

THE STRUCTURE OF THE GEOMAGNETIC FIELD DURING
POLARITY TRANSITIONS AND EXCURSIONS

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Doctor of Philosophy
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1983



ABSTRACT

Salloway, J.C. The Structure of the Geomagnetic Field during
Polarity Transitions and Excursions.

An investigation into the nature of the geomagnetic field over the past four million years was carried out using sediments from the South Atlantic Ocean, and from lacustrine and marine basins of Northern Italy. In particular the aim of the research was to identify smaller geomagnetic events or excursions, and to observe the structure of the field during changes in polarity. Consideration of the processes involved in the acquisition of a remanence by sediments enables the selection of the best rocks for this study. Sediments present an averaged record of the field, so in some cases smaller geomagnetic features may not be recorded by certain sediments.

Sediments from the South Atlantic record most of the last 4 m.y., that is, back to the Gilbert Epoch. A short excursion is seen at 3.95 m.y. Most of the polarity transitions are restricted in longitude, but there is no definite near-sided or far-sided pattern, in fact many of the transitional paths cross the equator 90° from the site.

The four river sections from Northern Italy which were investigated show a transition from marine sedimentation to continental fluviatile and lacustrine sedimentation, consequently the palaeomagnetic record is often interrupted due to periods of non-deposition. The major change in environment occurred between the beginning of the Jaramillo Event and the base of the Brunhes Epoch, and in one case the whole of this interval is missing. A composite section indicates the possible presence of excursions in the lower Brunhes

at about 0.45 and 0.68 m.y.

Additional work carried out on sediments from Italian glacial lakes, and from a series of cores in Tuscany suggest the presence of excursions in the Brunhes at 0.18 m.y. and in the Gauss at 2.65 m.y.

Two transitions can be studied in detail in these Italian sections, the Lower Jaramillo (R→N) seen at two sites crosses the equator approximately 60° W of the site. The Matuyama-Brunhes (R→N) crosses between 160° and 190° E of the site.

The Hoffman (1979) model for the Matuyama-Brunhes transitional field involves zonal components only, giving VGP paths confined longitudinally and passing through the site. The results from Tjepido and other European sites do not fit into this pattern, suggesting an additional source to the east of Europe. Further results from Europe and the Argentine Basin appear to indicate that transitions involving purely zonal fields are rare, and that additional sources such as current loops may often contribute to the transitional field structure.

Abbreviations used in the Text

A.F.	Alternating Field
A.R.M.	Anhyseretic Remanent Magnetization
C.R.M.	Chemical Remanent Magnetization
D.R.M.	Detrital Remanent Magnetization
G.R.M.	Gyroremanent Magnetization
I.R.M.	Isothermal Remanent Magnetization
M.D.F.	Median Destructive Field
N.R.M.	Natural Remanent Magnetization
S.I.R.M.	Saturation Isothermal Remanent Magnetization
V.G.P.	Virtual Geomagnetic Pole
m.y.	Million years

Note: The c.g.s. units for field strength and flux density are used throughout the text.

$$1 \text{ Oersted} = \frac{1}{4\pi} \times 10^3 \text{ Amperes per metre}$$

$$1 \text{ Gauss} = 10^{-4} \text{ Tesla}$$

$$(1\mu\text{G} = 0.1 \text{ nT})$$

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CHAPTER I

INTRODUCTION

When Motonori Matuyama (1929) reported normal directions recorded by recent Quaternary basalts and reversed directions recorded by older Quaternary basalts he effectively introduced the science of magnetostratigraphy. Although previous workers such as Brunhes and Mercanton had shown that some rocks recorded directions opposite to the present day field (see Cox, 1973), Matuyama was the first person to study the ages of the reversed rocks. As a result he showed that the Earth's magnetic field changed direction in comparatively short times.

More detailed refinement of geomagnetic reversal history had to wait until the development of an accurate method for dating volcanic rocks. Once the potassium argon method had been applied to younger rocks in the late 1950's a number of workers with the U.S. Geological Survey and the Australian National University were able to produce increasingly more refined records of the reversal sequence (see Cox, 1973). Initially the reversals seemed to occur regularly at about 1 million year intervals (Cox et al, 1963) but later the discovery of shorter events (e.g. Doell and Dalrymple, 1966) showed that the reversal sequence consisted of long and short intervals with the change from one regime to another seemingly occurring at random. Cox (1969) suggested that reversals were due to coincidence of extremes of dipole variation and non-dipole field turbulence, which gives a probability distribution function for the lengths of polarity intervals. Polarity intervals of all lengths should occur, however shorter polarity intervals are rarely seen, perhaps due to gaps in the formation of rocks or slow sedimentation rates.

More detailed investigation of the boundaries of these magnetic epochs showed that the field changed sign over a period of about 10,000 years, with lava flows recording field directions intermediate between the two stable directions (e.g. Watkins, 1969). This fact, along with the evidence that reversed rocks were distributed according to age, not rock type, effectively proved that reversal of the geomagnetic field had occurred, not self-reversal of the magnetic minerals.

Once a number of records of the actual transition between polarity states had been obtained it was clear that the structure of the transitional field was different for different reversals, sometimes the direction changed gradually, at other times the magnetic vector looped about its initial direction with increasing amplitude, then changed to the other direction, settling down via loops about this new direction.

The aim of this study is two-fold: to attempt to redefine the magnetic reversal history for the past four million years, in particular with respect to the shorter episodes which studies of reversal frequency suggest should occur; and secondly to investigate the actual structure of reversals of the magnetic field to discover whether there is any given pattern for successive reversals, and also to investigate the transitional field for given reversals at different sites around the Earth.

The study was undertaken in two major areas, both sedimentary basins. Although it can be shown by redeposition experiments that sediments are capable of carrying a record of the Earth's magnetic field from about the time of deposition, careful attention had to be paid to selecting and sampling the sediments for study.

The first deposits studied were the marine sediments of the

Argentine Basin, where hydraulic piston coring by the Deep Sea Drilling Project recovered virtually undisturbed sediment, covering an almost continuous interval extending to 4 m.y. b.p. The sedimentation rate in these sediments was extremely high enabling a detailed study of the intermediate field directions between polarity epochs.

The second area visited was northern Italy where the marine and continental deposits of the Po Valley present opportunity to study the magnetic field for at least the past 2 million years, although the coverage of the past one million years by the continental deposits is intermittent. Four river sections were sampled: the Stirone, Crostolo, Tiepido, and Panaro rivers, as shown in Figure 1. These investigations were supplemented by studies on glacial deposits in Lombardy where glacial traps allowed deposition in temporary lakes at various times during the ice age including those at Bagaggera, Pontida, Lefte, and Pianico (Figure 2). The different deposits were correlated with the aid of Italian geologists. One point of interest in the investigation was to find out whether the structure of transitions was different for different transitions and to see whether these could be used for correlation.

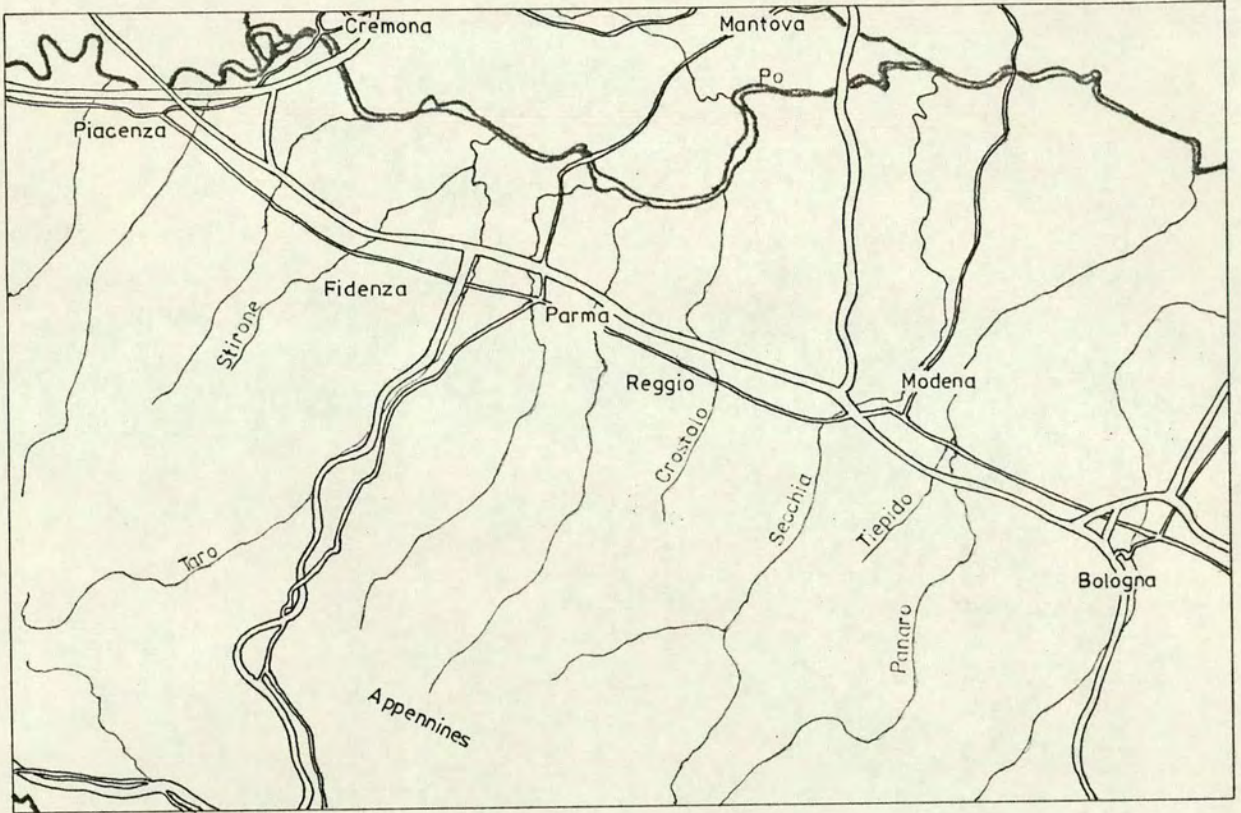


Figure 1. Map of Po Valley Sites

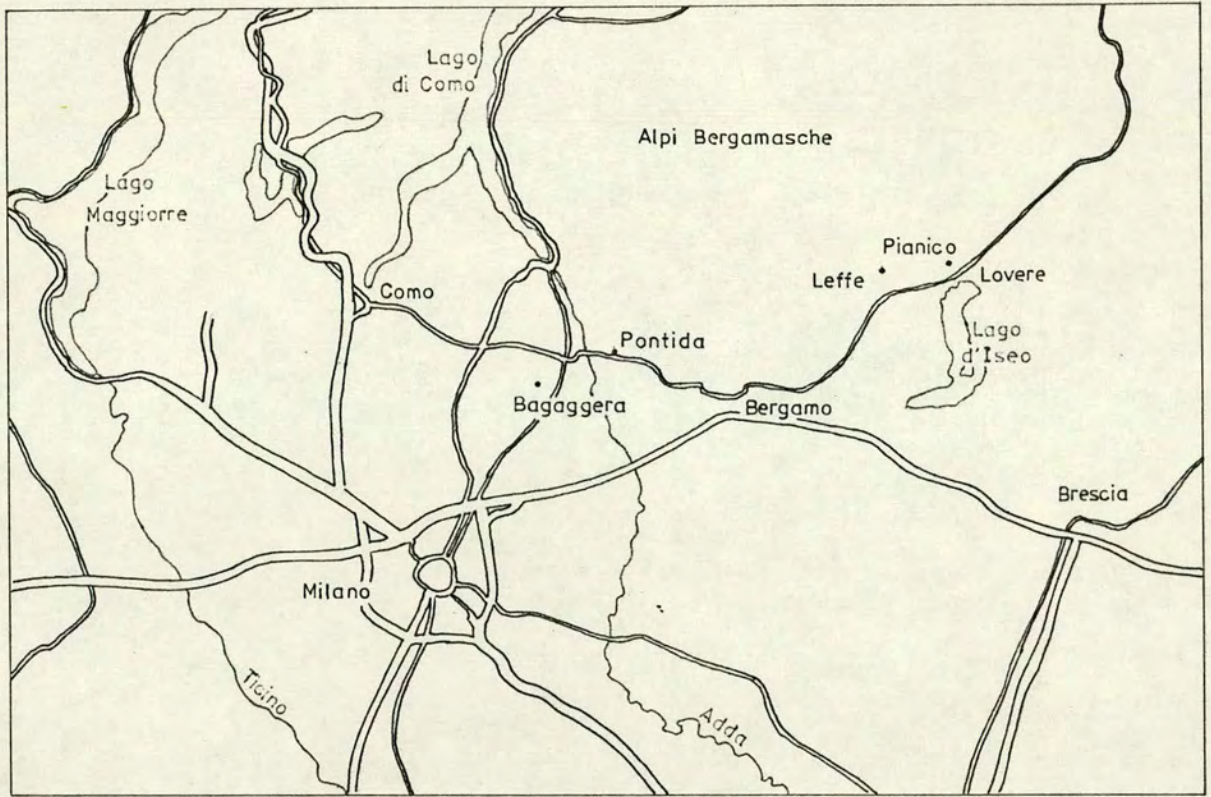


Figure 2. Map of Lombardy Sites

CHAPTER 2

METHODS

The palaeomagnetic determination of the ancient field direction can be divided into two parts: the process by which rocks recorded the ancient field, and the subsequent measurement of this record in the laboratory. The palaeomagnetist has no control over the magnetization process which introduces the largest errors, although consideration of the theory involved can enable the selection of the best rocks for study. The second part consists of sampling of rocks in the field and then of measurement of the direction and strength of the natural remanence, and of susceptibility and other magnetic properties of the rocks in the laboratory.

THE PROCESSES OF MAGNETIZATION

The rocks used in this study are all sediments, deposited in conditions varying from deep sea basins, through shallow marginal seas, to continental lacustrine and fluviatile environments. A few samples were taken from sub-aerial deposits such as loess. The major form of magnetization in most sedimentary rocks is detrital remanent magnetization, in which particles already possessing a remanence (usually magnetite grains with a thermal remanent magnetization acquired through igneous activity) give an average alignment in the ambient field direction. This may either form contemporaneous with deposition (depositional DRM) or a short time afterwards (post-depositional DRM). Formation of magnetic minerals such as haematite, within the sediment, through weathering and pedogenesis when the sediments are exposed at the Earth's surface, gives rise to a chemical remanent magnetization (CRM). Other factors such as viscous remanent magnetization (VRM) formed through relaxation of domains with time,

and isothermal remanent magnetization (IRM) formed by large fields associated with lightning strikes, may contribute to the natural remanence, but these effects can be removed by demagnetization, and by taking samples over a wide area.

DEPOSITIONAL DETRITAL REMANENT MAGNETIZATION

Initial work on glacial varves (Ising, 1943; Granar, 1958) revealed that they recorded the direction of the ambient field, but with a lower inclination. Granar noted that a grain falling through water was subjected to magnetic, gravitational, and hydrodynamic forces, and also that a systematic deviation was produced by deposition on a sloping surface. Redeposition experiments by Griffiths et al (1960) suggested that the inclination error was not related to grain size, and that currents could produce deviations of up to 10° in declination, although inclination error was reduced. Having studied the properties of magnetic grains, which were mainly spherical, and about the same size as the non magnetic fraction, with magnetite as inclusions, Griffiths et al were able to produce a theory for inclination error. Grains reaching the sediment-water interface will tend to roll into the nearest hollow. On a horizontal surface this rolling direction will be equally probable in any direction, however while rolling north will increase inclination in a normal field, rolling east, west, or south will decrease inclination. Averaging for all directions of rolling Griffiths et al found that the observed inclination (I_o) is related to the ambient field inclination (I_f) by:

$$\tan I_o = (2\cos\phi/1+\cos\phi) \tan I_f \quad \textcircled{1}$$

where ϕ is the average angle rolled. For deposition on a slope this angle is increased in one direction (downhill) and decreased in the opposite direction, and in addition the probability of rolling in the

first direction is increased. It was estimated that currents reduced the effectiveness of such rolling by introducing scatter.

King and Rees (1966) were able to consider the various factors affecting particle alignment. A grain of diameter D , density d , and moment j , at an angle θ to the applied field H , is acted upon by a magnetic torque

$$C_m = (D^3 \cdot jH \sin \theta) / 2 \quad (2)$$

A particle falling through a layer of laminar motion of velocity gradient dU/dz will tend to be rotated out of alignment by a hydrodynamic torque

$$C = D^3 \cdot v \, dU/dz \quad (3)$$

where v is fluid viscosity. Spherical grains will achieve equilibrium in a position governed by these two torques. On reaching the sediment surface the grain may tend to rotate into a hollow, or if the grain is non-spherical, to rotate until its long axis is horizontal. The gravitational couple is:

$$C_g = D^3 \cdot g (d-1)a \quad (4)$$

where a is the horizontal distance between the point of contact and the centre of gravity. For spherical grains and random packing $a = D/4$. King and Rees estimated that grains have intensities of about 2 emu cm^3 , and suggested that for a grain of $1 \mu\text{m}$ the magnetic torque will be dominant, but for a grain of $10 \mu\text{m}$ gravity will cause complete rotation. There will thus be a systematic deviation of remanent directions in a sediment at the time of deposition.

Additional factors contribute to introduce a randomization in the alignment of grains. The major effect of this will be a reduction in the intensity of the sediment as a whole.

