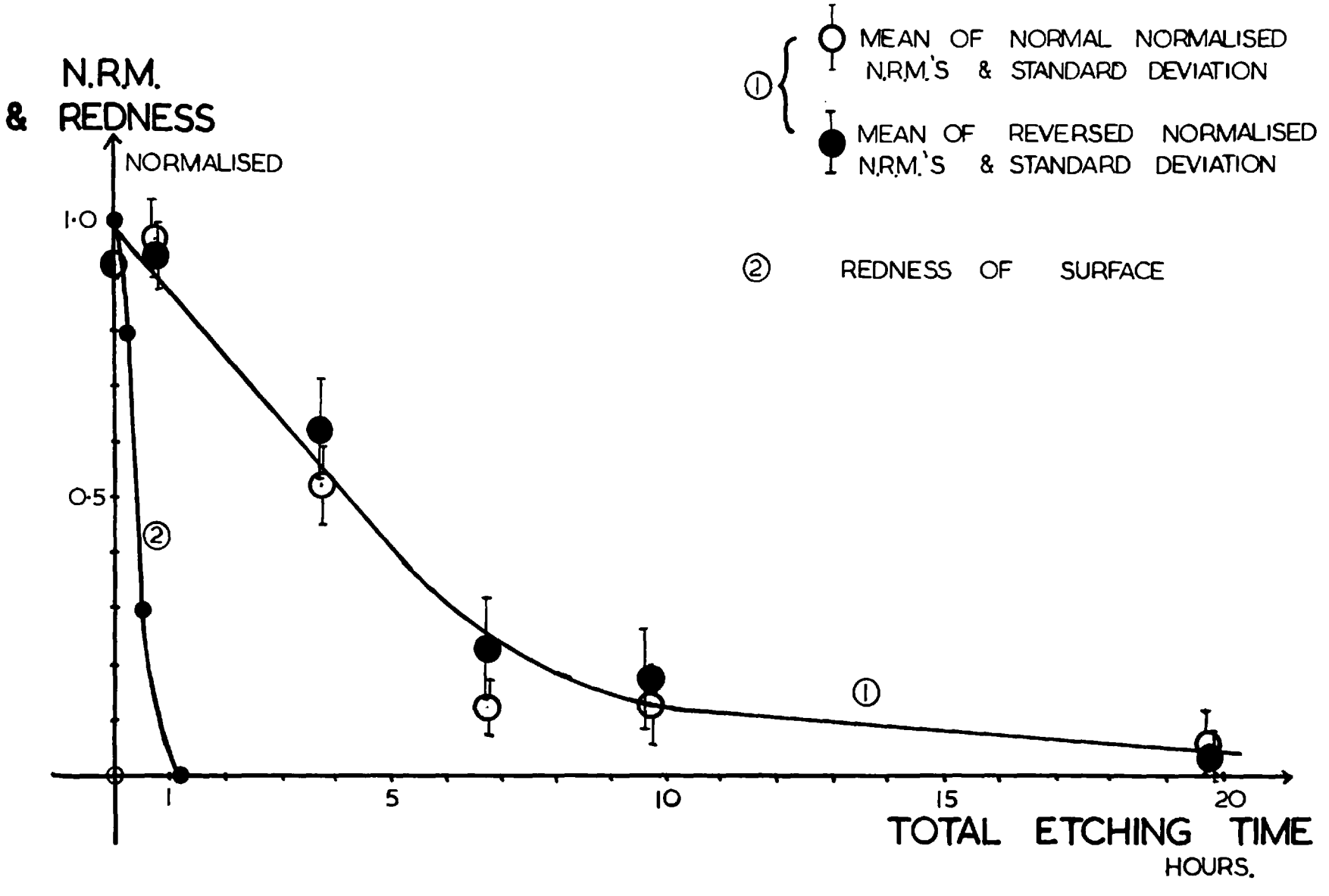

N.R.M.
& REDNESS
NORMALISED
1·0
0·5
1
5
10
15
20
TOTAL ETCHING TIME
HOURS.
①
②
① MEAN OF NORMAL NORMALISED N.R.M.'S & STANDARD DEVIATION
MEAN OF REVERSED NORMALISED N.R.M.'S & STANDARD DEVIATION
② REDNESS OF SURFACE

FIG 8.5

manner. To illustrate this point in more detail, 18 points were chosen over the area of the thin section which corresponded to high natural polarisations at zero time of etching. Nine of these polarisations were normal, and nine were reversed, and some of them correspond to the 'peaks' shown in Fig. 8.4(a). The value of each of these polarisations at each of the etching intervals was obtained from the corresponding traverse diagrams. A graph of polarisation plotted against total etching time was drawn for each of these chosen points of the thin section. Each graph was normalised, and the polarisation at zero etching was represented by 100. It was found that the fractional decrease of particular polarisation 'peaks' at each etching interval differed considerably for different 'peaks'. The average normalised intensity was calculated for the normal peaks, and also for the reversed peaks for each etching interval. These average values, together with their standard deviations are plotted against total etching time in Fig. 8.5, curve (1). Average reversed normalised values are denoted by shaded circles, and average normal normalised values are denoted by hollow circles. The standard deviations are indicated. Within the limits of the standard deviations normal and reversed polarisations are dissolved away at similar rates. After about 7 hours of etching when about 75% of both normal and reversed polarisations have disappeared, the rate of decrease of both normal and reversed polarisations slows down with the result that after 20 hours about 5% of the natural polarisation still remains. The averaged normal and reversed polarisations after 0.75

hours etching were measured to be greater than the corresponding non-etched polarisations, whereas for the first seven hours of etching there is a general decrease of natural polarisation with time.

This increase is likely to be apparent and probably is a consequence of the difficulty of keeping the thin section precisely 2 mms. away from the lower magnet at each measuring interval. At such a short distance the rate of change of sensitivity with distance must be expected to be high and although a concentrated effort was made at each measuring interval to mount the section at a constant distance from the lower magnet, each of the points in curve (1) Fig. 8.5 probably contains a systematic error as well as the indicated standard deviation. Curve (2) of Fig. 8.5 shows how the estimated general redness of the surface of the thin section is bleached away with total etching time. These estimates were obtained by comparing (by eye) the etched section at various etching times with a part of the same section which had not been etched. In about one hour the red colour of the surface had been completely destroyed. When the experiment was ended after nearly 20 hours of etching, the thin section remained in the form of a bleached-white crust which crumbled away into powder when touched.

In order to learn more about the way in which the acid attacked the volume of the thin section, a thin cylindrical specimen, 2.2 cm. diameter and 0.3 cms. thick, was left standing in concentrated HCl for 13 hours. It was then washed and dried and cut along its diameter.

The section thus exposed was studied using a watch glass. A thin bleached-white crust about 500μ thick had formed right around the specimen. Further inside, the specimen had apparently been untouched by the acid and showed the usual fresh red-brown colour. Between the two areas of different colour was a sharp dividing line of an intermediate colour and this probably represented the depth to which the acid had penetrated before the process was stopped. It seemed therefore that the acid was penetrating through the grit at an average rate of 38.5μ per hour. Applying this average rate to the thin section which was 650μ thick, the time required for the acid to penetrate through the whole volume, assuming that the acid attacked from both sides is 8.5. hours. In the case of the thin section however, the acid was circulating and this might cause the acid to penetrate at a slightly faster rate than still acid. After about 7 hours of etching the rate of decay of the natural polarisations of the thin section slows down, and this time agrees quite well with the calculated time required by the acid to penetrate through the whole volume of the thin section.

At this stage it becomes necessary to find out the petrological changes brought about by the etching process and this discussion will be continued after some petrological observations have been described in the next chapter.