The initial orientation of grains will affect the remanence if there is insufficient time for alignment to take place. The fraction

of grains aligned as a function of time (t) for n uniform grains is given by

$$J_r/J_0 = \tanh \{2M \cdot H \cdot t/\lambda\}/3 \quad (5) \quad *$$

where M is the moment of a single particle, and λ a viscosity coefficient of rotation ($=\pi v D^3$). Given $v = 0.01$ poise, $H = 0.5$ Oe, $M = (\pi D^3 J)/6$, then t_0 , the time constant for the alignment process is $0.12/J$. This implies that all but the weakest grains would be aligned within 1 second. The settling rate for most magnetic particles is only a few millimetres per minute, so in still water most grains would become aligned. Even in turbulent water, the boundary effect of the bottom gives rise to a layer of laminar flow, however there will be a critical grain size which falls through this layer too quickly to become aligned. King and Rees estimate this to be $50 \mu\text{m}$. The effect of high energy environments was noted by Thompson and Berglund (1976) who attributed scatter in coarser deposits to this. They suggested that sediments of greater than $62.5 \mu\text{m}$ (that is anything coarser than very fine sand) should not be used for palaeomagnetism.

Brownian motion will be acting continually to reduce the alignment. The mean amplitude of oscillation decreases with increased grain size, as given by:

$$\theta_{\text{rms}}^2 = 2KT/D^3 JH \quad (6)$$

ignoring smaller motions

$$\theta_{\text{rms}} > 0.1 \quad \text{if } D < 1 \mu\text{m}$$

King and Rees suggest that there will always be some preferred alignment, but it is difficult to see how particles of less than $0.1 \mu\text{m}$ could contribute to the magnetization of sediments containing magnetic grains larger than $1 \mu\text{m}$.

* J_r is the actual remanence and J_0 the remanence when all grains are aligned

The inclination error model produces a systematic error for spherical grains. For non-spherical particles or inhomogeneous particles the grain will come to rest with the upward force passing through the centre of gravity. If remanence is not related to particle shape, the result will be a random scatter about the field direction. If the remanence is soft it will preferentially lie along the long axis of the grain, and this will introduce a horizontal component which will reduce inclination.

Amerigian (1974) noted ways in which climate may affect sediment intensity and remanence direction. Increased carbonate production, which is controlled by climate, will dilute the density of magnetite in a sediment. He also suggested that the efficiency of alignment under DRM is related to grain size, which can be affected by bottom water velocity. Climate change may alter bottom water velocity which will also affect inclination in the boundary layer of laminar flow.

In another paper Amerigian (1977) reports redeposition experiments for different grain size ranges. For particles up to $38 \mu\text{m}$, the DRM is similar in stability to an ARM induced in the samples. The ARM is higher in intensity which is explained as due to the presence of inclusions in larger grains which contribute to ARM, but are unable to become aligned to contribute to the DRM. Above $38 \mu\text{m}$ the DRM is unstable under alternating field demagnetization above 400 Oe, possibly because grains of different coercivity are aligned by different factors. An ARM given to the same samples is stable.

Depositional Detrital Remanent Magnetization will be present in all subaqueous sedimentary deposits at the moment of deposition. Laboratory experiments suggest that at this point all the deposits will possess some inclination error, but in many rocks additional factors such as current velocity, and large grain size will lead to

even greater distortion in the recording of the ancient field. Sediments with grain sizes of over $62.5 \mu\text{m}$ (and possibly some smaller grained sediments) are unlikely to give an accurate record of the ambient field at the time of deposition. There does not seem to be any indication of a saturation remanence being reached when redeposition experiments are repeated at higher fields (Barton et al, 1980), which probably indicates that the percentage of grains contributing to the remanence is small.

POST-DEPOSITIONAL DETRITAL REMANENT MAGNETIZATION

Irving (1957) noted that slump beds within the Torridonian sandstones had magnetizations parallel to those of the overlying horizontal beds. As intensity in these rocks varied with specularite content not haematite staining, the highest intensities occurring in black-banded rocks, he concluded that the magnetization resulted from alignment of detrital grains which were still free to rotate, after deposition, in the pore spaces between quartz and feldspar grains which were larger than the specularite. This post-depositional rotation was, he suggested, inhibited after a certain period, at a critical water content. Irving also noted a relationship between dispersion and grain size: there was a marked increase in dispersion for coarser sediments. Subsequent redeposition experiments (Irving and Major, 1964) proved that if the sediments were allowed to stand for 70 hours before the water was drained off, then allowed to stand for a further 48 hours, the remanence directions would show no significant departure from the applied field. Irving and Major noted that intensity increased with applied field strength, indicating an increased alignment of grains.

Kent (1973) suggested that the origin of post-depositional DRM is related to Brownian motion or to disturbance caused by bioturbation.

He redeposited sediment, and stirred the slurries before allowing them to dry in the presence of a magnetic field. No systematic deviation from the applied field was seen, and intensity showed a linear response to the magnitude of this field. When the samples were not stirred inclination was recorded accurately, but remanence was lower.

Verosub (1977) noted that glacial varves retained an inclination error. Sediments deformed 13 years after deposition were unable to correct their directions. Some lake and shallow sea sediments with rapid accumulation rates gave a skewed distribution of inclinations suggesting that inclination error was present, on the other hand deep sea sediments with low deposition rates accurately record the ambient field. In these sediments bioturbation destroys the depositional DRM. Verosub considers that two types of environment can be distinguished: in sediments with low water content re-orientation is prevented, whereas post-depositional realignment takes place in environments with high water content, which may be created or maintained by bioturbation. In redeposition experiments Barton et al (1980) noted an increase in remanence with vibration, and Kent's (1973) results also support this theory. Eventually dewatering takes place due to compaction. Factors important in determining water content include grain size, clay mineralogy, shape, and also the ratio of non-magnetic to magnetic grain size. Verosub reports that PD-DRM is seen in some cases, but not in others in the same area. Subtle changes in environment influence the relative contribution of D-DRM and PD-DRM. For sediment with a single grain size and a single magnetic carrier size there should be a critical water content. Verosub et al (1979) redeposited sediments, and from the results estimated that only 10-20% of the grains were able to realign. In many cases their initial slurries had insufficient mobility as they were beneath the estimated 70% water content necessary for realignment. Barton et al (1980) suggest, however that short-

term post-depositional processes are not important in compacted fine-grained rocks.

The timing of PD-DRM can be studied by reversing the applied field during a redeposition experiment. Lovlie (1974) redeposited natural foraminiferal clay containing magnetite of less than 5 μm over a period of 100 days. The ambient field was reversed after 62 days, and the time marked by introducing calcium carbonate in the sediment. The remanent magnetization records the reversal over a five day period between 10 and 5 days earlier than the actual reversal. Further experiments (Lovlie, 1976) showed that intensity was decreased over the interval in which the reversal was recorded. Decrease was gradual before the transition, and increase rapid afterwards. Lovlie suggested that a variety of grains are affected, each being blocked in at a critical depth, with the larger grains in general being locked in before the finer grains. The observed pattern is best modelled, according to an exponential pattern (as in Figure 3). The minimum intensity (theoretically zero) will occur when half of the grains are locked in before the reversal, and half after it.

Tucker (1979) deposited synthetic sediment, mainly between 1 and 5 μm with 90% water content, after stirring and agitation. After 24 hours the field direction was changed through different angles for different samples. When water content had reached 70% the samples were measured. Inclination error was present at NRM, but demagnetization reflected this field change, the harder component having developed a PD-DRM, the softer component remaining aligned in the DRM position. This would support Lovlie's suggestion that smaller high coercivity grains become locked in later than larger, low coercivity grains.

Further redeposition experiments (Tucker, 1980a) compared the

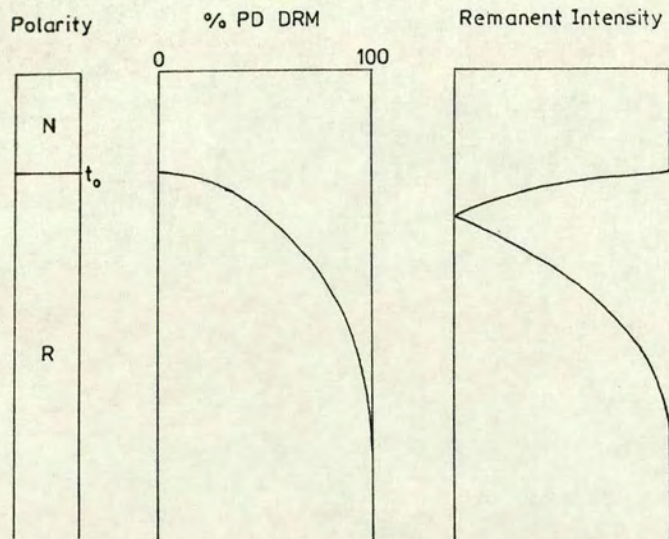


Figure 3. Model of PD-DRM Acquisition
(from Løvlie, 1976)

effect of grain size, applied field, interstitial fluid, and compaction. Only 10% of the remanence was available for realignment, this occurring within 24 hours. Realignment increased with increasing matrix size, however mobility was reduced with depth. Tucker recognized four types of post-depositional realignment: Zone 1 consists of grains which are more or less reversible, they are held in minima of gravitational or surface tension energies. These are responsible for an initial sharp increase with time, related to field strength. Zone 2 consists of grains which rotate within water filled voids, and respond freely to magnetic torques. They show a logarithmic increase in alignment up to saturation point, when the applied field is removed they suffer long term decay due to external perturbations. Zone 3 occurs above a critical field of 35 Am^{-1} , and probably results from rotation of grains through distortion of the void. This factor is not seen in sands. Zone 4 is only seen above 350 Am^{-1} and represents grains rotating against surface tension forces. This component increased when an interstitial fluid with a lower surface tension coefficient was used.

The grains are blocked in by dewatering and compaction. Dewatering occurs between 70% and 68% water, causing the removal of a lubricant for rotation. Compaction decreases void size and increases resistance to deformation. Only a small fraction of the grains were mobile at a depth of 30cm. Tucker lists the factors controlling PD-DRM, these include depositional conditions, mineralogy, organic content, and particle size (all of which affect void size), as well as the initial water content.

Both Tucker (1980a) and Verosub et al (1979) note that in redeposition experiments only 10 to 20% of the remanence is able to rotate after deposition. Total remagnetization may result from disturbances

such as bioturbation, slumping, or the upward movement of gas bubbles, all of which temporarily increase water content. Tucker (1980b) studied stirring as an analogue for post-depositional disturbances. Slurries of 75% water were continuously measured while being stirred. With slow stirring rates a percentage of the grains retained an alignment. For faster stirring rates the remanence on the cessation of stirring was higher. The remanence was ten times greater than for similar sediments which settled in a field without stirring. Stirring liberates the grains from clusters and allows them to become aligned in the ambient magnetic field. The constraining forces which block the grains in reassert themselves a certain time after the disturbance. The magnitude of PD-DRM depends on the type and scale of the disturbance. The depth to which realignment can occur depends on the depth of burrowing. Weaver and Schultheiss (1983) noted burrows over 2m below the surface. Although sediment is not mixed greatly the burrows increase permeability so greater water content may enable re-orientation.

Post-depositional Detrital Remanent Magnetization will be present only in those sediments which maintain a sufficiently high water content for a certain length of time after deposition. Sediments with high deposition rates such as glacial varves will reach a critical stage of compaction before the grains have had time to align themselves more accurately. Amerigian (1974) suggests that in any sediment the number of grains available for post-depositional rotation will be less than the number of grains which become oriented during deposition. Unless the DRM is destroyed by disturbances such as bioturbation, then the remanence will be partially erroneous. The results of Verosub et al (1979) and Tucker (1980a) support the suggestion that PD-DRM is limited in undisturbed sediment, however

Lovlie (1974, 1976) shows that disturbance is not necessary to produce a time lag in the majority of the remanence, and Channell et al (1982) show by demagnetizing sediments deposited during a geomagnetic transition that a chemical remanence carried by haematite can form in situ before the detrital remanence carried by magnetite is locked in. Clearly the timing of post-depositional re-alignment, and the percentage of grains able to react to field changes varies with sediment type.

Tucker (1979) points out that if the smaller grains have higher coercivity and these grains become locked in at a later date than the larger, lower coercivity grains, then demagnetization may remove an older component and leave a slightly younger component.

As the rock becomes coherent, compaction will produce scatter and also decrease inclination. Whatever processes give rise to the remanence there will be an inherent variability in the palaeomagnetic recorder, as noted by Verosub (1979). Glacial varves in New England show changes that would imply secular variation of $1.5^\circ/\text{yr}$ which is much faster than that observed at present. Verosub also reports that the same horizon at different sites within the same lake shows differences of as much as 8° in inclination and 15° in declination.

Post-depositional DRM will cause both a delay and a smoothing of the magnetic signal recorded by sediments. This problem is particularly pertinent in the study of transitions. The amount of smoothing involved will be governed by the width of the interval over which locking-in occurs, while the delay of the transition is caused by the offset of the lock-in zone. The shape of the lock-in zone will affect both the smoothing and the delay, by giving different weighting to shorter or longer lock-in offsets.

The effects of PD-DRM can be illustrated by a series of depositional models constructed by computing the effect of depositing grains during a transition¹. The direction and strength of the ambient field, and the shape of the grain response curve for the sediment are put in to the program which then calculates the remanence at each level. It is assumed that there exist a number of grain sets having different delay times ($\tau_1, \tau_2, \dots, \tau_n$) each grain set becoming locked in along the field direction existing i time units after it was deposited. Each grain set is, as a whole, completely aligned along this direction (it is unlikely that a grain would be unable to rotate as fast as the field changes). Within each grains set the alignment of individual grains is proportional to the ambient field strength, so the intensity of the remanence carried by that grain set is itself proportional to field intensity. In addition to the grain sets which do become aligned with the ambient field there is another set of grains which are not oriented. If there is no current or shape anisotropy these grains will be randomly oriented and will not affect the remanence.

These models use various field configurations including an instantaneous reversal, great circle reversals, a complex reversal, and excursions, all with or without intensity decrease. The grain delay curves include no-delay, which models depositional DRM, but can also be applied to post-depositional DRM which is locked in at a single depth. The second model is a linear grain delay curve, the third is an exponential curve similar to Lovlie's (1976) suggestion, and the fourth involves a maximum in the grain response at a given depth below the sediment-water interface as modelled by Denham and Chave (1982). This is called the 'S' grain delay curve (Figure 4).

Figure 5 shows the affects for an instantaneous transition, comparable with that used by Lovlie. A decrease in intensity is

1 The program is listed in Appendix A

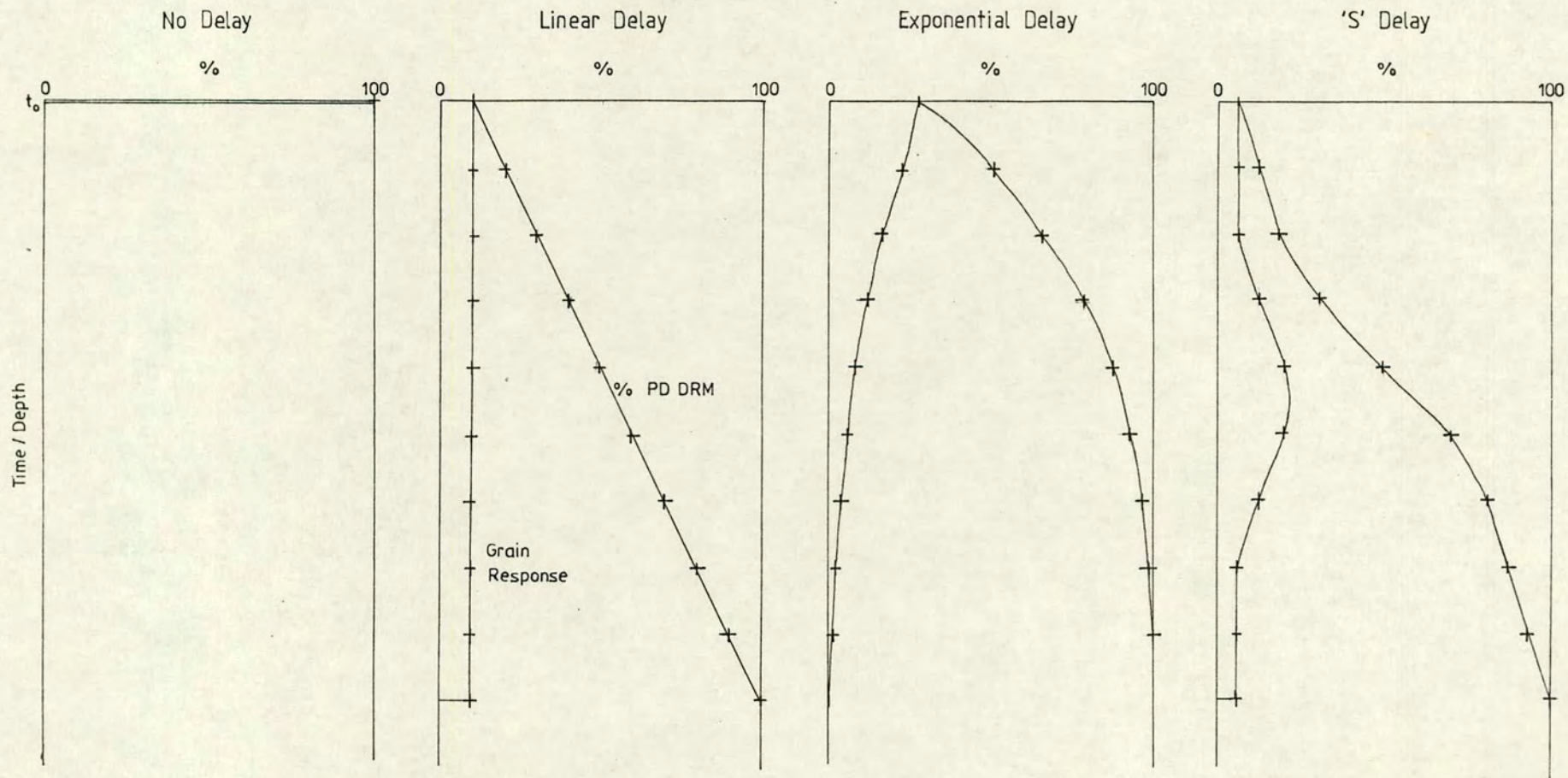


Figure 4. Grain Delay Curves for Depositional Model

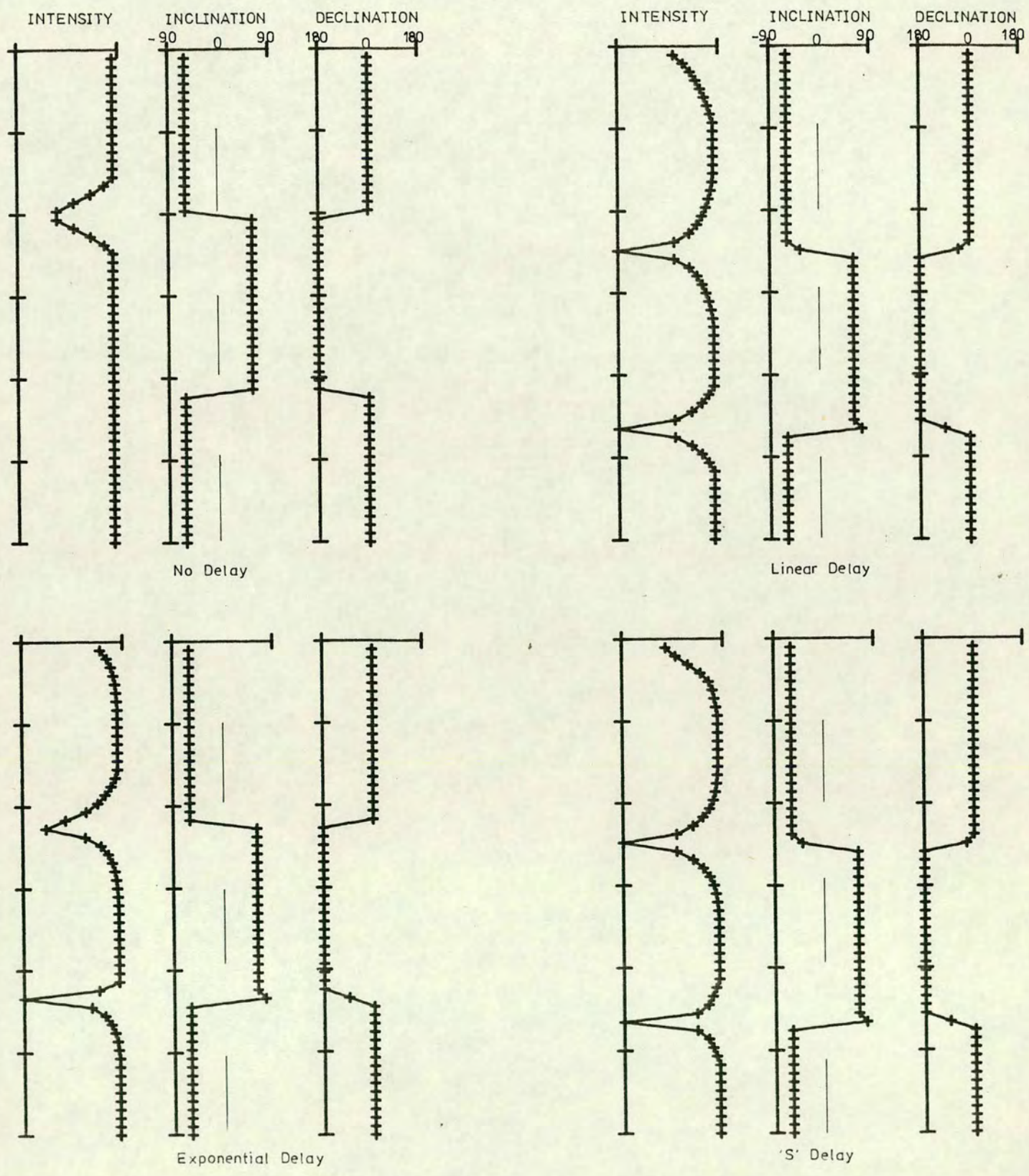


Figure 5 Effect of Sediment Grain Delay on an Instantaneous Transition

introduced due to opposing grains sets cancelling each other out. This decrease is symmetrical for linear and 'S' delay, but sharper after the transition for exponential delay if there is no decrease in the ambient field, as seen by Lovlie (1976). If the transition is accompanied by a decrease in intensity, the exponential delay may cause a steeper decrease before the change in direction. As the normal and reversed directions are directly opposite, no intermediate field positions are seen. A slight bias in the two opposing directions will give a great circle path. This will be far-sided if there exists a grain set with an inclination error (that is one unable to undergo realignment). The transition occurs at the point where more than 50% of the grains have reversed. This is nearer the actual date of the transition for the exponential delay model used than for the linear delay curve.

Where the transition is of finite length (T_r) the depth interval representing the transition is extended to $(T_r + \tau_{max})C$ where C is the sedimentation rate, (Figure 6). The directions do not cancel each other out completely so intensity decrease is smaller than for an instantaneous reversal (where the theoretical minimum intensity is zero). The resultant directions are smoothed, this will not affect a great circle path, however complex reversals will become more even (Figure 7). The exponential delay curve gives more weighting to shorter delays, so the linear delay curve will give a smoother path than the exponential delay.

Excursions² will also be smoothed and may be considerably reduced if the smoothing interval is long compared with the excursion. The smoothing is more marked if there is a decrease in intensity during the transition or excursion, as this gives less weighting to the anomalous directions. Figure 8 shows an excursion with anomalous

2. An excursion is here taken to be a deviation of the VGP to between 45°N and 45°S
See the discussion on p. 46

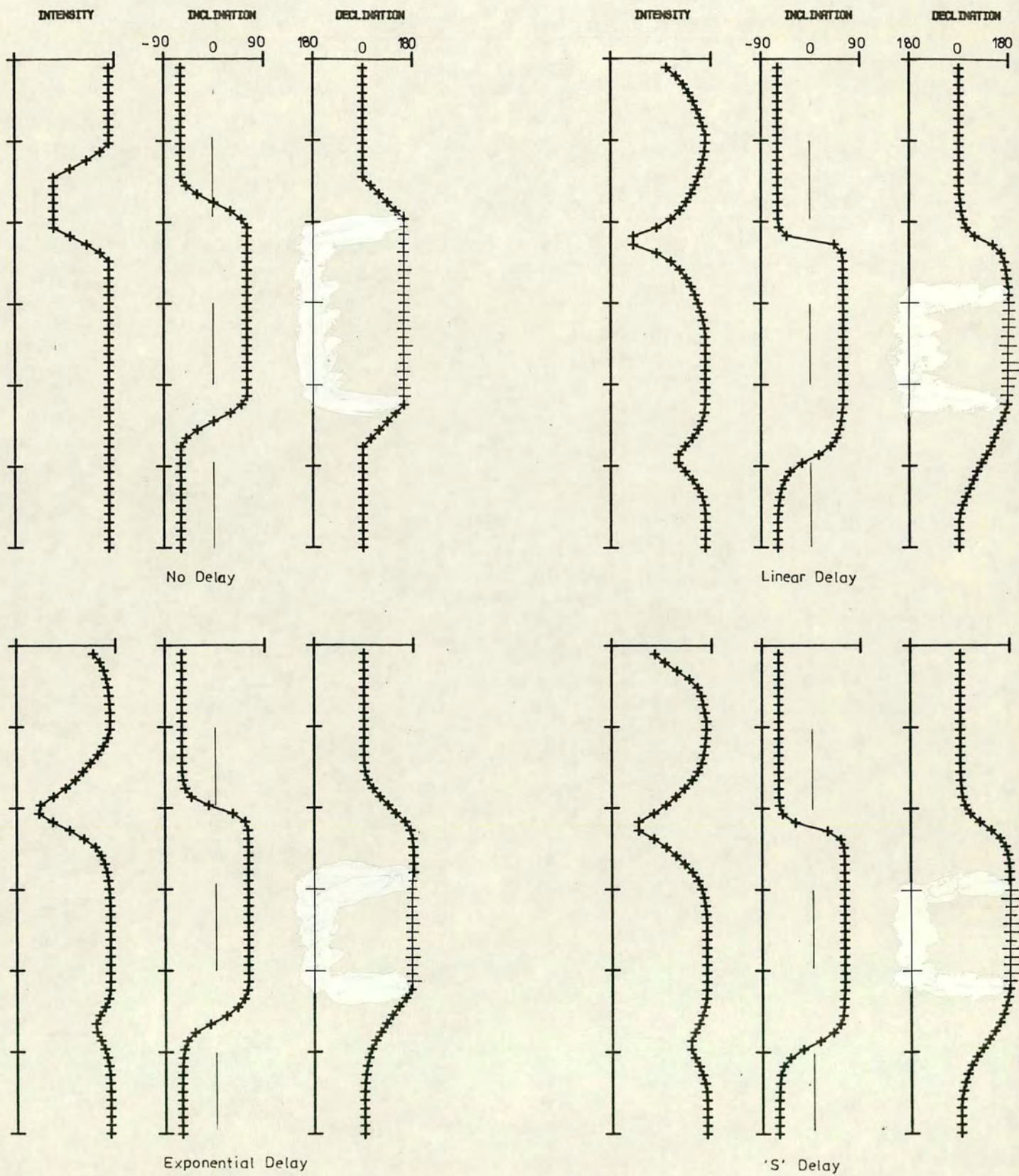
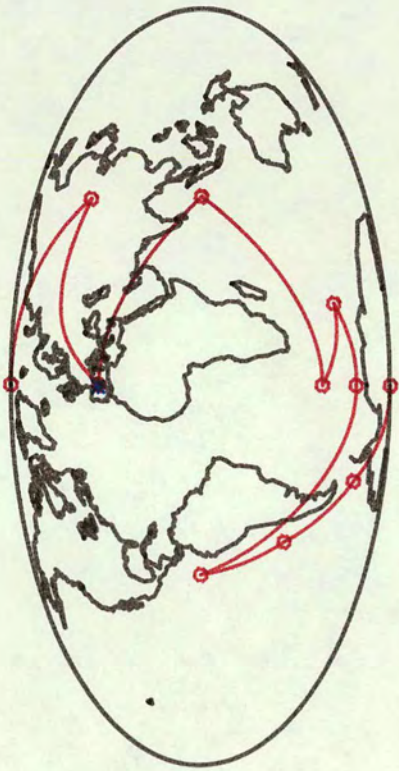
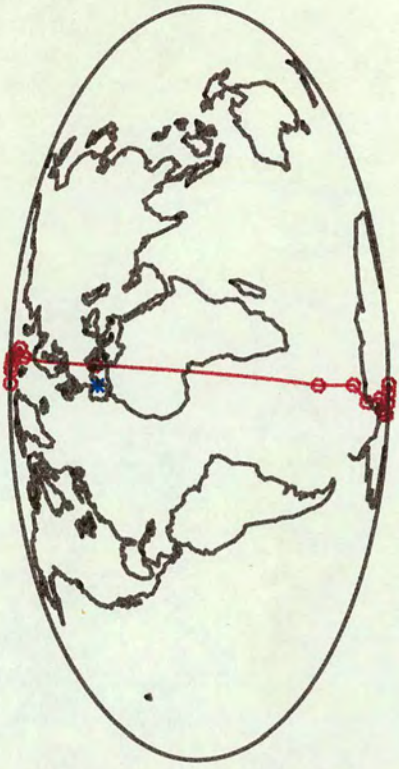


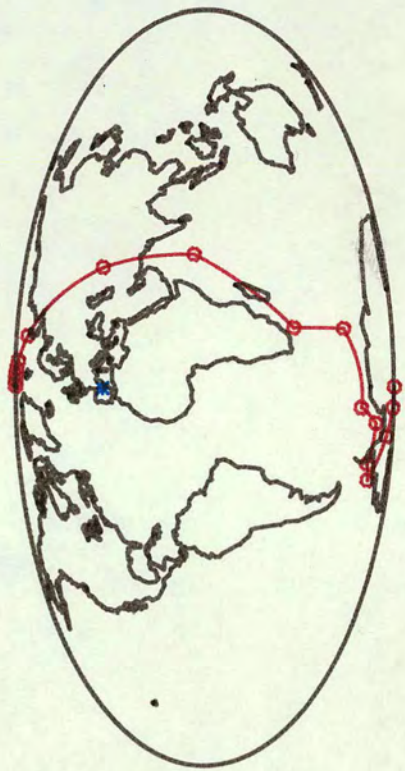
Figure 6. Effect of Grain Delay on a Transition of Finite Length



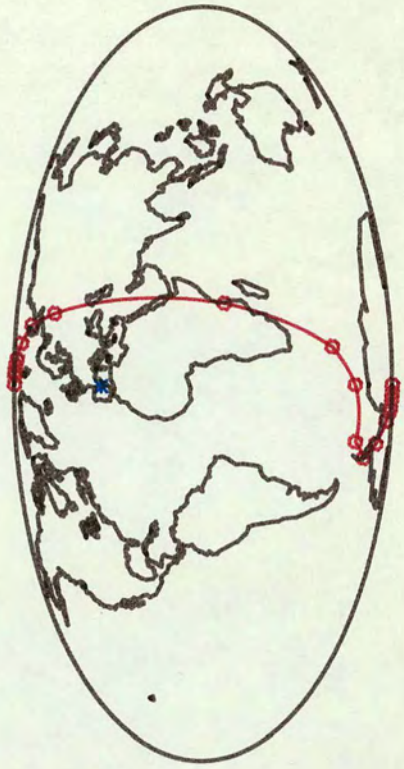
No delay



Linear Delay

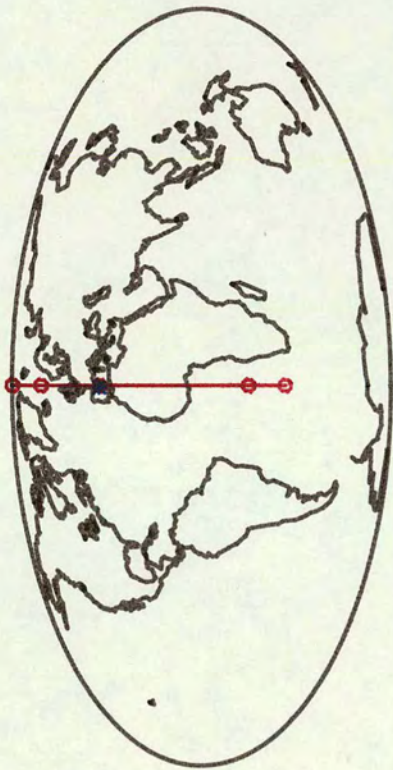


Exponential Delay



'S' delay

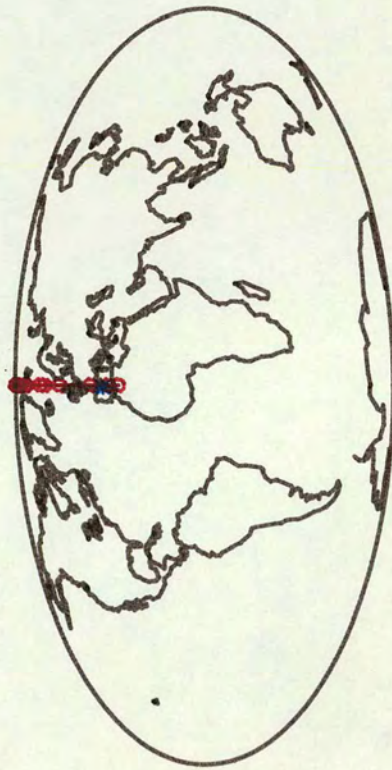
Figure 7. Smoothing of a Transition by Different Sediments



No Delay



Linear Delay



Exponential Delay



'S' Delay

Figure 8. Effect of Grain Delay on an Excursion

directions for seven time units, and intensity reduction to a minimum of 10% spread over 10 time units. In addition to the no-delay sedimentation model, Figure 8 shows the effects of a linear delay curve (with 50% of the grains aligned within 4 time units), an exponential curve (50% within 2 time units) and an 'S' curve similar to Denham and Chave (1982), (50% within 4 time units). Probably only the exponential delay results would be interpreted as an excursion.

The deposition rates are constant for each model. A change in deposition rate or a change in sediment will give a change in the grain delay curve. If this occurs during a reversal the reversal may appear to be repeated. However if the grain delay curve is constant, the transition will always appear simpler than it is in reality. Another thing to note is that the recorded intensity is also lower than field intensity during a reversal due to the opposing directions of grain sets. The longer the reversal interval, the less difference there will be between true intensity and recorded intensity.

FACTORS AFFECTING MAGNETIZATION AFTER DEPOSITION

The samples that comprise this study are taken from sediments between about 10,000 and 4,000,000 years old. Since deposition most of the sediments have been uplifted, in some cases folded and faulted, and exposed to weathering and erosion. (Only the deposits from DSDP Site 514 had remained unmoved between deposition and sampling.) In the intervening period the magnetization carried by the sediments may have been affected by viscous decay or chemical alteration.