Summary of Chapter:

No chemical difference between normal and reversed parts of the grit has been detected. Normal and reversed polarisations are etched by concentrated hydrochloric acid at similar rates and in a similar manner.

Chapter 9

PETROLOGICAL EXAMINATION

1. General Properties.

Two thin sections and two polished sections were prepared for examination under the microscope. The two polished sections were prepared by slicing along the axis of two cylindrical cores which had been drilled vertically through the grit, and by polishing the plane vertical surfaces. The N.R.M. of different areas of both the polished surfaces were measured by traversing with a small magnetometer (described in appendix II).

Photographs (a),(b) and (c) of photograph P.5 were taken in transmitted light, under a magnification of about 100. The white areas are quartz sand grains which are set in an apparently homogeneous opaque cement. A number of the sand grains contain cracks which are filled with the cement.

Photographs (a), (b), (c),(d) and (e) of photograph P.6 were taken of different areas of a polished section (6K) in reflected light. (a) and (b) are of reversed areas whereas (c),(d) and (e) are of normal areas. These show sand grains set in a non-homogeneous cement.

The cement consists generally of two forms. They are (1) highly reflecting (bright) areas, and (2) darker areas. The bright areas when examined under oil immersion give a high reflectivity and are a clear

TRANSMITTED LIGHT



(a)



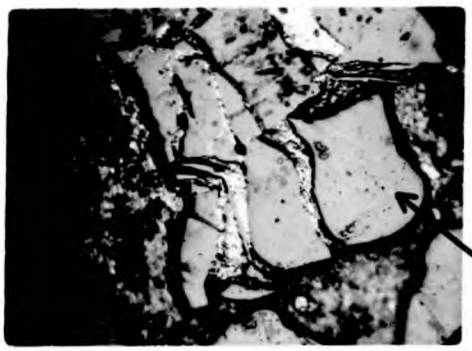
(b)



(c)

P5

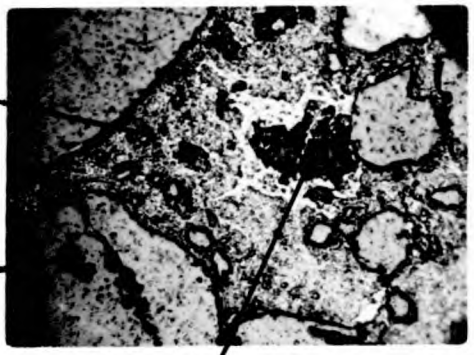
REFLECTED LIGHT



(a)

DARK CEMENT

SAND GRAINS

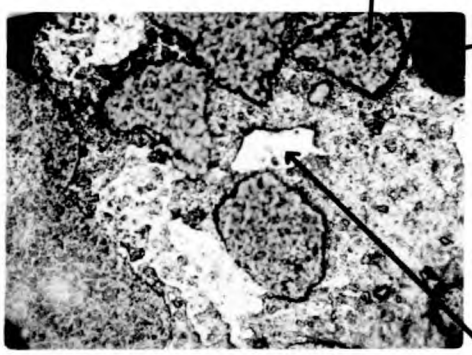


R

(b)

HOLE WITH MASSIVE HEMATITE RIM

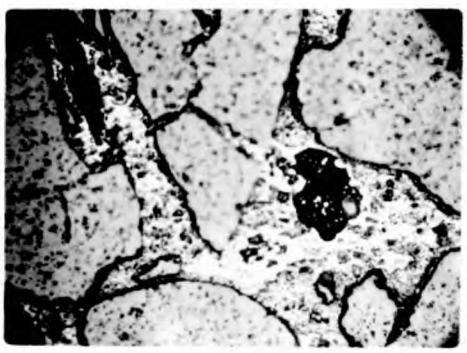
HOLE WITH NO RIM



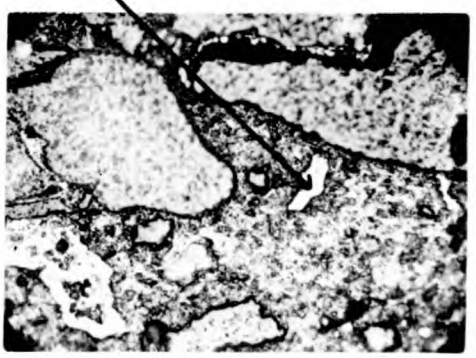
N

(c)

DISCREET PARTICLES OF MASSIVE HEMATITE



(d)



N

(e)

P6

white colour. Dr. J. Ade-Hall (Geophysics Department, Imperial College) concludes that they are areas of massive hematite. These massive hematite areas may be classed into two general types. One is in the form of discreet particles with dimensions of the order of 50 microns, having a definite boundary and structure. These are, however, rather rare. The more abundant form are the rather nebulous structures of massive hematite often having no definite shape and having a badly defined boundary: their dimensions are of the order of 150 microns, and occasionally they form a rim around a hole in the cement.

The second kind of cement is shown by the darker areas which, when examined closely appear to consist of a large number of very small bright and dark areas mixed together to give a speckled appearance. Sometimes a hole with dimensions of the order of 100 microns or more is observed in the cement. The red areas of the grit in the hand are associated with the darker parts of the cement when observed under the microscope. Dark grey areas of the cement of the grit in the hand correspond to those parts of the cement having a high proportion of massive hematite.

Some of the sand grains contain cracks which are filled with both the fine grained and the massive hematite cement. Cracked sand grains filled with cement were also observed in transmitted light. This observation suggests that the sand grains of the grit have been under considerable stress. Mr. D.J. Shearman (Royal School of Mines, Imperial College) points out that a chemical growth of the hematite cement might possibly produce great stresses on the sand grains. For example,

it is possible that crystals of the cement might have grown, under suitable conditions, out of solutions containing iron which might either have been deposited contemporaneously with the sand grains or which might have originated in the Gault clay or Folkestone sands. During their growth, the crystals may have forced the sand grains apart and would possibly form inside any imperfections or small cracks of the sand grains. These cracks would then be aggravated by a further growth of the crystals.

Alternatively, it is possible that large pressures acting on the grit might have caused the rupturing of the sand grains. In this case the cement has formed inside the ruptured sand grains either during or after the application of the pressure. In both of these cases, it is indicated that a part or all of the hematite cement has been formed, possibly chemically, after the deposition of the sand grains which were laid down on the base of the gault sea some 100 million years ago.

Under the microscope, normal and reversed areas of both polished sections appeared similar. To compare the petrology of normal and reversed areas in more detail a number of quantitative tests were devised.

2. Petrological Examination of normal and reversed areas.

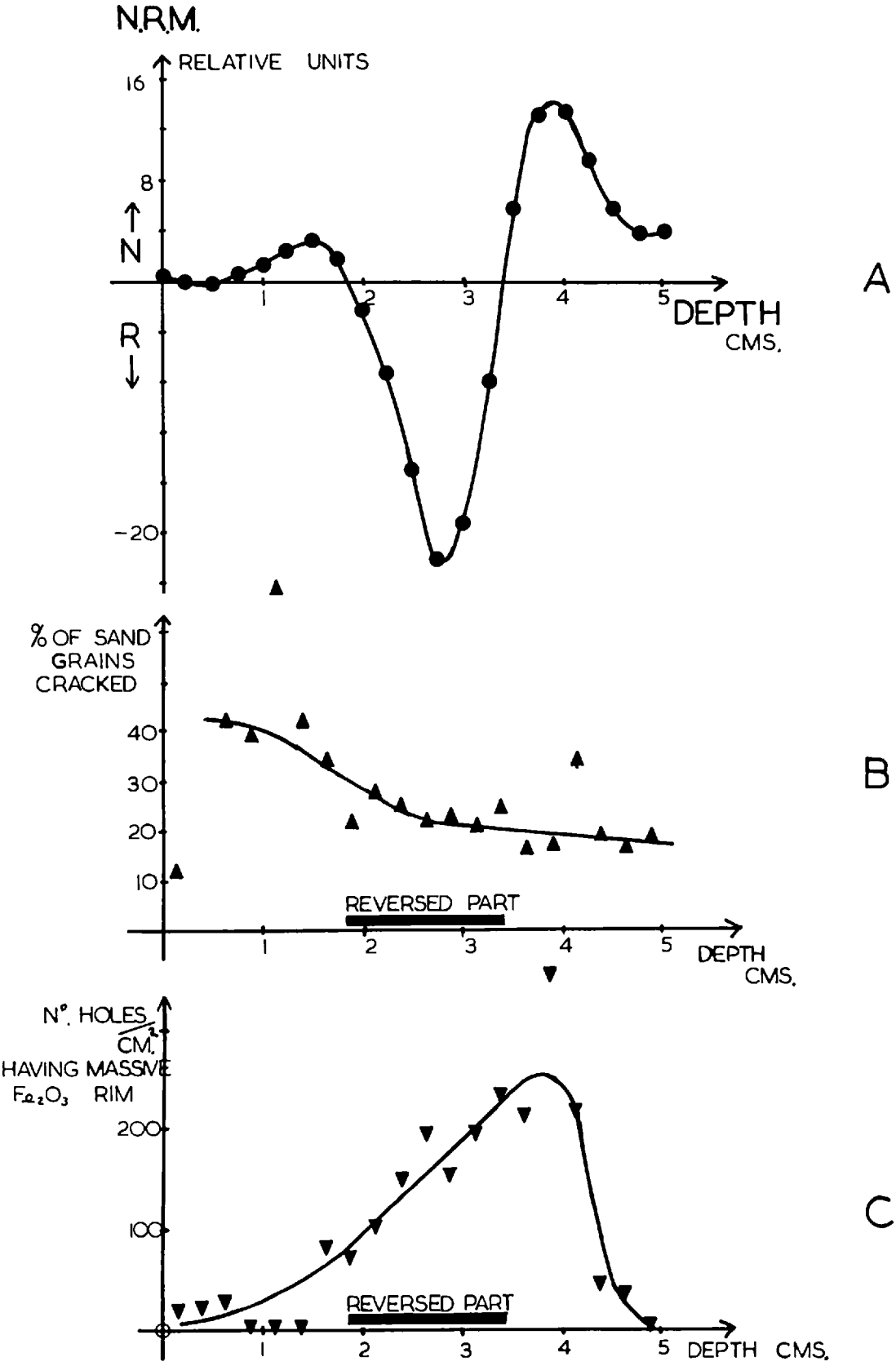
Horizontal lines, 0.25 cms. apart were drawn over the length of the two polished vertical sections. Each was traversed vertically along three different vertical paths with the small astatic magnetometer described in appendix II. The three traverses carried out for each of the

polished sections gave similar patterns of N.R.M. versus depth indicating in each case that normal and reversed areas were arranged in approximately horizontal strips. The average curve of N.R.M. plotted against depth for each of the polished sections are shown in Figs. 9.1(A) and 9.2(A). The total number of sand grains, and the number of sand grains which were cracked were counted for each horizontal strip of the polished sections. In Figs. 9.1(B) and 9.2(B) the percentage of sand grains which were cracked was plotted as a function of depth for each of the polished sections respectively.

Another quantitative test consisted in counting the number of holes in the cement which had a massive hematite rim. In photograph P.6(B) the large dark area to the right of centre is a hole which has a massive hematite rim. The dark area in the top right hand corner of photograph P.6(C) is a hole with no rim. In Figs. 9.1(C) and 9.2 (C) the number of holes per cm^2. having a massive hematite rim is plotted against depth.

In these diagrams there is apparently no relation between any of the quantities measured and the natural remanence. Other tests carried out included counting the number of holes per cm^2. without massive hematite rims, counting the number of discreet particles of hematite per cm^2., and counting the total number of sand grains per cm^2., and plotting as a function of depth for each polished section. Some of these quantities did not give smooth curves but those that did gave a curve which indicated no relation whatsoever to the N.R.M. curve of the corresponding polished section.

FIG 9.1
POLISHED VERTICAL SECTION 6K



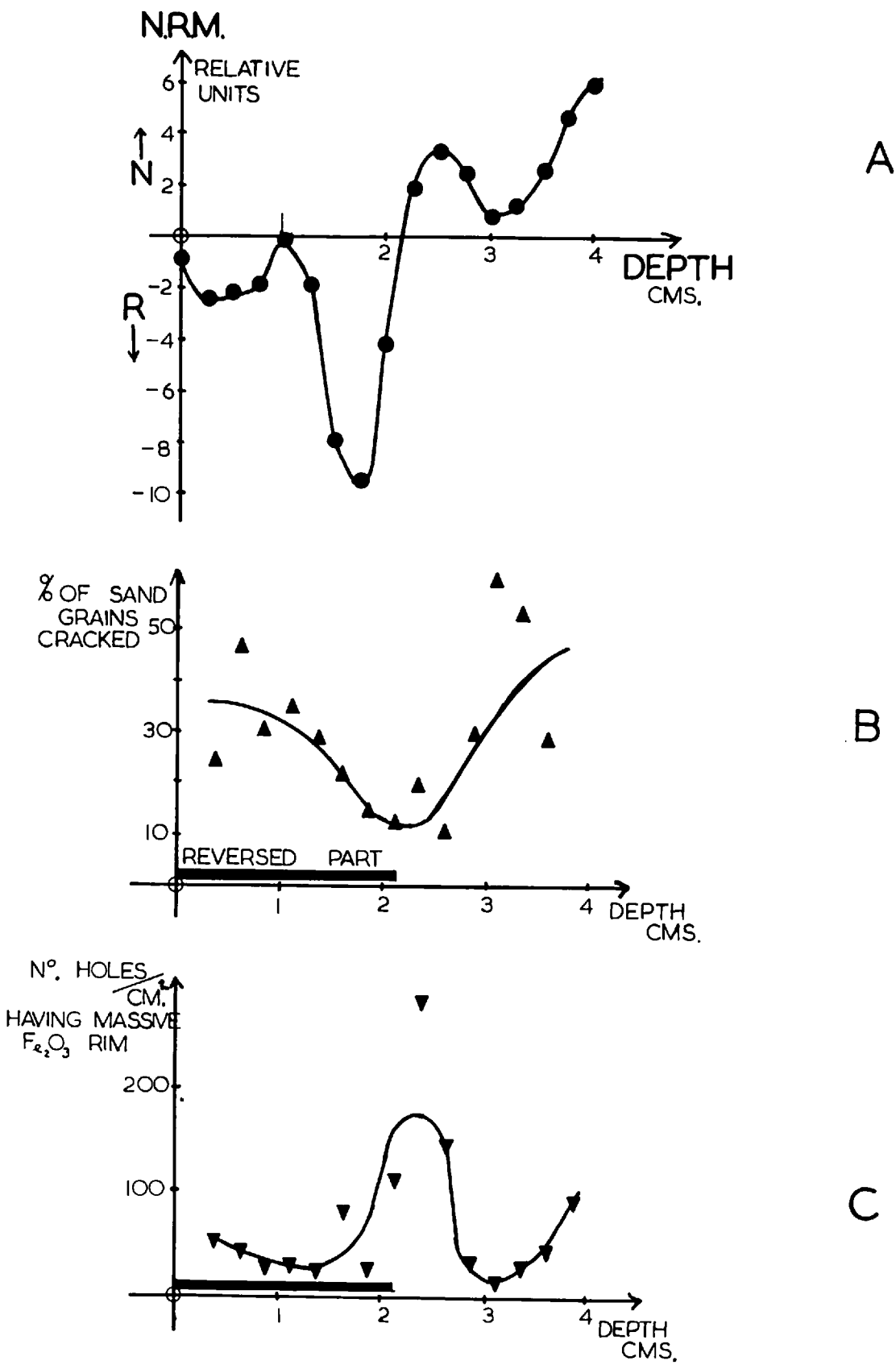

POLISHED VERTICAL SECTION 6MI
N.R.M.
RELATIVE UNITS
6
4
N
2
-2
R
-4
-6
-8
-10
2
3
4
DEPTH CMS.
A
% OF SAND GRAINS CRACKED
50
30
10
REVERSED PART
1
2
3
4
DEPTH CMS.
B
N°. HOLES / CM.² HAVING MASSIVE Fe_2O_3 RIM
200
100
1
2
3
4
DEPTH CMS.
C

FIG 9.2

No petrological difference between normal and reversed areas of the polished sections was discovered.