The main carriers of detrital remanent magnetization are titanomagnetites which possess thermal remanent magnetizations. The magnetization of a single domain grain may change as a result of thermal fluctuations.

A given grain set will decay from its initial moment M_0 to M_r at time t according to

$$M_r = M_0 \left(\frac{t}{\tau} \right) \quad (7)$$

where τ is the relaxation time, and is related directly to coercivity. Relaxation time is small for small grains when temperature is high, but may increase to 10^{11} years for $0.1 \mu\text{m}$ grains at 25°C (McElhinny, 1973). In a sediment there will exist a number of grains with high relaxation times which retain their magnetization from the time of deposition. In addition there will be a number of grains which have decayed since deposition, and are aligned along the present Earth's field. Two methods may be used to remove the effect of this viscous remanence: demagnetization (which will be discussed later) and storage in a zero field. Samples were left in a zero field for periods of 1-12 months before measurement. Any grain moment which decays during this time will assume a random orientation and the set of such grains should cancel each other out. There will however still exist a viscous remanence due to grains with relaxation times between 1 year and up to 4 million years, which must be removed by demagnetization.

Exposure of sediments at the Earth's surface may lead to weathering which can cause chemical alteration of the ferrous oxides to ferric oxides, that is oxidation of magnetite (Fe_3O_4) to haematite (Fe_2O_3). As it grows the haematite will develop a chemical remanence when it reaches a critical diameter. In most cases this will mask the original depositional remanence, however in some Italian soils the extent of alteration is such that all of the magnetite has been altered to haematite. Haematite is generally more resistant to alternating field demagnetization than magnetite so chemical overprinting can prevent the identification of the primary

magnetization. To avoid this problem the samples collected should be taken from unweathered sediments. In the case of the palaeosols of northern Italy the purpose was to date the weathering in which case samples were taken from the dark red matrix.

If the sediments are subjected to high fields, even for short periods of time an isothermal remanence may form. This effect can be produced by lightning, so it is necessary to avoid prominent exposures while sampling. McElhinny (1973) notes that a lightning strike of 5×10^4 amps produces a field of 100 Oe at 1m, and that the effect can be removed by demagnetization at this field.

A large number of factors may give rise to a change in direction after deposition, and it must also be remembered that the direction after deposition (and post-depositional realignment) may not have been exactly that of the ambient field at that time. For this reason all results must be treated with caution, particularly isolated samples bearing anomalous results.

SAMPLING

Most of the samples from Italy were taken from exposures in quarries, river banks, and road cuttings. This involved cleaning the exposure of weathered material and trimming the section to a vertical face (measured using a specially constructed device consisting of two perpendicular spirit levels). The samples were taken in plastic boxes which are 2cm cubes, open at one end. These are pushed into the vertical face using the spirit level device to keep the sides of the sample box vertical. The orientation of the sample is measured using a magnetic compass before it is removed, and its lid replaced. Magnetic North is about $1^{\circ} 11'$ west of true North at Bagaggera and $1^{\circ} 10'$ east of true north at Tiepido, no correction is made for the

use of a magnetic compass which probably has an error of about 1°. The rocks are weakly magnetized so they do not affect the results. (Declination was calculated for 1981 using information on maps 32II S.E. and 86 I S.E.) The measurement of vertical and the variation of sample position during insertion probably add up to errors of around 5°.

The boxes have a hole in the base to allow air to escape while the box is being inserted into the sediment. These holes are sealed with 'Lasso' tape, and the samples kept in sealed tupperware containers to prevent loss of moisture, as drying may lead to disturbance of the magnetic grains.

Occasionally three samples were taken from the same stratigraphic level to enable the comparison of separate records of what should be the same ambient field. The agreement can be expressed as the alpha 95 angle for the mean direction, that is the half angle of a cone of 95% confidence about that mean.

The deposits of Lefte and Sovero were too hard to be sampled using plastic boxes, so these were cut to 20cm cubes in the field and later cut down to 2cm cubes in Edinburgh. Orientation was preserved by trimming the top surface of the block while it was in situ, until it was horizontal (as measured by two spirit levels) and inscribing an arrow on this surface in the direction of magnetic north.

The sediments of Piombino and DSDP Site 514 were retrieved using coring methods. In both cases disturbance is kept to a minimum, and at Piombino relative orientation was maintained. Samples were taken from the cores using square plastic boxes, and in addition, plastic cylinders were used on board the Glomar Challenger, and small cylindrical boxes for Piombino cores. The DSDP cylinders are similar to the cubic boxes in that they are pushed into the sediment however the

Piombino samples were taken using a hollow metal tube, and were subsequently extruded into the round boxes. The surface area which is pushed into the sediment is much smaller for the thin metal tube than for the cubic boxes, so less deformation takes place.

THE MEASUREMENT OF NATURAL REMANENCE

The Glomar Challenger samples were measured on a Digico magnetometer at Edinburgh University, whereas all other samples were measured on the cryogenic magnetometer.

The Digico spinner magnetometer uses a fluxgate to measure the magnetic signal produced by a rotating sample. The amplitude of this signal is related to the intensity of the magnetization in the plane of rotation, and the phase difference is governed by the direction of magnetization in this plane relative to a reference mark on the sample holder. Six separate measurements are made with the sample in different positions enabling the resultant to be calculated. The three mutually perpendicular axes (x, y, and z) are each measured four times, ideally with two measurements in an opposite direction to average out the remanent intensity of the holder. The noise level of the magnetometer is due partly to the holder and partly to electronic noise which decreases with the number of spins made (usually 32, sometimes as many as 512). When the holder is spun with no sample the results for one measurement can be as high as $1.5 \mu\text{G}$, however after six measurements this averages out to between 0.1 and $0.2 \mu\text{G}$ (at 256 spins). The Glomar Challenger samples were measured twice (that is two sets of six readings) and the resultant direction calculated from two results usually within 10° . Intensity is calibrated by comparing with a sample of known intensity.

The cryogenic magnetometer consists of three independent S.Q.I.D.

systems (SQUID stands for Superconducting Quantum Interference Device). These are arranged so as to provide an output voltage proportional to the three orthogonal components of the magnetization of a sample. The remanence of a sample can thus be measured with one reading, however three separate measurements were made with the sample in different orientations to cancel any remanence carried by the sample holder. The sample holder varied in intensity with use, and it appears that it was susceptible to viscous remanence, particularly developing a magnetization when left at the top of the magnetometer due to the field at the entrance to the mumetal shielding. The sample holder was therefore demagnetized at regular intervals and left in a zero field when not in use. The remanence of the sample holder could be kept down to $0.1 \mu\text{G}$, with three measurements this averaged out to around $0.05 \mu\text{G}$, which is equivalent to an intensity of less than $0.01 \mu\text{G}$ for a sample with a volume of 6.4cm^3 . Samples with intensities of less than $1.0 \mu\text{G}$ were measured twice and the average direction found. In most cases the two results were very close ($\pm 2^\circ$). It is possible to obtain consistent results from samples with intensities of $0.05 \mu\text{G}$. Occasionally one of the three SQUIDs would begin to drift badly, or not respond to tuning. In these cases it was possible to measure only two of the three orthogonal components in one reading. Four separate readings were then used to find the remanent magnetization of the sample.

ALTERNATING FIELD DEMAGNETIZATION

Demagnetization is used to test the magnetic stability of samples and to remove any unwanted secondary components, such as viscous remanences. The most common method used for sediments is the alternating field method in which samples are subjected to alternating

magnetic fields which are raised from zero to a preset maximum, and then reduced to zero. Grains with coercive forces of less than this field will follow the field as it alternates, each grain becoming fixed in the direction of the field at its coercivity. Relaxation time is proportional to coercivity so those grains whose magnetic alignment is destroyed will be those more likely to have acquired a viscous remanence. In order that the grains do not align themselves in any preferential direction as the alternating field strength decreases through their individual coercivities the demagnetization takes place in a zero field. Ideally the weaker grains will then be aligned equally in the two opposite directions of the alternating field, however fields inside the demagnetizer cannot be completely removed, so the sample may be tumbled along two or more axes during demagnetization. Alternatively the sample is demagnetized along three mutually perpendicular axes, and then demagnetized along the reverse of the third axis at half the maximum field, in this case any anhysteretic magnetization formed through the existence of small fields inside the demagnetizer will cancel out if the range of coercivities are equally distributed about this half field.

Stephenson (1980 a, b) has pointed out the dangers of gyroremanent magnetization (GRM) which may develop through tumbling during demagnetization or through stationary demagnetization of anisotropic material. As Stephenson (1980b) points out gyroremanence results from rotation of a magnetic moment, and is formed by the moments becoming inclined towards the rotation axis. Figure 9a shows a simplified alternating field demagnetization trace with opposite spikes in field strength (from Stephenson, 1980 a).

In a stationary rock demagnetization will cause the grain moments to oscillate between two antiparallel directions. The motion

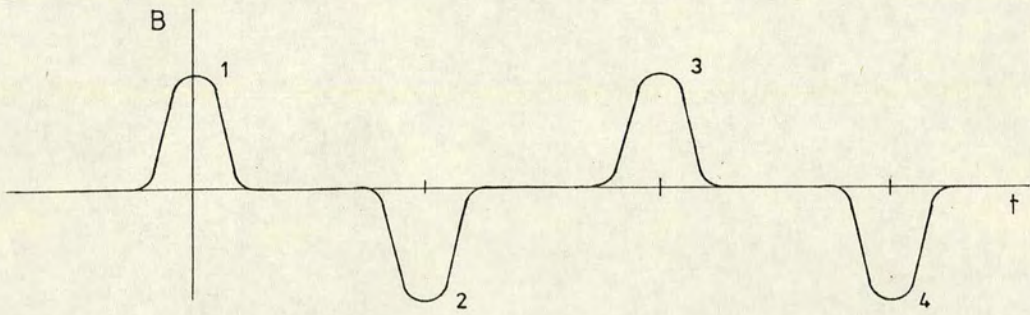


Figure 9a. Simplified A.F. Trace

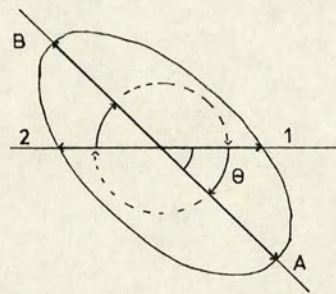


Figure 9b. Effect of Demagnetization on a Stationary Anisotropic Grain

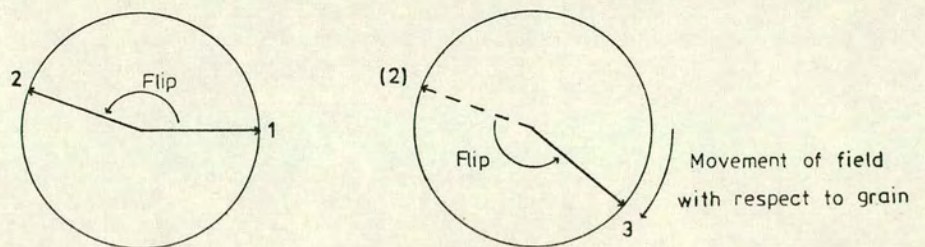


Figure 9c. Effect of Demagnetization on a Rotating Grain

of the grain moments between the two directions will be random if the grain is isotropic. However if the grain is anisotropic with its easy axis at an angle θ to the applied field the moment will flip to its easy axis as the field oscillates between opposite peaks. Consider the grain shown in Figure 9b, when passing from an eastward direction (1) the rotation will be via position A, when passing from a westward direction (2) the flip will be via position B. Thus the motion will always be clockwise. The magnitude of the gyroremanence is dependent on the time taken for this flip between directions, which is itself dependent on the frequency of the alternating field.

The speed of tumbling usually used is not great enough to produce this effect, however a close analysis of the path of individual grain moments between each opposite field peak shows that there is a preferential direction for the flip. Between successive opposite peaks the sample shown in Figure 9c will have rotated so that the direction of the opposite peak (2) is less than 180° from the first peak (1). (Imagine the sample stationary and the field rotating clockwise.) The third peak (3) will be the same angle away, and the flip will be in the same direction. The amount of flip depends on the ratio of rotation frequency to field frequency. If these are identical a GRM will not develop, however an IRM will form because each alternating field peak coincides with a particular orientation of the grain.

Stephenson suggests that the best method of demagnetization is to rotate samples, changing the direction of rotation at the end of each cycle (discussion of a paper at UKGA Cardiff, 1982). This is not possible at Edinburgh at present, so an investigation into the best method of demagnetization was undertaken. There are two demagnetizers at Edinburgh, known by the names of their designers (De Sa and Molyneux). The Molyneux demagnetizer has a tumbling device

attached, however this cannot be used with the De Sa demagnetizer.

Twenty four samples were taken from Section 127 of Piombino core MTO. The NRM results (Creer et al, 1979) showed that the remanent intensity of these samples was very high (150-200 μ G) and the directions were all closely grouped around the normal field direction (they date from the upper Gauss Epoch). Six samples were demagnetized with tumbling in the Molyneux demagnetizer, up to 600 Oe, and then demagnetized again at 600 Oe but with the position reversed with respect to their inner rotation axis. Figure 10 shows that at 600 Oe the direction was almost entirely dependent on the position with respect to the inner rotation axis. In fact the anomalous directions first appeared above 350 Oe. When x, y, and z directions are considered it can be seen that the z component (the one aligned with the inner rotation axis) varies with direction, having a reversible remanence of 15 to 25% of the initial remanence. In addition x occasionally changes by up to 10% perhaps due to inefficient tumbling.

Six samples were demagnetized using the four axes method in the Molyneux demagnetizer. At 900 Oe the samples were demagnetized three times with different arrangements. None of the samples showed any large anomalous components: the individual components were usually less than 5% of the initial remanence, but there is no dominant orientation. Reversing sample X3 in the y and z directions produced variation of 4% of the initial remanence, but this is about the level of variation for sample X1 which remained in the same position. This variation is thus due to the weakness of the samples not to any growth of an anomalous remanence (Figure 11).

The remaining twelve samples were demagnetized in the De Sa demagnetizer along 4 axes, repeating the measurements at 900 Oe with three sample positions (the second time with y and z reversed, the third time with x and z reversed, see Figure 12: for example MTO X19,

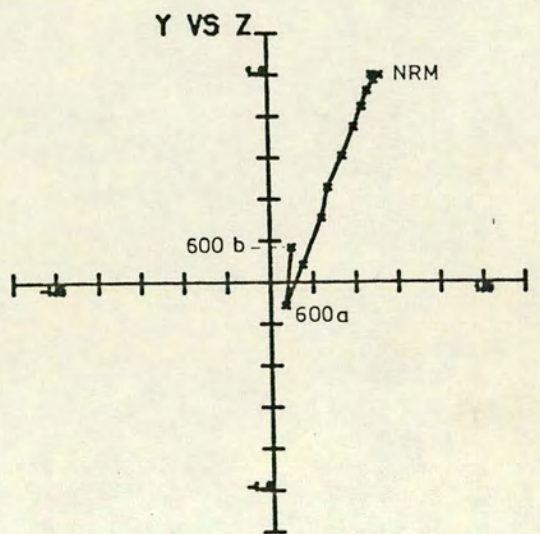
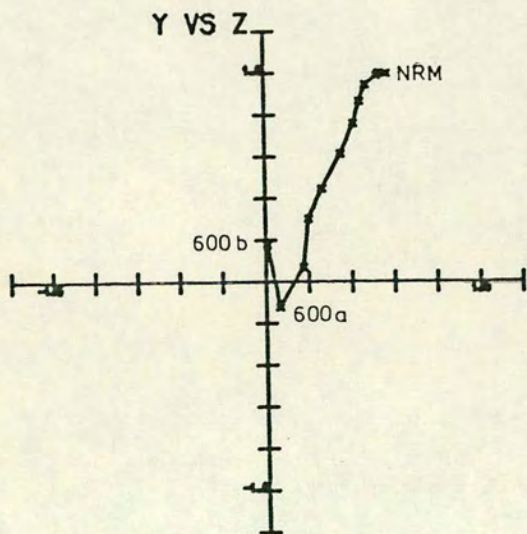
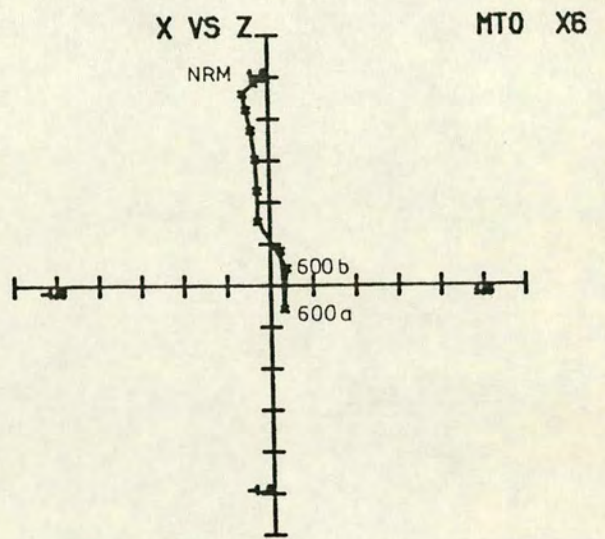
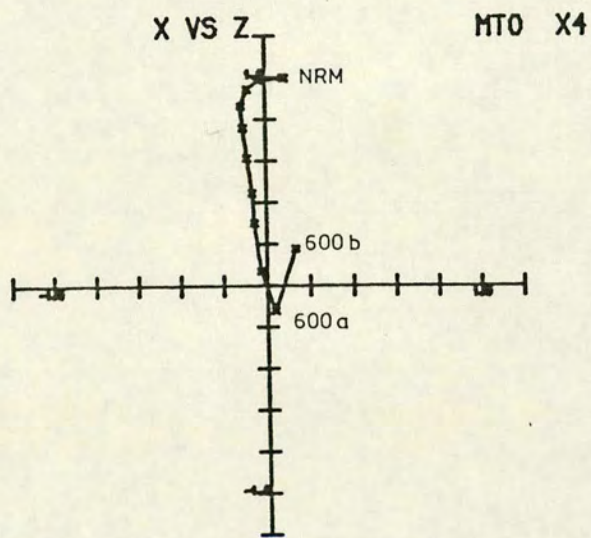


Figure 10. Rotational Remanent Magnetization at 600 Oe.