3. Etching with concentrated HCl.

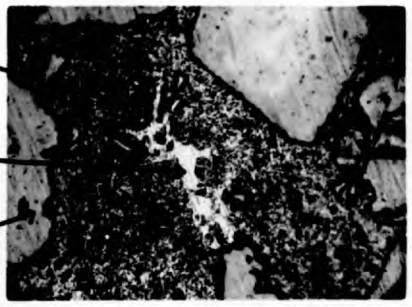
In Chapter 8, the decay of the natural polarisations of a section 650μ thick, was observed at different etching times. This paragraph is concerned with observing petrologically the effects of the acid on the fine grained red cement and on the massive hematite particles of the cement. A polished section was examined under the microscope, and a few rather well defined particles of the massive hematite were located: the turn-table co-ordinates of their positions were recorded for future use. Photographs P.7 (a) show two of these particles. The surface of the polished section was then dipped into a bath of concentrated hydrochloric acid and was taken out at different times and examined. Photographs P.7 (b),(c) and (d) show the same two locations as P.7(a) at different times of etching. After 5 minutes of etching both massive hematite particles showed up very clearly against the general background of finer grained cement. After about one hour of etching cracks started to appear in the cement, but the general definition of the massive hematite particles remained good. After about 7 hours both particles were starting to merge into the general background. For longer times of etching the particles did not show up well on photographs but they remained visible up to 13 hours of etching after which time there was a slight colouration at the positions where they were originally seen. On the other hand the general

EFFECTS OF ETCHING STUDIED IN REFLECTED LIGHT

(a)



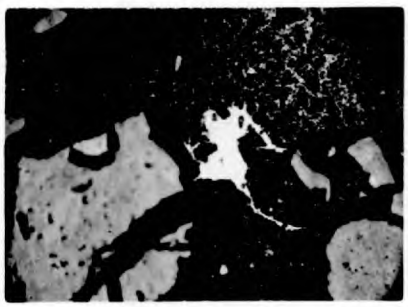
UNETCHED



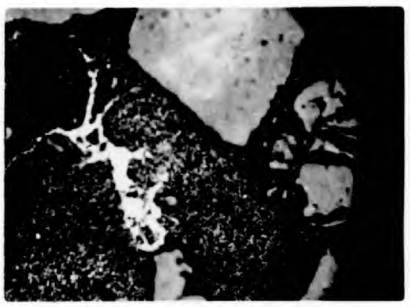
UNETCHED

(a)

(b)



5 MINS. ETCHING



5 MINS. ETCHING

(b)

(c)



2 HOURS ETCHING



5 HOURS ETCHING

(c)

(d)



7 HOURS ETCHING



7 HOURS ETCHING

(d)

redness of the polished section was bleached away at a more rapid rate. After one hour of etching the polished surface was estimated by eye to be about 30% of its original redness and before 3 hours the surface was completely bleached.

The results of the etching experiments carried out on the thin section described in Chapter 8 can now be discussed. If it is assumed that the natural polarisation of the grit is carried by both the massive hematite parts (grey areas) and the fine grained parts (red areas) of the hematite cement, then the decrease of the rate of decay of the natural polarisations of the thin section after about 7 hours of etching (Fig. 8.5 curve 1)possibly receives a simple explanation. It has already been calculated, (Chapter 8) that the acid would probably take less than $8\frac{1}{2}$ hours to come in contact with the whole volume of this thin section. During this time it would therefore be reacting with both the fine grained cement (rapidly) and with the massive hematite particles (less rapidly) as it progressed into the section. Any part of the natural magnetisation associated with each of these two types of cement would presumably be progressively destroyed. However, when the acid had finally penetrated fully through the specimen, before $8\frac{1}{2}$ hours in this case, all the red parts of the cement together with their natural polarisations would be destroyed. The remainder of the natural polarisation carried by the massive hematite particles would continue to be destroyed at a slower rate. This explanation could possibly account for the bend

observed in Fig. 8.5. curve 1 after 7 hours of etching. It therefore seems possible that the natural polarisation of both normal and reversed parts of the grit is carried by both the massive hematite particles (dark grey areas in the hand) and the fine grained hematite cement(red areas in the hand). This conclusion would account for there being no correlation whatsoever of N.R.M. with redness (Fig. 7.2).

SUMMARY

The cement of the grit is composed of fine grained hematite and massive hematite, each of which probably carry part of the natural polarisation. The evidence of cracked sand grains suggests that the cement has been produced (possibly chemically) after the laying down of the sand grains of the grit.

No petrological difference has been detected between normal and reversed areas of polished sections.

Chapter 10

DISCUSSION AND CONCLUSION

The following two points will be considered.

(1) The identification of the magnetic mineral or minorals which carry the natural polarisation of the iron grit.

(2) The process or processes by which normal and reversed parts of the iron grit have become magnetised.

(1) The Magnetic Mineral Associated with the N.R.M.

Identification of the major magnetic component of the iron grit is the easier task and will be considered first.

The chemical analysis, described in Chapter 8, showed that the grit contains about one-third by weight Fe_2O_3 and about half a percent of FeO, these being the only minerals which could possibly account for its magnetic properties. The Fe_2O_3 might exist either as hematite or as maghemite. The half percent of FeO might indicate the presence of up to about 1.5% magnetite (Fe_3O_4) whose saturation magnetisation is 200 times greater than that of the same weight of hematite. The major magnetic component of the grit is therefore due either to one of the minerals, magnetite, maghemite or hematite, or to a mixture of these three minerals. The results obtained show that the major magnetic componont of the grit is associated with only one mineral. The thermal demagnetisation

of the T.R.M. acquired by a normal and a reversed specimen in 0.5 Oe (Fig. 7.6) shows a smooth curve of near rectangular shape which has one curie temperature only. One curie temperature indicates that there is one major magnetic component within the grit with no trace of a minor component. The remanent hysteresis curve, Fig. 7.14 curve (1) confirms this. This shows remanence plotted against reverse field for an unheated specimen after it had been placed in a field of 11,000 Oe. It is a smooth curve which suggests one magnetic component only. Further, Fig.7.18 shows induced magnetisation plotted against field for fields up to 4,000 Oe. The induced magnetisation varies linearly with field for increasing and decreasing fields, indicating one magnetic component. The results thus show that the major magnetic component of the grit is associated with one mineral only, and fail to show the presence of a minor magnetic component. The major magnetic component can now be identified.

Fig. 7.10 shows remanence plotted against reverse field for 5 specimens of the grit after each had been placed in 29,000 Oe. The curves show that none of the remanences are completely saturated for fields up to 29,000 Oe. The remanent coercive forces range from 3,000 to 10,000 Oe. No other oxide of iron but hematite is known to have a coercive force as high as several thousands of oersted. These results indicate then that hematite is possibly the only mineral responsible for the magnetic properties of the grit. The curie temperatures obtained by thermally demagnetising T.R.M.'s (Acquired in 0.5 Oe) and high field remanences (induced in 10,000 to 15,000 Oe) range from 580°C to 620°C. (Fig. 7.7).