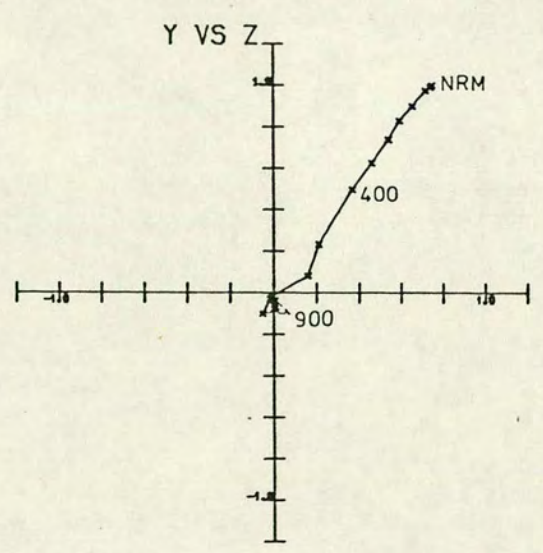
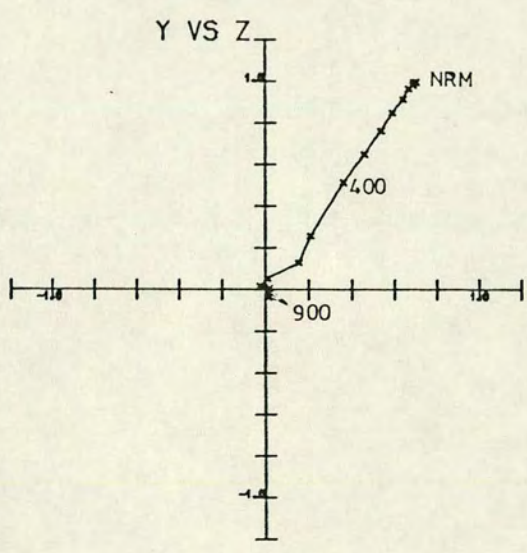
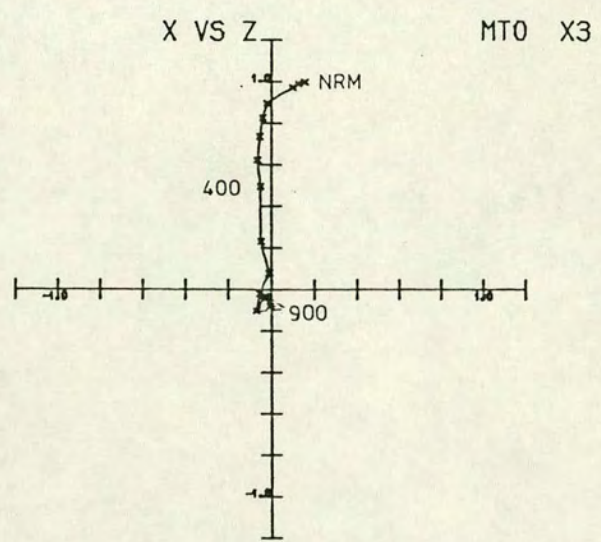
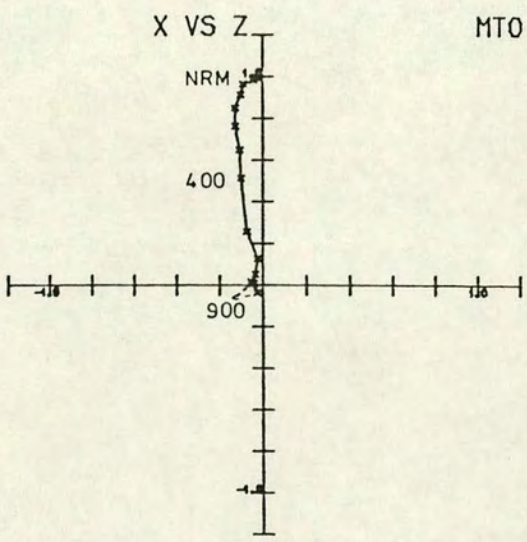


Figure 11. Stationary Demagnetization using the Molyneux Demagnetizer

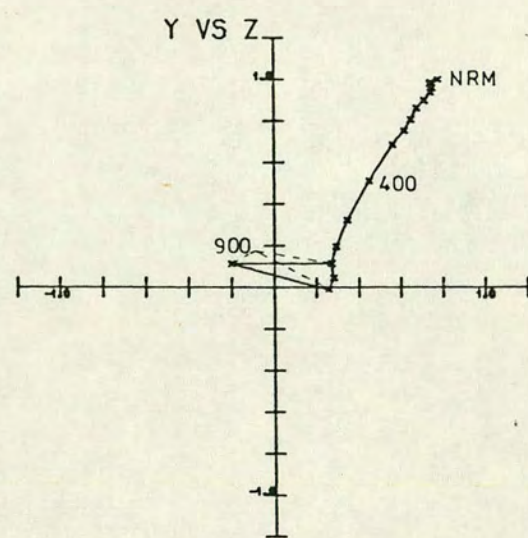
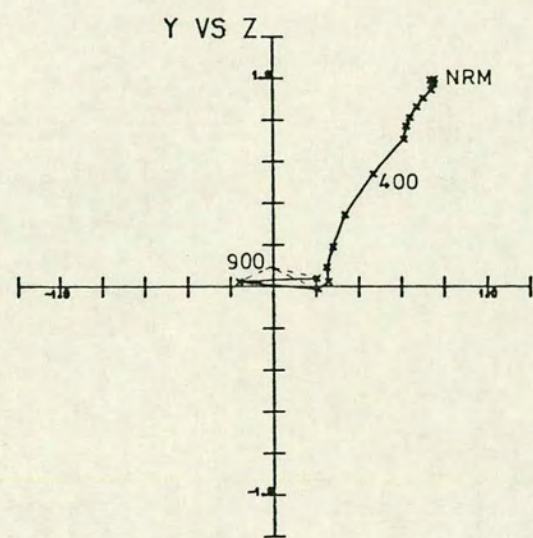
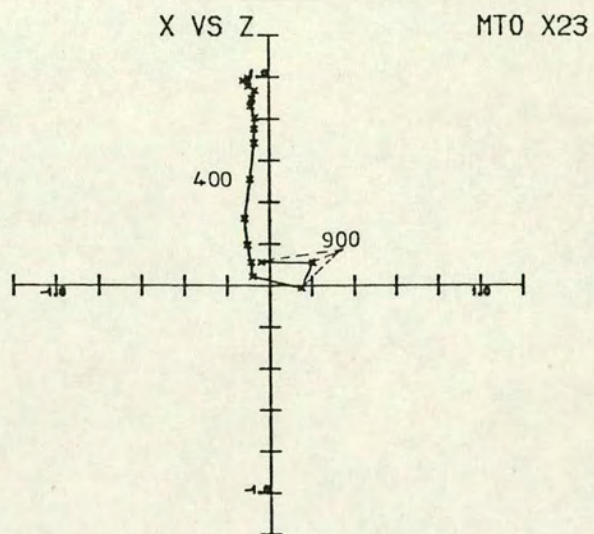
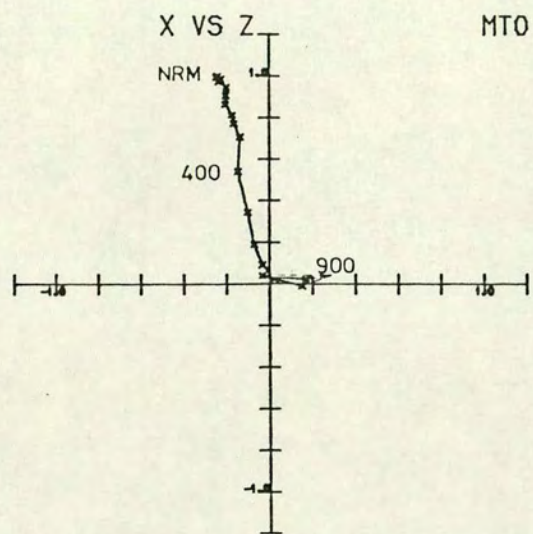


Figure 12. Stationary Demagnetization using the De Sa Demagnetizer

MTO X23). At 900 Oe reversing the direction usually produced a change in the component along that direction. The largest ARM is that in the y direction (about 20% of the remanence). This axis was the one parallel with the direction of the alternating field, and the ARM in this direction probably arose due to irregularities in the alternating field. ARMs produced in the other directions were about 5% of the initial remanence.

The Molyneux demagnetizer was used for all demagnetizations with samples being demagnetized along four axes. As the samples were too weak to measure at high fields there is a danger of ARMs. Dankers and Zijderveld (1981) suggest measuring the sample after each step of the 3 axes method and using the component parallel to the coil axis, summing after three measurements. This involves three times as many measurements, and does not cancel out any effect due to asymmetry of the alternating field. In most cases the only remanent component needed to be removed is a low coercivity viscous remanence so the problem of ARMs at high fields is not important in this study.

Usually ten or twenty samples from a particular site were demagnetized at fields increasing in steps of between 25 and 100 Oe from 0 to 600 Oe. This will reveal a number of components with different coercivities. Apart from a primary remanence some samples possess a secondary magnetization developed in the direction of the present Earth's field. This is removed by alternating fields of about 100 Oe. Generally all samples are demagnetized at 150 Oe, after inspection of pilot demagnetization results, although some samples were unstable at moderate fields, so they were demagnetized at 100 Oe.

A number of weathered samples showed that a stable component was still present at 600 Oe. This is due to haematite which is resistant

to alternating field demagnetization. In order to remove this chemical remanence the samples were soaked in a sodium dithionite - sodium citrate solution with a sodium bicarbonate buffer (Mehra and Jackson, 1960, Kirschvink, 1981). This should ideally dissolve Fe_2O_3 but not Fe_3O_4 . Unfortunately the samples tended to collapse completely after 3 or 4 hours, without any marked change in remanent direction. This was partly due to the loosening of the material due to removal of haematite cement, and partly due to swelling of clays through removal of aluminium.

SUSCEPTIBILITY, ARM AND IRM

The amount of magnetic minerals present in a sediment can be measured by inducing an artificial remanence in the sediment, or by measuring its low field susceptibility. Comparison of these parameters can give information on the type of mineral and the grain size involved.

Low field susceptibility is measured on the Digico susceptibility bridge, and is calibrated using a sample of known susceptibility made from copper sulphate. Susceptibility gives a measure of the total magnetic mineral content (including superparamagnetic grains) but it is more sensitive to coarser grains. The Königsberger ratio (Q-ratio) is the ratio of intensity to susceptibility, and is a measure of the efficiency of grain alignment in sediments.

Samples are given an ARM by placing them in a 0.75 Oe direct field, whilst applying a 1000 Oe alternating field which decreases to zero. Like susceptibility this gives a measure of the total magnetic mineral content, but is more sensitive to smaller grains. Plotting ARM against susceptibility can give an idea of the grains involved (see King et al, 1982; Figure 8) provided no haematite is

present.

Samples were given isothermal remanent magnetizations in direct fields of up to 10,000 Oe. The IRM at this peak value is usually referred to as the saturation IRM (J_{sr}), however samples containing haematite may not be completely saturated at this field. Magnetite grains saturate at between 1000 and 2000 Oe. In addition to using the saturation IRM as an indicator of magnetic mineral content, the rate of increase of this remanence with increasing fields can be studied to determine mineralogy. Stober and Thompson (1979) suggest that the reverse IRM should be studied after samples have been given a saturation IRM. This eliminates the effects of any initial remanence.

The coercivity of remanence (H_{cr}) is the reverse field necessary to reduce the saturation remanence to zero (Figure 13). This is less than 1000 Oe for magnetite and over 5000 Oe for haematite (see McElhinny, 1973 pp37 and 38). The parameter 'S' is defined by Stober and Thompson as the ratio of IRM in a reverse field of 1000 Oe (following saturation at 10,000 Oe), to the saturation IRM. A magnetite grain saturating at 1000 Oe will give $S = 1.0$, a haematite grain becoming saturated at 10,000 Oe will give S equal to or less than zero.

Levi and Banerjee (1976) discussed the possibilities of using susceptibility ARM, and SIRM to normalize the intensity of natural remanence. Consideration of the acquisition of detrital remanent magnetization shows that intensity is dependent on depositional environment, and ambient field intensity as well as magnetic mineral content. However if the depositional environment has remained constant over the period of sedimentation intensities can be normalized providing the natural remanence is carried by the same

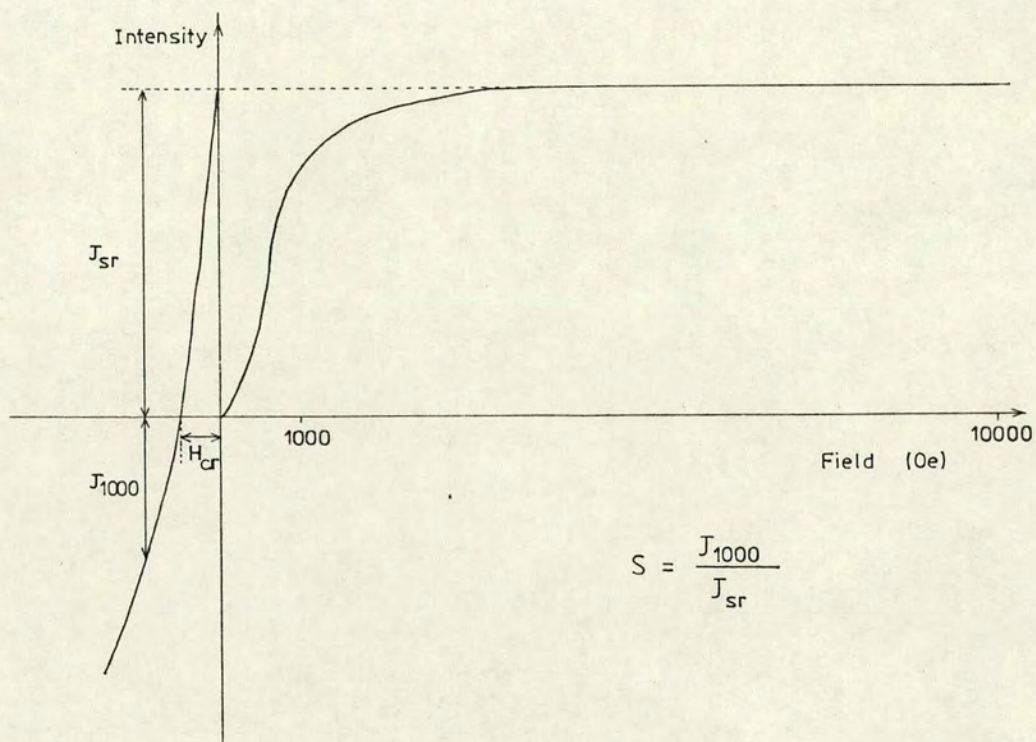


Figure 13. Parameters used in the Study of Isothermal Remanence

grains as those which contribute to susceptibility, ARM, or SIRM. ARM tends to emphasize the smaller grains while susceptibility and SIRM emphasize larger particles. To discover which artificial magnetization is closer to the natural remanence the decrease in intensity with demagnetization is compared for each type of remanence. The normalization parameter is chosen so that its demagnetization curve most closely resembles that of the NRM, that is the artificial magnetization is carried by grains with a similar coercivity spectrum to those carrying the natural remanent magnetization.

PRESENTATION OF RESULTS

Various computer plots are used for the presentation of the results, some of which need, perhaps, a little discussion. The pilot demagnetization plots are generally intensity versus field graphs together with stereographic projections of directions. A typical stable sample will show no change in direction, and will decrease gradually in intensity. Initial increases in intensity may be due to secondary overprints. This method of plotting enables calculation of the median destructive field; the field at which half of the natural remanence had been removed, which is a measure of the coercivity spectrum of the grains carrying the remanence.

Zijderveld (1967) suggested an alternative method of plotting demagnetization results in which x, y, and z components were plotted against each other, magnetization components being indicated by straight line segments. The primary direction is identified as a segment moving towards the origin with higher fields. Both methods are equally useful in isolating stable components, however the stereographic projection is used throughout this work as it more clearly shows how a sample is behaving with respect to the normal direction.

Hoffman and Day (1978) suggested that magnetization components carried by grains with overlapping coercivity spectra could be better identified by plotting the vector removed at each step. This method enhances any random noise between each step and in samples of low intensity it can give very inaccurate results.

The plots of intensity, declination, inclination, susceptibility etc with depth are straight forward, note however, that intensity and susceptibility are plotted logarithmically. Virtual geomagnetic pole latitude (calculated from each pair of declination and inclination readings) is used to determine polarity. Some plots include a sedimentary column, the key to which is shown in Figure 14.