Such a range is not inconsistent with a major magnetic component of impure hematite, but is a little too high to represent magnetite. Experience has shown that impurities lower the curie temperature of a mineral. Carmichael[246] (1961) found that ilmenite - hematite crystals from the Allard Lake region of Quebec had a curie temperature of 600°C. These crystals had a composition of about 10 mol. percent of ilmenite in hematite. The results therefore suggest that an impure form of hematite is responsible for the magnetic properties of the grit. There is no trace of another magnetic component.

However, although the major magnetic component of the grit is hematite, it does not necessarily follow that the natural polarisation is carried by this mineral, since the natural remanence is less than 10^{-3} of the saturation remanence. It is possible that the N.R.M. might be carried by a previously undetected mineral of which there is only a trace present. Two points however, support the possibility that the mineral responsible for the major magnetic component is also the seat of the natural remanence. They are (1) that thermal demagnetisation of natural remanences gives a range of curie temperatures whose mean value is close to the curie temperatures obtained by the thermal demagnetisation of T.R.M.'s and high field remanences, and (2) that alternating field demagnetisation has little effect on both natural and high field remanences for alternating fields up to 750 Oe.

It appears that the N.R.M. of the grit is carried by hematite which is in the form of a red-brown cement. It was concluded at the end of Chapter 9 that the N.R.M. of both normal and reversed parts of the grit is possibly associated with both the massive particles and the fine grained parts of this cement.

(2)
Possible magnetisation processes.

The results illustrated by Fig. 6.3 have shown that normal and reversed parts of the grit generally form approximately horizontal bands whose thicknesses vary from a few millimetres to 2 cms. . Any theory concerning the magnetic history of the grit should account for this observed sequence of reversals. A number of possible processes by which the grit might have become magnetised are ;

(a) by thermal processes (T.R.M.)

(b) by the orientation of magnetic particles during deposition,

(c) by isothermal inducation caused by the earth's field over long periods of time,

(d) during chemical formation of the magnetic minerals.

(a) The grit has had a sedimentary origin (Kirkaldy[14] 1935). It is very unlikely that the grit has ever been heated to temperatures above about 500°C during the course of its history, since if this were the case

both the Folkestone sands and gault clay which are both in direct contact with the grit would show marked igneous effects. They show no effects of heating. It is therefore rather unlikely that the N.R.M. of the grit is thermoremanent.

(b) It is possible that the N.R.M. of the grit might have originated by the statistical alignment of ferromagnetic mineral grains along the direction of the earth's field during deposition on the bed of the gault sea some 100 million years ago. Assuming an average rate of sedimentation of 780 feet per million years (obtained from Holmes Revised time scale (1959)[12] 6 inches of grit would have been deposited during a period of the order of 10^3 years. During this relatively short time the earth's field would have probably been in either a normal or a reversed sense and the grit would have become magnetised in the same sense. Subsequent to deposition the grit has suffered a certain amount of alternation and cementation. It is possible that during this later cementation process the original depositional N.R.M. has become considerably altered with the result that parts might have become magnetised in the opposite sense. For simplicity, a simple but possible example will be considered.

It is possible that the grit was originally magnetised by the alignment of particles of magnetite during deposition while the earth's field was in either a normal or a reversed sense. During alteration and cementation at a later date these magnetite particles might have become oxidised to hematite. Graham (1953) has proposed a plausible

mechanism based on a consideration of one of Neel's (1952) mechanisms which might possibly account in this case for the reversals of the natural magnetisation. Oxydation of the outer layers of the original magnetite grains to hematite may or may not result in the hematite becoming magnetised in the opposite sense to the magnetite grain depending on the geometry of the magnetite grain.

No doubt there are several other ways by which parts of the grit might have become self reversed during the alteration and cementation processes after deposition. In the case of the example considered above, and in the other possible processes one would expect that a geometrical or petrological difference might exist between normal and reversed parts of the grit. No such difference has been observed. Most of the massive hematite particles from both normal and reversed areas have no defined geometrical shape and on the contrary are rather nebulous structures. The rest of the cement is very fine grained. However, it is possible that a petrological difference once existed but has since been obliterated.

Also in the case of the example considered above, or in other possible cases, one might expect that the N.R.M. might consist of two separate magnetic components. One component might be the original depositional N.R.M. whereas the second component would be that produced during the alteration process. Only one magnetic component has been found in the grit. Again however it is possible that the original depositional N.R.M. has been obliterated during the alteration processes.

The only available direct evidence does not however favour the N.R.M. as having a depositional origin. The palaeomagnetic record for Europe (obtained from Blackett et al (1960)[15]) indicates that 100 million years ago when the grit was deposited the dip of the earth's field in Britain was 52°. It is generally accepted that in most cases of depositional magnetisation the dip of the acquired magnetisation is often less than that of the ambient field, sometimes by as much as 10°, and by 20° in some cases (Rees). One might therefore expect that if the N.R.M. of the grit had had a depositional origin, its dip might be less than 50°. This is not the case. The observed dip is 69°, and on correcting for the tilt of the grit which is 3° in a southerly direction, becomes 72° relative to a horizontal sea bed. A depositional origin of the N.R.M. of the grit is therefore hardly consistent with the observed dip.

(c) Another possibility which might account for the reversals of the natural magnetisation in the grit is that both normal and reversed polarisations have been induced isothermally in the earth's field over long periods of time. It has been shown by Neel[22] (1949) that the relaxation times for long period phenomena depend very critically on the grain size and on the composition of the magnetic minerals present in the rock. It is therefore possible, owing to very small differences, for different sections of the same rock mass to follow changes in the external field with vastly different time lags, and so have different polarisations at the present time. If we accept the estimates of Hospers (1951)[9] and Cox et al (1963)[10] and take the average

period between reversals of the earth's field to be of the order of 10^6 years, it must be assumed that the reversed sections of the grit have relaxation times greater than 10^6 years whereas the relaxation times of normal parts are considerably less than 10^6 years. Further it must be assumed that the earth's field has recently been in a reversed sense for a long enough time (greater than 10^6 years) to induce most of the magnetic grains of the grit to a reversed sense. In this case, since the last reversal of the earth's field to a normal sense all the grains with relaxation periods considerably less than 10^6 years would become magnetised approximately along the direction given by an axial dipole. This is in fact observed. The mean normal direction of the N.R.M. lies close to that which would be given by an axial dipole.

On the other hand, this theory requires that a physical difference exists between normal and reversed parts of the grit. In particular one might expect the thermal demagnetisation of normal polarisations to give a different result to the thermal demagnetisation of reversed specimens. This is not the case. No significant physical difference has been detected between normal and reversed specimens, and the thermal demagnetisation of normal polarisations gives a curve very similar in shape to that of reversed polarisations. One third of both normal and reversed polarisations require temperatures above $550^{\circ}C$ for thermal demagnetisation (see Fig. 7.6). It is however possible that such a physical difference does exist between normal and reversed polarisations

but is so slight as to remain undetected.

Finally, the close similarity between the spread of directions about the mean normal direction and the spread of directions about the mean reversed direction (Fig. 4.1(A) is not consistent with this theory. If the reversed polarisations were stable over long periods of time whereas the normal polarisations were unstable and had followed the earth's field to a normal sense (as postulated), then one might reasonably expect that the spread of the normal directions about their mean direction would be either appreciably more, or considerably less than the spread of the reversed directions about their mean direction. As it happens, both normal and reversed directions are fairly well grouped about their respective mean directions by about the same extent (see Fig. 4.1(A).)

In general, owing to the great experimental difficulties involved in obtaining reliable information concerning long period relaxation phenomena, present knowledge on the subject is scanty, and it becomes difficult to estimate in any further detail whether or not the natural magnetisation of the grit has been induced isothermally in the earth's field over long periods of time.

(d) Another possibility is that both normal and reversed polarisations of the grit have had a chemical origin, and are chemical remanent magnetisations (C.R.M.'s). This is a plausible theory and would be consistent with many of the results described. The structure of the hematite coment which carries the N.R.M. consists in parts of massive

hematite grains of varying sizes whereas other parts are extremely fine grained suggesting a chemical growth. Such a process would automatically fit in with the alteration and cementation processes which Kirkaldy (1935) reports as having taken place in the grit subsequent to deposition. Also, Shearman (private communication) has pointed out that observed cracks in some of the quartz sand grains suggests that they have been caused by the crystal growth of the hematite cement after deposition of the sand grains. It therefore seems likely that a large part of the alteration and cementation processes which have taken place in the grit have consisted of the crystal growth of the cement and it is possible that the N.R.M. has originated during these processes as a C.R.M.

The shape of the thermal demagnetisation curves of normal and reversed natural polarisations is consistent with their being chemical remanent magnetisations. Haigh[17] (1958) has shown that the thermal demagnetisation curve of a C.R.M. has a similar shape to that of a T.R.M. produced in the same mineral but is a little less rectangular. Accordingly, thermal demagnetisation of the natural polarisation of the grit produces a curve resembling the thermal demagnetisation curve of its T.R.M. but is less rectangular (compare curves 1 and 2 of Fig. 7.6). Assuming then, that the N.R.M. of the grit has originated during the chemical growth of the cement subsequent to deposition, two possibilities might now account for the presence of both normal and reversed polarisations within the grit.

The first possibility is that the chemical process which produced the hematite crystals was completed in a period short compared with the period between reversals of the earth's field, the latter being generally accepted to be about a million years. The ambient field directing the magnetisation processes would in this case probably be in either a normal or a reversed sense, and any parts of the grit that have become magnetised in the opposite sense are likely to be self reversed. Neel (1951)[4] has predicted four possible self reversing mechanisms, two of which postulate that the original magnetisation can under certain circumstances reverse over long periods of time : one of these two mechanisms might apply in the case of the grit, and it is possible also to visualise variants of the Neel processes which might cause self reversals to occur in a sedimentary rock which has acquired a chemical remanent magnetisation. In general, self reversing mechanisms are not uncommon. Reversal of the spontaneous magnetisations of rock and synthetic samples on cooling from above their curie temperature in a magnetic field have been reported by Uyeda and Gorter respectively: Carmichael (1961)[6] has observed a partial reversal of the spontaneous magnetisation of some ilmenite-hematite crystals when cooled in a magnetic field. However, at present, chemical remanent magnetisations have not been studied as extensively as thermo-remanent magnetisations and it is difficult to estimate whether or not a self reversing mechanism would account for either the normal or the reversed polarisations of the grit.

If however a self reversing mechanism were responsible for either the normal or the reversed polarisations, one might expect that a physical, chemical or petrological difference has existed between normal and reversed parts. The only possible difference that has been detected is that the strengths of normal polarisations do not apparently range as high as those of reversed specimens (Chapter 7 paragraph 2). This is not supported by any other physical difference and it is difficult to estimate whether or not this result would favour a self reversal: in any case, its true significance is questionable (see Chapter 7 paragraph 2).

On the other hand it is possible that a significant difference between normal and reversed parts does exist but that the applied tests have not been sufficiently sensitive to detect them. Alternatively, any differences which may once have existed may possibly have since been obliterated.

The second way by which a chemical magnetisation might account for the presence of both normal and reversed polarisations within the grit is based on field reversal.

It is possible that the hematite cement crystals have grown at a sufficiently slow rate to include one or even more reversals of the earth's field. In this case, normal polarisations would have been chemically magnetised by a normal field, and reversed polarisations by a reversed field; no statistical difference between normal and reversed

parts of the grit would be required. However this theory requires that a time difference of the order of a million years has elapsed between the chemical formation of normal and reversed parts of the cement which are sometimes only a few millimeters apart. The failure to detect a consistent correlation between the colour pattern and the natural magnetic pattern, which consists generally of normal and reversed parts arranged in approximately horizontal bands, might suggest that the chemical growth of the cement crystals was a slow but continuous process forming approximately horizontal layers one after the other. Within the present bounds of knowledge, not a great deal is known about chemical remanent magnetisations and less is known of the speeds by which natural chemical reactions and crystal growths are completed in the field at ordinary temperatures. It is difficult therefore to estimate which of the two possible chemical processes considered might be the more likely.

3) Summary and Conclusions.

It has been shown in Part I of this thesis that normal and reversed parts of the iron grit are usually arranged in approximately horizontal layers whose thicknesses generally range from a few mms. to 2 cms.

Part 2 has described the results of experiments investigating the physical, chemical and petrological properties of the grit. These

experiments indicate that the N.R.M. is carried by one magnetic component which has been identified as an impure form of hematite existing, with small amounts of other minerals, as an inhomogeneous opaque red-brown cement. Examination under the microscope reveals that parts of the cement are very fine grained whereas other parts consist of particles of massive hematite with dimensions of about 150μ or less. It has been suggested on the basis of experiments measuring the rate at which concentrated hydrochloric acid destroys the N.R.M. of a thin section that the fine grained and massive hematite parts of the cement are both possibly associated with the N.R.M.

The most likely origin of the N.R.M. is that it has been acquired chemically during the crystal growth of the hematite cement. The date at which this crystal growth took place cannot be fixed with much certainty: the evidence of cracked sand grains indicates that it has occurred sometime after deposition, which took place 100 million years ago on the bed of the gault sea. The only other available clue to the date of the magnetisation of the grit is given by the mean polarisation directions which are very close to the directions given by an axial dipole. This result might suggest that the grit has become magnetised possibly within the last 20 million years.

The actual process by which a depth of less than six inches of grit has acquired two oppositely directed polarisations is however not at all clear. This problem, which originally stimulated the investigation

has certainly been made more intriguing by the results obtained but its correct explanation at present remains uncertain. Two completely different theories of chemical magnetisation have been considered: whereas one supposes that the earth's field has reversed the other does not require field reversal. Because of the failure to detect a significant difference between normal and reversed parts of the grit, the results of this work must be interpreted as slightly favouring field reversal as an explanation, rather than a self reversal. However this theory is based on a negative result and is therefore extremely difficult to prove.

The results obtained by workers in rock magnetism are generally held to indicate that the earth's magnetic field has periodically reversed over past geological ages. However, within the circumstances of the present investigation, it is not possible to be certain whether or not the reversed parts of the grit (which show no apparent self reversal properties) do or do not indicate an ancient reversed field. It is possible that on a more extensive investigation the correct magnetic history of the grit may be revealed. In the mean time the present investigation underlines the importance of treating all cases of magnetic reversals in rocks with caution. In each case the implications of the magnetic reversal should be considered cautiously until the magnetic history of the rock can be established.

A C K N O W L E D G M E N T S

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Dr. J.A. Clegg supervised the first few months of this work and I am grateful to him for locating some of the best exposures of the iron grit.

I thank many others who have helped me in many ways while I have been a member of the Rock Magnetism Group at Imperial College. In particular Dr. J. Ade-Hall and Mr. D.J. Shearman for their important help with the petrology of the grit; Miss Jennifer Langbein for carrying out the chemical analyses; Mr. G.W. Masse for his assistance during rock collecting trips; Mr. M. Lewis for taking the coloured photographs of the exposures; Dr. J.F. Kirkaldy for a discussion which helped to locate the grit, and Dr. A.E.M. Nairn for supplying me with some samples of the grit.