Transitions are studied using plots of the virtual geomagnetic pole position. There has been much debate about the meaning of such plots as there will only be a transitional pole at the position indicated if the transitional field is dipolar. Recently Hoffman (pers. com.) has suggested plotting directions rotated so as to appear to start at one geographic pole and end at the other. The major debates about transitional paths concern whether the VGP path passes through the site or at 180° to it, which can be equally effectively shown by both plots; and whether successive transitions take the same path or not. Similarities can be better identified by comparing geographic locations of, albeit imaginary, poles rather than by comparing similar directions.

The plots used for transitions are Mollweide's Projection which gives a more realistic shape near the poles than the Sinusoidal plot. The Mercator projection extends the polar regions to the same width as the equator, giving the impression that reversals may begin from different positions. A simple transition is shown on the three projections in Figure 15. Stereographic Projections are used to study



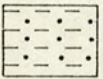
Clay



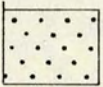
Silty Clay



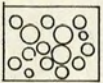
Silt



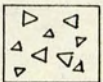
Silty Sand



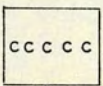
Sand



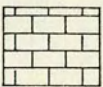
Gravel



Breccia



Shell Bed

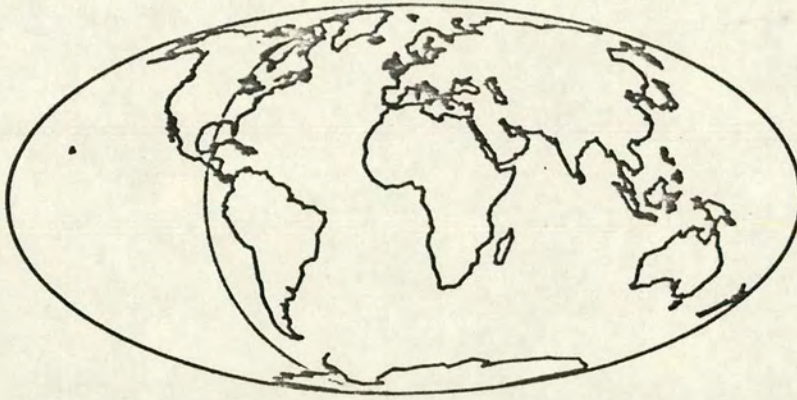


Bioclastic Sand



Palaeosol

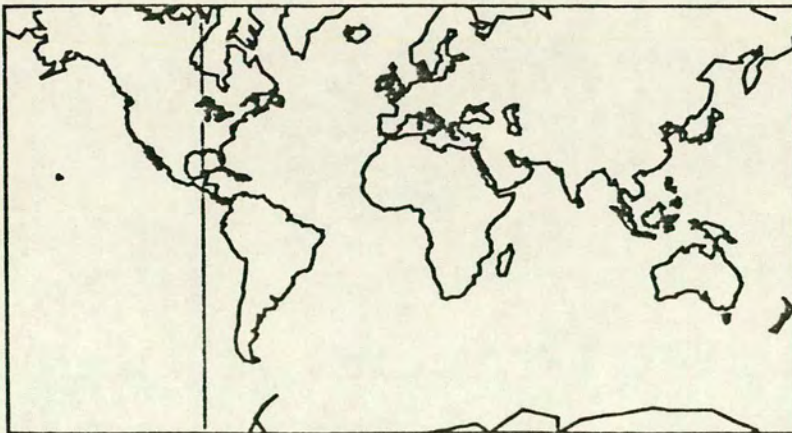
Figure 14. Key to Sedimentological Sections



Mollweide



Sinusoidal



Mercator

Figure 15. Global Projections

variation around the polar regions. On the plots virtual poles are joined using great circles, however for poles almost 180° apart this path has little meaning.

The term 'excursion' is used throughout the thesis, and although one of its aims is to define these phenomena, it is necessary to have a temporary definition. Those reversed intervals which are too short to be recorded as such by some sediments with low deposition rates, and those attempts by the field to reverse which fail may appear in the palaeomagnetic record as changes in magnetic direction of between 45° and 135° from the stable direction. These are referred to in the text as excursions.

The magnetostratigraphic frame work used in the text is taken from Mankinen and Dalrymple (1979) and is shown on p. 300. Note that current usage is for Chron to replace Epoch, and Subchron to replace Event.

CHAPTER 3

ARGENTINE BASIN

Site 514 was drilled in February 1980 as part of DSDP Leg 71. The Site is located at 46°S, 27°W on the west flank of the Mid-Atlantic Ridge in the Argentine Basin (see Figure 16). Slightly more than 150m of sediment were retrieved from a water depth of 4138m using the hydraulic piston coring method. The core tube is forced into the sediment to a depth of 4.4m, then the outer core is drilled down around this core length. The 4.4m of sediment is then removed and another core is taken to cover the next 4.4m. DSDP convention refers to the entire sequence as the 'Site' or 'Hole', to the 4.4m sediment length as a 'Core', and to the three c1.5m working divisions of the Core as 'Sections'. Any sample is defined by its Site number, Core number, section number and depth within a Section, for example 514-2-288 to 90 cm. As all samples in this study refer to Site 514 this prefix will be dropped.

Deformation due to drilling disturbance is reduced by hydraulic piston coring, in particular the relative orientation of samples along the 4.4m core lengths is preserved, whereas with rotary drilling diskings often takes place. It was hoped that relative orientation would be preserved from one core to another by stamping an aluminium ring as the core is taken, however movement of the core holder before firing due to the poor weather conditions led to the aluminium ring moving continuously and being stamped repeatedly giving confusing results. Recovery was very high at Site 514 (92%), however significant gaps occur in the upper part of the sequence, particularly at 23 to 27.5m (Core 7).

The sediments recovered are Plio-Pleistocene grey-green

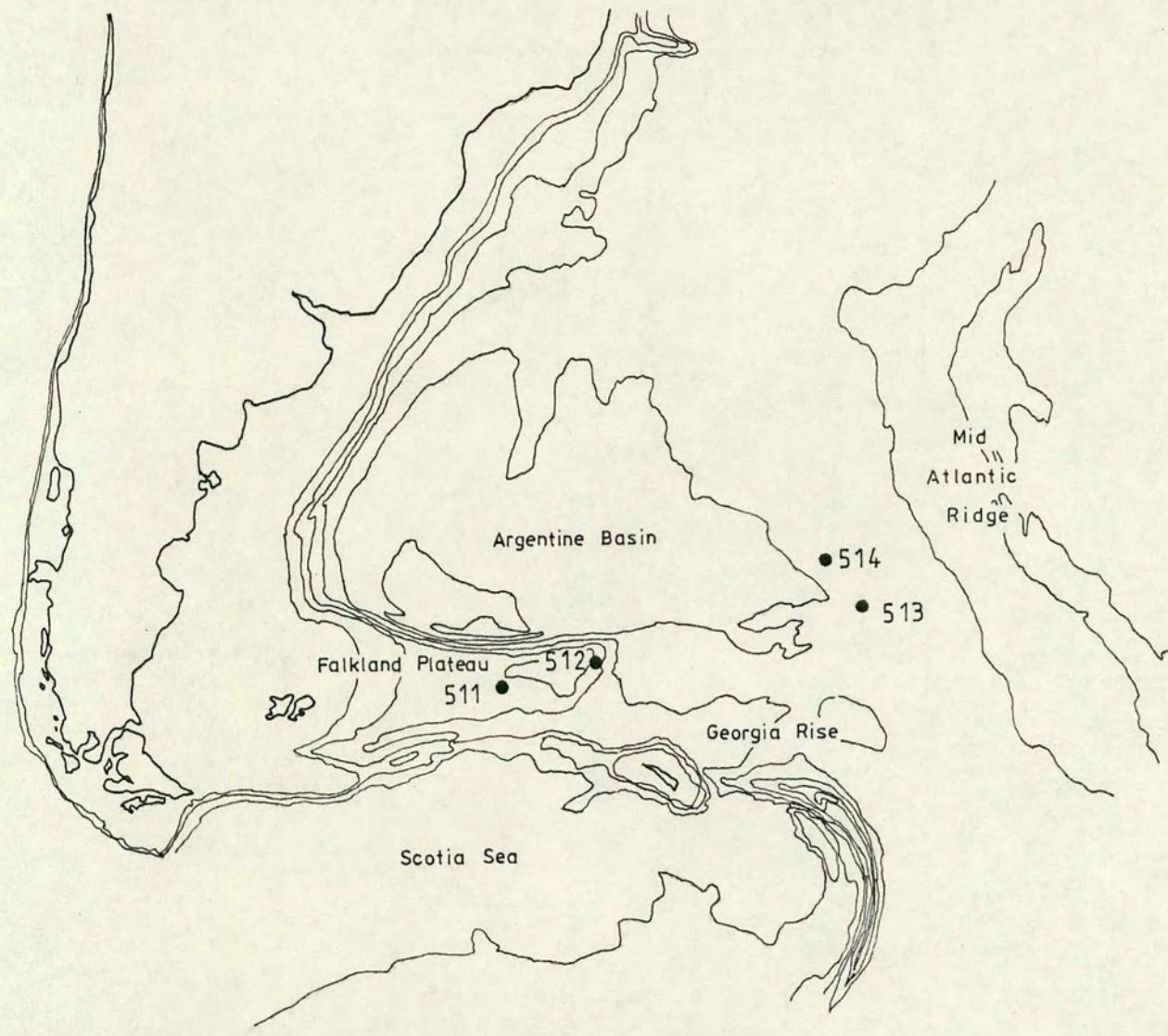


Figure 16. Map of sites, DSDP Leg 71

diatomaceous clays of a similar lithology throughout the hole. Bioturbation is present at most levels, but it is only of minor intensity. Quartz silt and manganese are seen towards the top of the Pleistocene deposits.

Study of radiolarians and diatoms has enabled the zonation of the sediments as shown in Figure 17. (In fact the results of this site led to the redefinition of some diatom zones for the southern oceans: see Ciesielski, in print¹). The section appears to be complete save for an unconformity in the lower Pleistocene and a possible unconformity in the Brunhes. The lower unconformity is placed at 112m, representing the interval 3.9 to 3.1 million years, coincident with the first glaciation in Argentine Patagonia. Above this level a large number of reworked microfossils are seen. The lower Brunhes Stylatractis universus radiolarian zone has not been identified, but an equivalent diatom zone is present. There may be an interval of low sedimentation rate or a hiatus here. Sedimentation rates are generally quite high, particularly in the lower half of the section: 10-20cm/1000 years for the interval up to about 2 m.y. (c30m), and then about 1.5cm/1000 years following this.

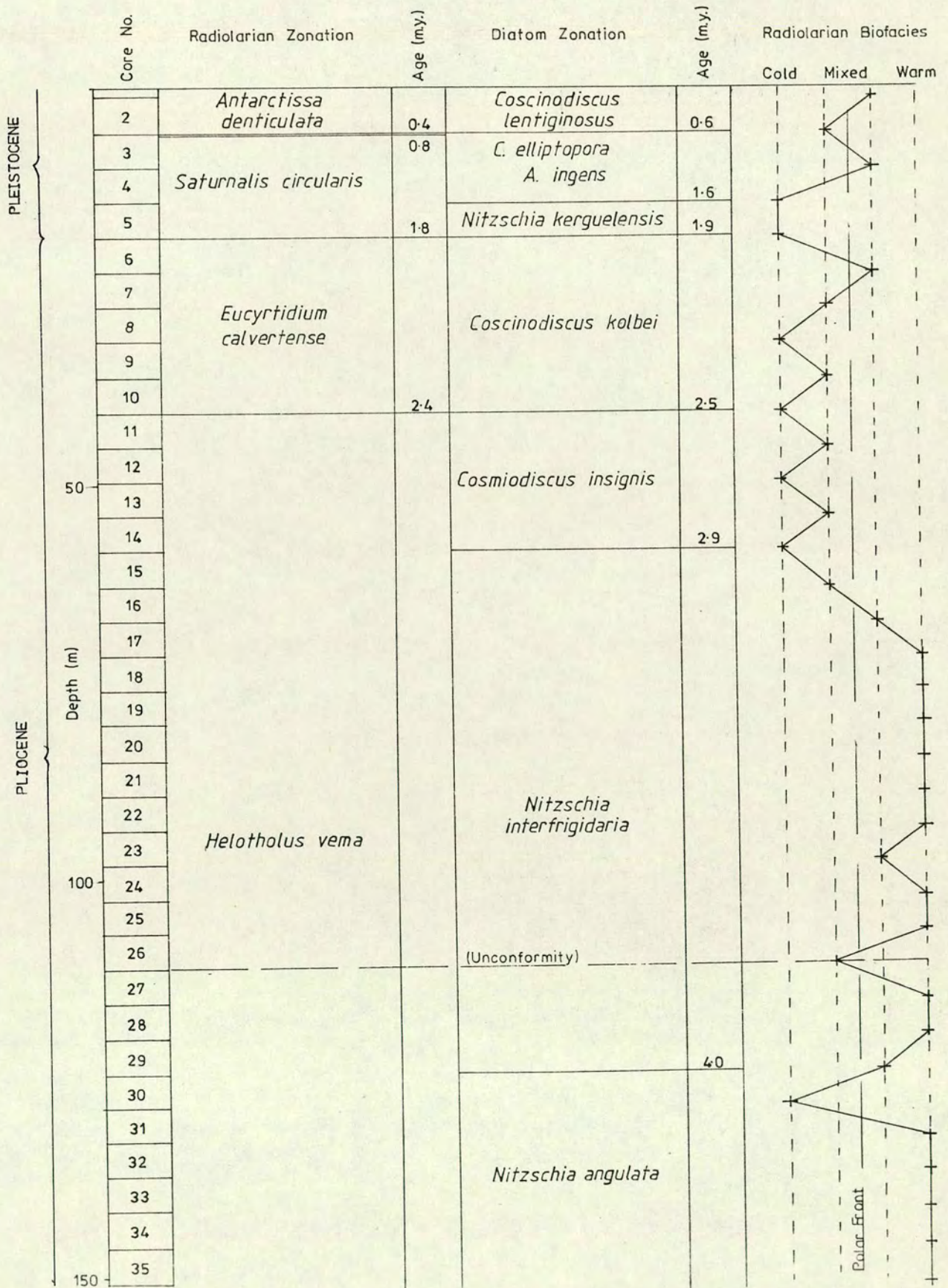
Analysis of radiolarians shows that the area was north of the Polar Front (i.e. warm) for most of the period 4.2 to 2.7my.b.p.(the latter date being the approximate age of the formation of the North American ice sheet). Since this time the site has been to the south of the Polar Front (i.e. cold), apart from three short intervals, including the present (see Figure 2, in part from Ludwig et al, 1980).

SAMPLING

Samples were taken from the working half of each core section on board the Glomar Challenger, and later supplemented by further samples

1 Due to appear in volume 71 of the Initial Reports of the Deep Sea Drilling Project

Figure 17 Micropalaeontological Zonation



taken at the Core repository in New York. The shipboard samples were taken using 2.5cm plastic cylinders which were pushed into the core, oriented by a notch pointing up the hole. These were sealed with adhesive tape. The samples taken in New York were the standard 2cm boxes used for the majority of the other work in this study. All the measurements reported here were made on land, mainly on the Digico magnetometer at Edinburgh. (The ten or so samples taken in New York were measured on the cryogenic magnetometer while it was at Southampton,)

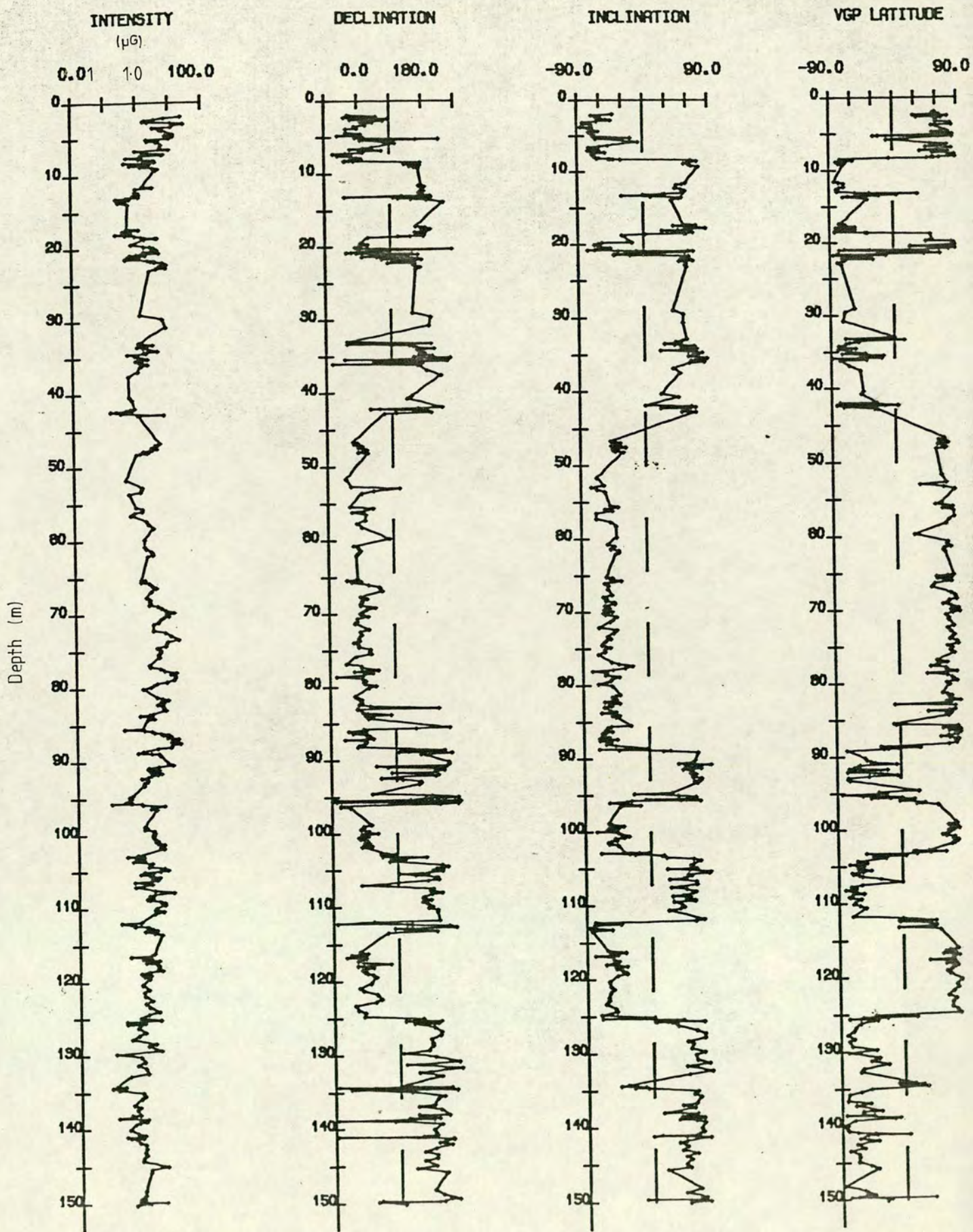
Apart from the interval represented by Core 7 which was not recovered, there were gaps in sampling at 0 to 1.80m, 9.30 to 11.50m, and 42.80 to 46.60m due to the poor quality of recovered material, in these sections water had entered the core and 'diluted' the sediment causing it to flow. It was also noted that rust flakes collected at the top of each core having been removed from the inside of the drill string as the core tube was lowered into position, and settling at the top of the sediment inside the core during the coring process. A small amount of deformation sometimes occurred at the bottom of each core as a result of flow of the sediment due to creation of a vacuum during removal of the core. Samples with anomalous directions at the top and bottom of the core can be rejected, particularly when intensity is up to 100 times the normal amount.

RESULTS

NRM results for samples from Site 514 are shown in Figure 18. The declination within each core was more or less constant, except where a polarity transition was seen in inclination, when a coincident change of 180° was seen in declination. The declination in Figure 18 has been corrected so that the mean declination of all samples representing



Figure 18. NRM Results for DSDP Site 514

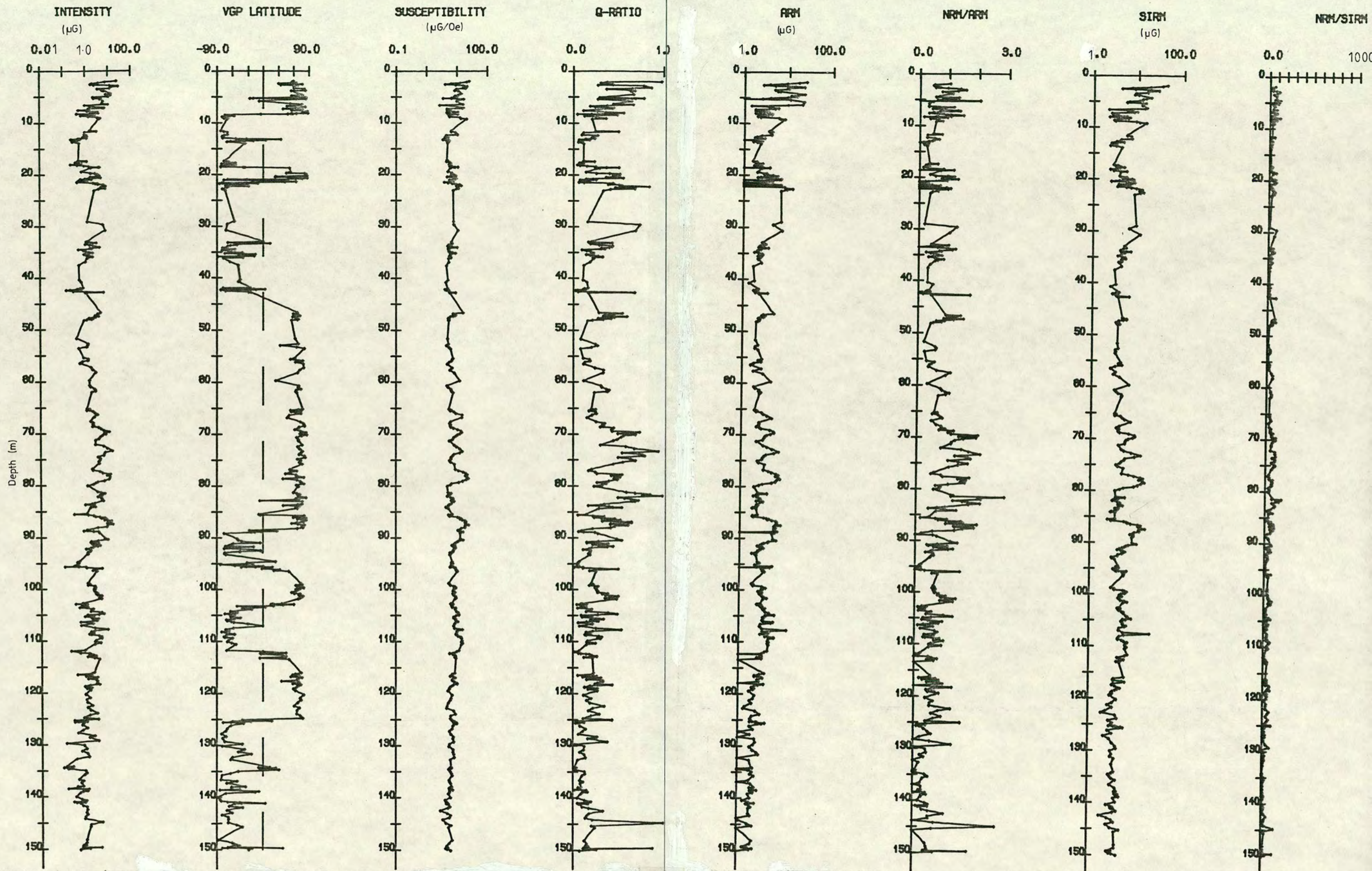


stable normal polarity is zero in each core (and is 180° for reversed polarity). Inclination has an absolute mean value of $51.0 \pm 17.0^\circ$ and gives clearly defined polarity zones. Intensity averages $2.7 \pm 3.1 \mu\text{G}$ and is higher in the uppermost 10m of the core, and between 70 and 90m. There are a large number of fluctuations throughout the section.

Jan Bloemendal has measured the susceptibility of each of the samples together with the ARM produced by a direct field of 0.4 Oe in an alternating field of 1000 Oe, and the IRM produced by a direct field of 10,000 Oe (Figure 19, see Bloemendal, in print). Susceptibility, ARM, and IRM all show larger values in the uppermost 10m. Susceptibility shows a slight increase at 70-90m but the normalized intensity curves all show higher values here. Average susceptibility is $8.5 \pm 3.9 \mu\text{G}/\text{Oe}$ giving Q-ratios of 0.28 ± 0.22 . Average ARM is $3.4 \pm 2.8 \mu\text{G}$, and average IRM is $552.6 \pm 390.1 \mu\text{G}$. Bloemendal interprets the short period fluctuations as variations in current strength giving increased ratios of heavy magnetic minerals to lighter grains. Comparison of the demagnetization characteristics of natural, anhysteretic and isothermal remanences show that NRM is softer at Site 514 than ARM and always harder than IRM. Because NRM is not carried by similar grains to these artificial magnetizations Bloemendal suggests that normalization of NRM by them is not possible. However it does seem that the harder² grains (represented by ARM) have a similar distribution with respect to depth, to the softer grains (represented by IRM), so it is possible that grains of intermediate hardness also have a similar distribution down the hole. If hardness is inversely related to size it seems unlikely that the middle of the range should vary while the ends remain constant.

Examples of pilot demagnetization are shown in Figure 20. Many samples from the top of the section were very stable (e.g. 2/2/89 at

Figure 19. Normalized intensity at Site 514



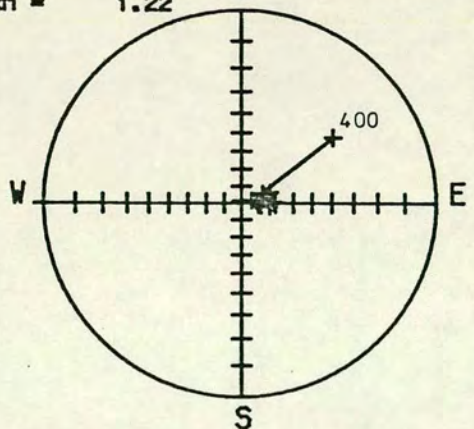
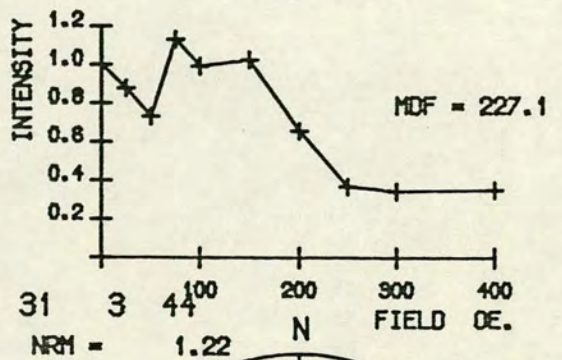
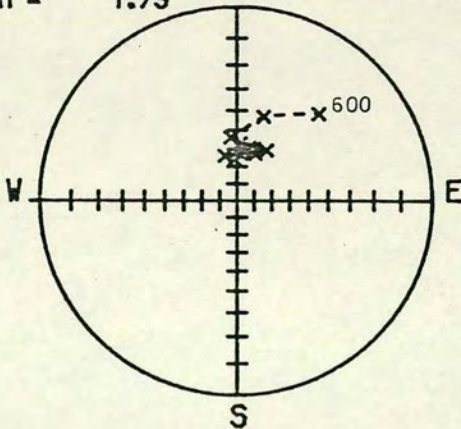
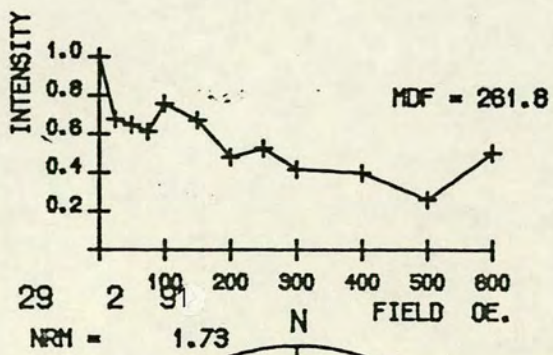
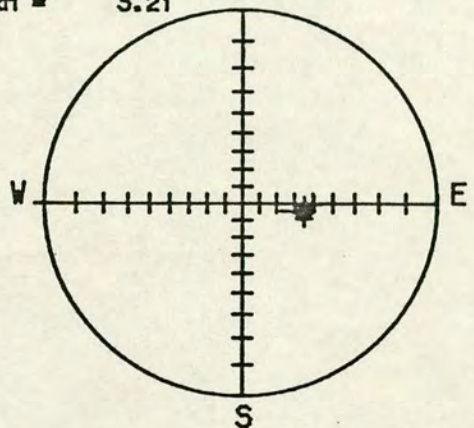
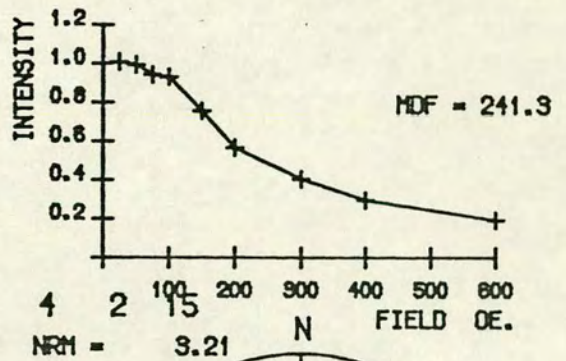
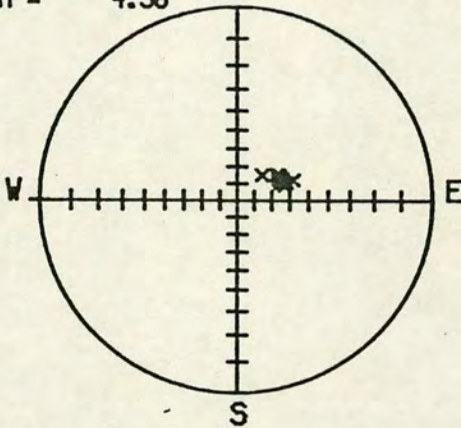
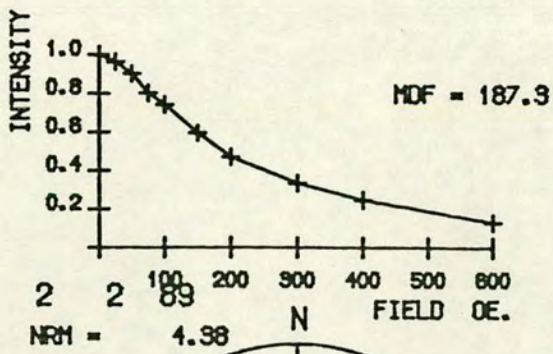


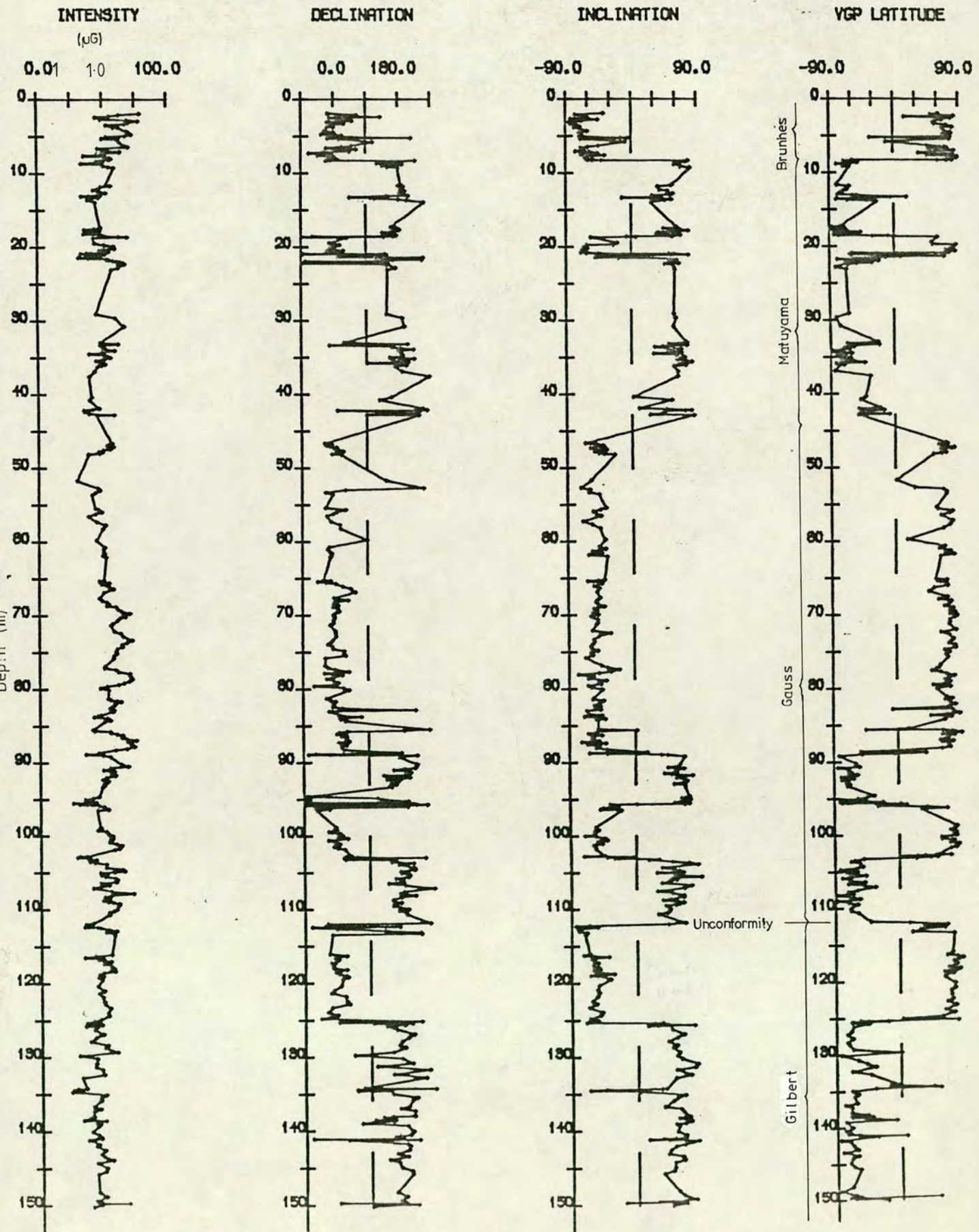
Figure 20. Examples of Pilot Demagnetization from Site 514 (+ positive inclination, x negative inclination)

3.90m and 4/2/15 at 11.66m). The remanence of samples from the lower half of the hole tended to move about the initial direction, this is probably due to the high noise of the Digico magnetometer (for example 29/2/91 at 122.41m). Median destructive fields show a large amount of variation, but are usually between 150 and 300 Oe for the more stable samples. Demagnetization behaviour was often complicated when samples which were apparently stable, that is showed no change in direction, displayed sudden jumps in intensity (e.g. 31/3/44 at 132.25m). It cannot be definitely proven, however, that this was due to changes in the sensitivity of the Digico, although many samples were demagnetized while using the cryogenic magnetometer and this behaviour was not seen. Samples from Site 514 left in the magnetic field of the laboratory for periods of up to one month did not show significant changes in direction or intensity suggesting that large viscous remanences are not the cause.