Finally, Mrs. M.E. Aviss typed this thesis and Mr. E. Sparks photographed the diagrams: I am indebted to both for their speedy and efficient co-operation in completing this thesis.

APPENDIX I

(a) POSITIONS AND STATE OF EXPOSURES OF THE IRON GRIT.

Most of the exposures and their positions have been excellently described by Kirkaldy. (Kirkaldy 1935). However some of these were unsuitable for palaeomagnetic work as little of the grit actually in situ could be found. The exposures which are suitable for collecting samples for palaeomagnetic work will be briefly described.

The best exposure is at the top of the large sand quarry worked by the Marley Brick and Tile Company just south of Chantry Mill, an eighth of a mile south east of Storrington. Here the Gault Clay is very thin and may be shovelled away to expose a large quantity of grit.

Another good exposure where the clay can be shovelled away quite easily is the sunken lane by Willshers Yard, 700 yards south of Cootham.

At the sand pit near Fittleworth Station the clay has been removed from above and the sand below has been dug away for some distance and the grit juts out. This grit is much more weathered than usual and is very difficult to core without cracking.

Other good exposures are the road side exposures near Duncton Post Office and by Dunford Lodge near Heyshott Green. At the latter the thickness of the grit is less than 1 inch and is obviously approaching its western extreme.

Another exposure may be found in the hollow about 300 yards North West of the junction of the Storrington and London-Worthing roads.

(b) METHOD USED TO NUMBER EACH SPECIMEN ACCORDING TO ITS POSITION IN SITU IN THE GRIT

Rock samples all representing the full thickness of the grit at their respective sites were collected. They were assigned the numbers 17, 5, 6, 21, 22, 23, 26 and 29 (See map of Fig 1 for their sites). A number of vertical cores were drilled from each of these samples. Consider for example cores drilled from sample 21. They were marked 21A, 21B, 21C .... Each core was then sliced into several specimens. The top slice of core 21B, for example, was marked 21B1, the next 21B2 and so on. It is therefore a simple matter to find out merely from their numbers, whether any two specimens were, for example adjacent to one another when in situ. Very often such specimens have oppositely directed polarisations.

APPENDIX II

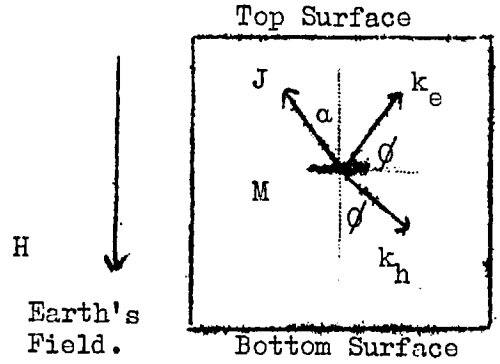
THE MAGNETOMETER AND METHOD USED TO DETERMINE THE MAGNETIC PATTERNS OF SECTIONS

Sections cut vertically through the iron grit were available. It was required to measure the field two mms. from the plane sections due to the vertical component of the N.R.M.

A small astatic magnetometer system was constructed. It consisted of two magnets each made of vicalloy wire, 5 mms. long and 0.25 mms.diameter oppositely directed and glued to opposite ends of a glass spindle of length 2.3 cms. and 0.5 mm. diameter. A small circular mirror was also glued on the spindle. The strength of each magnet was 0.16 e.m.u. The system was suspended by a phosphor bronze ribbon suspension, 40 cms. long and .003" in width, and enclosed in a glass casing of diameter 3.0 cms which had to be pointed with aquadag to eliminate electrostatic disturbances. Angular deflections of the system were measured by a light beam and scale. The casing was attached to the wall by dexion frame and a turn-table was arranged on the bench directly below. The sections of grit were arranged on this turn table in such a position that their plane surfaces were about 2 mms. below the bottom magnet of the astatic pair. It was impossible to place the usual thick copper disc for damping purposes below the bottom magnet owing to a lack of space in this case. The astatic system was

adequately air-damped by means of thin strips of light paper attached to the glass spindle. The experimental procedure consisted in arranging the section on the turntable so that the lower magnet of the astatic pair was perpendicular to the section's vertical direction. Since it was known that the grit was usually magnetised approximately in a vertical sense (dips about $\pm$ 68°) it was reasoned that a deflection of the system was caused by the natural remanent magnetisation of that small volume of grit immediately below the lower magnet plus the polarisations induced in the same small volume of grit by the earth's field and by the field of the lower magnet, which was estimated to be about 20 Oe. at the surface of the section nearest to the magnet. Experiments measuring the variation of induced polarisation with field had been carried out and these indicated that for fields up to 2,000 Oe the induced polarisation practically disappeared on removal of field. Experiments concerning the effects of A.C. demagnetisation on the N.R.M. of the grit show that alternating fields up to 750 Oe have little effect. Hence it was assumed that on rotation of the turntable the N.R.M. vector was not appreciably affected by either the earth's field or the field due to the lower magnet. It was also assumed that there was no appreciable rotational hysteresis of the induced polarisations caused by fields due to the earth and lower magnet. The following theory shows that the induced polarisations due to the earth's field and the field of the lower magnet can be eliminated by rotating the section through 180° about an axis coincident with the axis of the astatic magnets and subtracting the two deflections obtained.

It is assumed for the purpose of this theory that the grit is anistropic. Let k_e be the susceptibility in the easy direction of magnetisation and k_h the susceptibility in a direction 90° to this, both directions being in the plane of the surface of the section considered. In the diagram M is the lower magnet.



J is the projection of the N.R.M. onto the plane surface and makes an angle α with the normal to magnet M. H is the earth's field in the direction shown. Let H_m be the field at the section caused by magnet M. The deflection, ϑ_1, of the system, assumed small, will be proportional to the component of the magnetisation (normal to magnet M) of the small volume of grit which lies immediately below M. i.e.

$$\vartheta_1 \propto J\cos\alpha + k_e H_m \cos\phi\sin\phi - k_h H_m \sin\phi\cos\phi - k_H H\cos^2\phi - k_e H\sin^2\phi$$

i.e.

$$\vartheta_1 \propto J\cos\alpha + H_m \frac{\sin 2\phi}{2}(k_e - k_h) - H(k_h\cos^2\phi + k_e\sin^2\phi) \qquad \ldots\ 1.$$

Rotation of the section though 180° makes

$$\alpha \longrightarrow \alpha + 180$$

and

$$\vartheta \longrightarrow \vartheta + 180^\circ$$

Hence the new deflection ϑ_2 is proportionally given by

$$\vartheta_2 \propto \ldots - J\cos\alpha + \frac{H_m \sin 2\phi}{2} (k_e - k_H) - H (k_h \cos^2\phi + k_e \sin^2\phi) \quad \ldots.2.$$

Subtracting the (2) from (1) gives a deflection 2ϑ, proportionally given by

$$2\vartheta \propto 2J\cos\alpha$$

$$\text{or} \quad 2\vartheta \propto J_\alpha$$

where $2\vartheta = \vartheta_1 - \vartheta_2$ which is independent of any induced components due to the fields of the earth and lower magnet.

J_α is the vertical component (with respect to the grit in situ) of the N.R.M. of a small volume of the grit immediately below the magnet M.

Before carrying on with experiments on the grit, it was estimated that the magnet M when a distance of 2 mms. away from the grit surface might induce a polarisation of up to 1000 x 10^{-6} e.m.u./grm. which is an order of magnitude greater than the N.R.M. The induced component dies off proportionally as the inverse cube of the distance within the grit from the magnet M. If the grit were isotropic this induced component would produce no deflection of the magnetometer. However on the other hand, if the grit were highly anisotropic the deflection due to an induced anisotropic component might possibly be considerably larger than that due to the N.R.M. Subtracting two deflections $(\vartheta_1 - \vartheta_2)$ to eliminate a large anisotropic

quantity to obtain a smaller quantity (N.R.M.) might in this case possibly introduce serious errors in the measurement of J_a. Since it was very difficult to estimate theoretically the actual effect of any induced anisotropic polarisation it was decided to carry out an experiment to find out whether or not sensible results were being obtained.

A plane section, cut vertically from the grit was chosen and placed on the turntable so that the plane surface was 2 mms. from the lower magnet. Keeping the grit's vertical direction normal to the lower magnet, the section was moved about until a reasonable deflection corresponding to a normal N.R.M. was obtained. Rotation through 180° and back again gave three measurements which enabled one to obtain 2θ independent of the steady drift of the zero which was in any case quite small on this instrument. The turntable was then rotated by 20° in a clockwise direction and another value of 2θ was measured by rotating through 180° from and back to this position. This procedure was repeated at 20° intervals for a complete revolution. The same experiment was carried out for a reversed portion of the same section of grit. The results obtained are plotted in Fig. A1. Clearly in both cases, sensible results were being obtained. For, since each measurement consisted in obtaining the difference between two deflections as indicated by the previous theory, the deflection 2θ is a measure only of the component of the N.R.M. normal to the lower magnet M of the small volume of grit near to M. As the section is rotated this component should vary as a $\sin\theta$ curve. (Anisotropic components induced by the lower magnet vary as

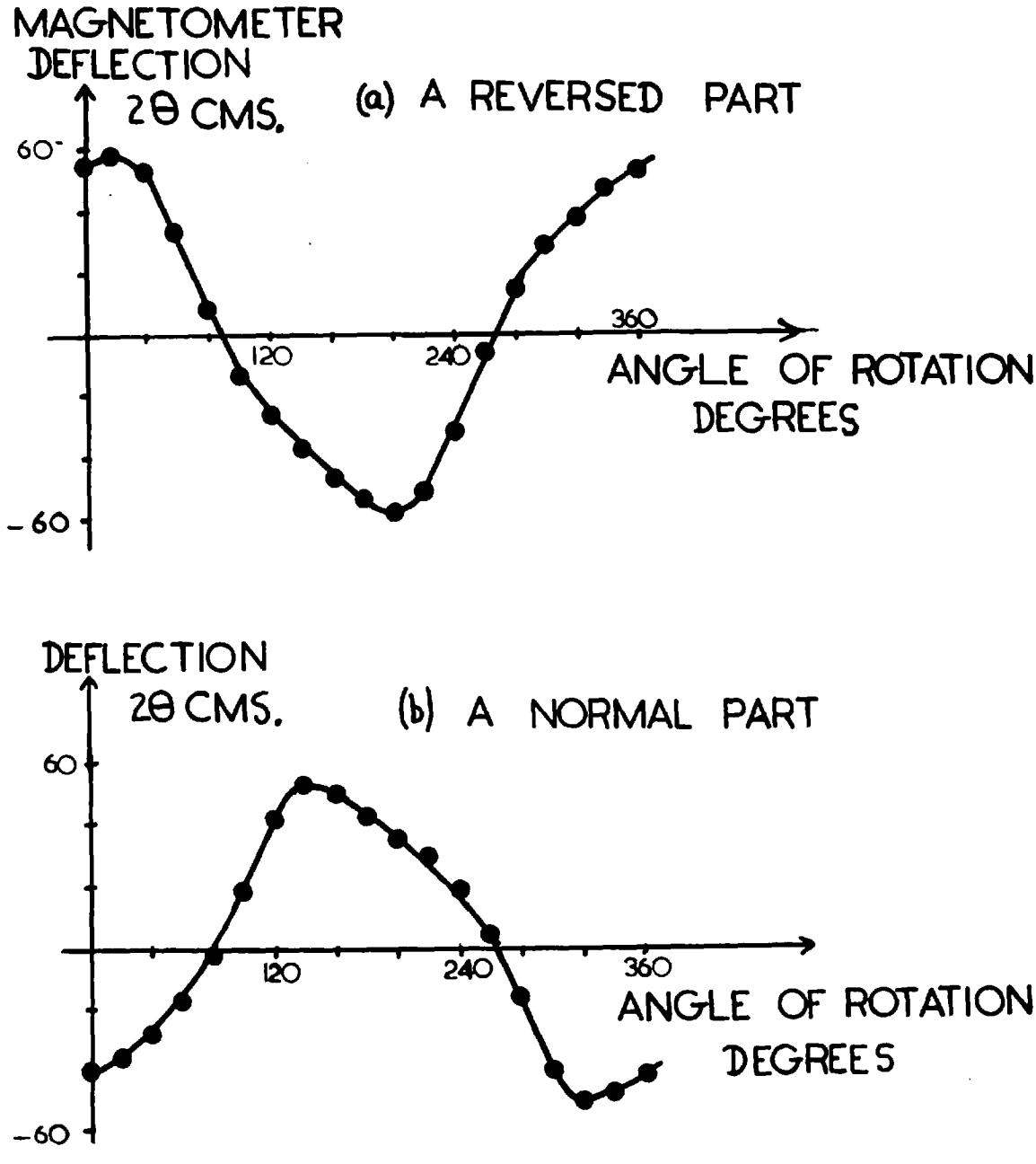

MAGNETOMETER
DEFLECTION
2θ CMS.
(a) A REVERSED PART
60
-60
120
240
360
ANGLE OF ROTATION
DEGREES
DEFLECTION
2θ CMS.
(b) A NORMAL PART
60
-60
120
240
360
ANGLE OF ROTATION
DEGREES

FIG A.I

sin 2θ curves - see previous theory). Both curves of Fig. A.1 seem to be fairly good approximations to sinθ curves. The reason why they are not accurate sinθ curves is probably due to the rapid variation of the N.R.M. of the section with distance. The results described in chapter 6 show that the N.R.M. of grit changes considerably and often reverses its sign over distances of but a few mms. Since it was extremely difficult to centre the turntable to an accuracy of more than about a mm., different areas of the section will move directly under the magnet on rotation. One must therefore expect a slight deviation from a sinθ curve in this case.

The maximum and minimum values of 2θ for the curve representing the reversed part of the section occurs after the section had been rotated by 20° and 200° respectively. The maximum and minimum values of 2θ for the curve representing the normal part occurred after the section had been rotated through 140° and 320°. This result is reasonable since it is known that the grit is on the average magnetised at an angle making about 20° to 30° with the vertical.

Centering the turntable.

A glass rod, the same diameter as the axis of the astatic magnets was mounted vertically on the turntable and moved until on rotation of the latter the rod appeared to be stationary. The glass rod then represented the axis of rotation of the turntable. A light was then shone

into the casing of the magnetometer on the astatic magnetometer system and its axis (a glass rod) was viewed from two directions 90° apart by means of small windows left in the aquadag paint covering for this purpose. The vertical reflection of the axis of the magnetometer system could be seen in the flat glass at the base of the casing. The glass rod representing the axis of rotation of the turntable was observed at the same time, and the table moved laterally until its axis coincided with the vertical reflection of the astatic pair when viewed from two directions making an angle of 90° with each other. The table was then estimated to be centred to an accuracy of about a mm. Such an accuracy was sufficient for the experiments described in Chapter 6 since it was only required to distinguish between normal and reversed areas which usually existed as strips which on the average were about 5 mms. thick.

This was then considered to be a quick and reliable method for investigating the pattern of reversals of the grit. It also gives an estimate of the relative strengths of normal and reversed strips.

The similarity between the magnetic patterns obtained for particular rock samples by this method and those obtained for the same rock samples by the previous method of slicing up cores further demonstrates the validity of the method (See Chapter 6).

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