Blanket demagnetization was carried out at 200 Oe (Figure 21). Average intensity was reduced by 42% to $1.57 \pm 1.75 \mu\text{G}$, while absolute inclination increased slightly to $53.5 \pm 16.0^\circ$. There is very little change in the overall magnetostratigraphy. Five reversed, and five normal zones can be recognized (note that this site is in the southern hemisphere so normal polarity is represented by negative inclination). By comparison with the micropalaeontology the magnetostratigraphy is incomplete: the Nitzschia interfrigidaria diatom zone should stretch from the top of the Kaena Event to the Gilbert beneath the Cochiti Event. However in this interval (125-60m) only two reversed zones are seen. The unconformity at 112m therefore spans the Upper Gilbert Event. The magnetostratigraphy is thus as follows:

The Gilbert Epoch occurs from the base of the core to 112m with the Cochiti Event above 125m. A small event is seen at 135m, which

Figure 21. Results for Site 514 after Demagnetization



tends to become thinner with demagnetization, although the inclination of two samples becomes more normal, giving VGP latitudes of 46° N at 134.35m and 55° N at 134.50m. Sample 32/1/129 at 134.50m is more or less stable with demagnetization, however samples 31/1/92 (134.13m), 32/1/96 (134.17m), and 31/1/105 (134.26m) have low intensities and show large changes in direction with demagnetization. It seems likely that a short excursion exists as similar anomalous directions have been seen in other cores from this region (Ciesielski pers. comm.). If the base of the sequence is assumed to lie just above the Nunivak Event, the excursion can be dated at around 3.95 million years with a length of 3000 to 6000 years.

The Gauss Epoch occurs between 112m and 45m, with the Kaena Event at 89 to 96m and the Mammoth Event at 103 to 112m. The top of the Gauss was not sampled, but the lowermost Matuyama sediments have low VGP latitudes due to variation in both inclination and declination. This interval is core 11 which contained sediment which may have been disturbed during drilling.

The Matuyama Epoch occurs between 45 and 8m, cut by one normal event at 18.5 to 21m, interpreted to be the Olduvai Event. At 13.32m a sample occurs with shallow negative inclination and easterly declination, giving a VGP latitude of 4° S, while an adjacent sample has northerly declination giving a VGP latitude of 17° N. This is interpreted to be the Jaramillo Event, although it must be stressed that the interval between 9.30 and 11.50m was not sampled, so the Jaramillo Event may have been missed completely. If this is the case then the excursion seen at 13.32m can be dated at approximately 1.15 my, by assuming a constant sedimentation rate. Using the assumption of constant sedimentation rate throughout the Matuyama, then the Reunion Events will also have been missed due to the non-recovery of Core 7

(23.0m to 27.5m).

The Brunhes Epoch occurs above 8m. Two possible excursions are seen represented by single samples at 5.21 and 5.79m, although the former is at the base of Core 2 and the latter at the top of Core 3, so both may be from disturbed sediment.

TRANSITIONS

Intermediate field directions were seen in almost all of the polarity transitions recorded. The Matuyama-Brunhes transition occurred between two adjacent samples, however seven transitions with intermediate poles are seen at Site 514, these are shown in Figure 22, together with two short events. In some cases these paths are slightly different to those published in the Initial Reports of the Deep Sea Drilling Project (Salloway, in press). The original paths were the results after blanket demagnetization at 200 Oe, whereas for Figure 22 the most stable direction was chosen for those samples that were demagnetized stepwise.

The Upper Matuyama excursion, referred to here as the Jaramillo Event for convenience, does not involve complete reversal. VGP positions reach the equator in Africa, then return to the South Pole, giving an excursion and suggesting that this may in fact not be the Jaramillo. The normal to reversed transition at the top of the Olduvai Event involves drift westwards to Australia from the eastern Pacific giving a far sided path. The Lower Olduvai boundary includes three reversals, two of which pass through the Indian Ocean (i.e. 90° east of the site), although the final reversed to normal path has no intermediate poles. The third path, which is the oldest of the three is similar to the Upper Olduvai path in that it crosses the western Pacific, this time passing from the Indian Ocean to near Hawaii before



Jaramillo Event



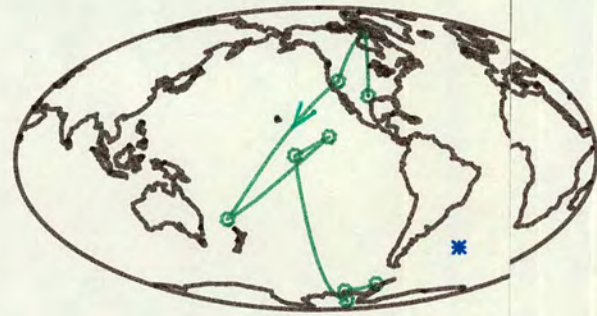
Upper Olduvai



Lower Olduvai



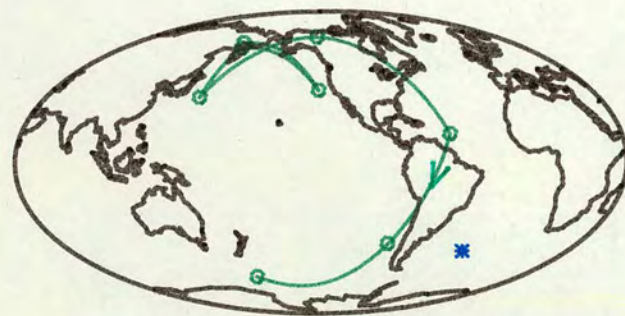
Upper Kaena



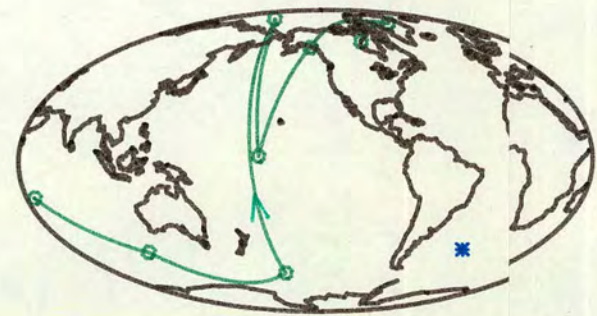
Lower Kaena



Upper Mammoth



Upper Cochiti



Lower Cochiti



Gilbert Epoch Event

Figure 22. VGP Plots for Transitions at Site 514
(* sampling site)

reaching the North Pole.

Assuming constant sedimentation through the Matuyama gives a very large estimate for the length of the Lower Olduvai transition (over 40,000 years), so either sedimentation was faster in this interval, or a hiatus occurred causing the Reunion Event to appear much nearer the Olduvai Event.

The three reversals in the Gauss Epoch all show short returns to lower latitudes at the end of the transition. The Lower Kaena (normal to reversed) transition has the least amount of deviation from a smooth, longitudinally confined path, crossing the equator at about 145°W, more than 90° west of the site. The Upper Kaena transition is just near-sided, passing through the east Pacific, 60°W of the site, but returning to low southerly latitudes in Australia after the main reversal. The Upper Mammoth reversed to normal transition passes through the Indian Ocean (slightly more than 90° east of the site) but momentarily returns from the North Pole to the mid Pacific.

The Upper Cochiti (normal to reversed) transition is near-sided, passing through South America, and apparently reaching high southerly latitudes just before the unconformity. The Lower Cochiti reversal is sharp, but includes a return from the North Pole to the mid Pacific after the transition. The Gilbert Epoch excursion at 134m (starting from reversed polarity) is concentrated on the near-side, with the lower part to the east of the site, and the return part mainly to the west.

The five transitions from the Gauss and Gilbert Epochs were recorded in sediments with higher accumulation rates, and give reversal durations of 3,000 to 10,000 years (averaging 6,500 years) which is of the same order as other estimates for the time taken by the field to reverse.

The Site 514 data probably offer the best opportunity to study the variation of field strength within these transitions. The intensity of sedimentary rocks is dependent upon magnetic mineral content, conditions of sedimentation and geomagnetic field strength. Most of the other sites studied in this report have varying conditions of deposition so variations in intensity are chiefly controlled by current velocities, and grain size of the matrix. At Site 514 the deposition conditions have probably been more or less constant through the past four million years, although variations in current strength may have led to increased amounts of magnetic minerals being transported to the area at some stages. The total magnetic mineral content may perhaps be normalized by ARM or IRM of the grains which carry them have the same distribution with respect to time as the carriers of the natural remanence. This would appear likely as any change in supply would presumably affect either end of the grains size range before affecting the middle, that is assuming a single source for the magnetic minerals which is highly probable for mid-ocean sediments.

Figure 23 shows the intensity across each of the transitions normalized by susceptibility, ARM, and IRM. Although in many cases there are large fluctuations in normalized intensity outside the transitional zones, it would certainly appear that lower field intensity occurred during most of the transitions including reversals of both senses. For example the Lower Olduvai transition at 21m occurs in an interval with Q-ratio less than 0.25 between 20.61m and 21.60m, while either side of this interval Q-ratio is greater than 0.35. Similarly NRM/ARM changes from less than 0.4 to greater than 0.55, and NRM/SIRM from less than 0.3×10^2 to over 0.4×10^2 . This 1m section compares with the interval between 20.79m and 21.60m which defines the

Figure 23. Intensity during Transitions recorded at Site 514; Normalised by Susceptibility, ARM, and SIRM

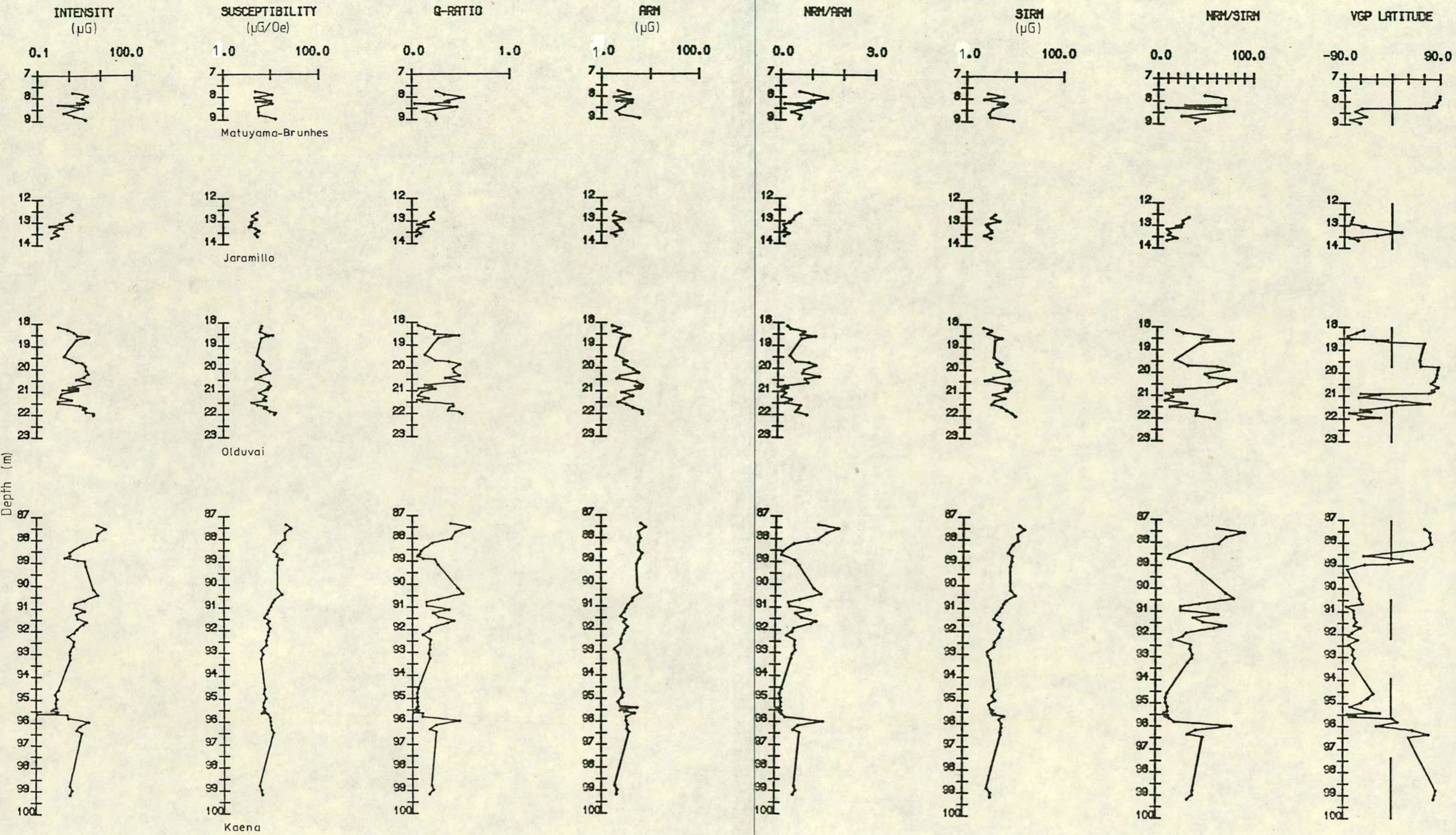
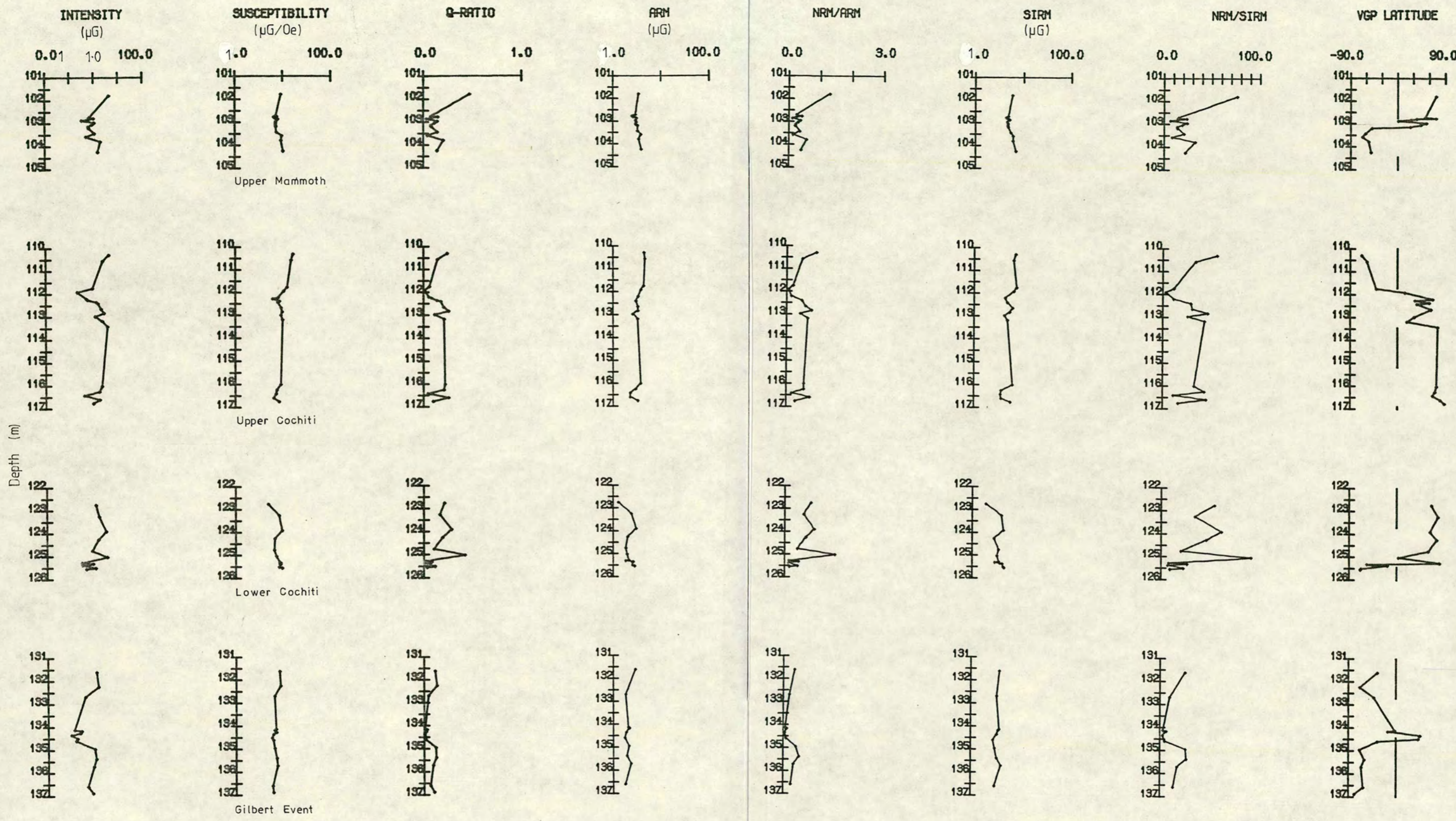


Figure 23 continued



change in direction associated with this transition. The Upper Olduvai transition at 18.58m coincides with higher than average normalized intensity, but other normal to reversed transitions such as the Lower Kaena transition (96-95m) are associated with low intensity. It is, however, difficult to estimate the amount of decrease because of the large fluctuations which are present in intensity.

CHAPTER 4

PO VALLEY DEPOSITS

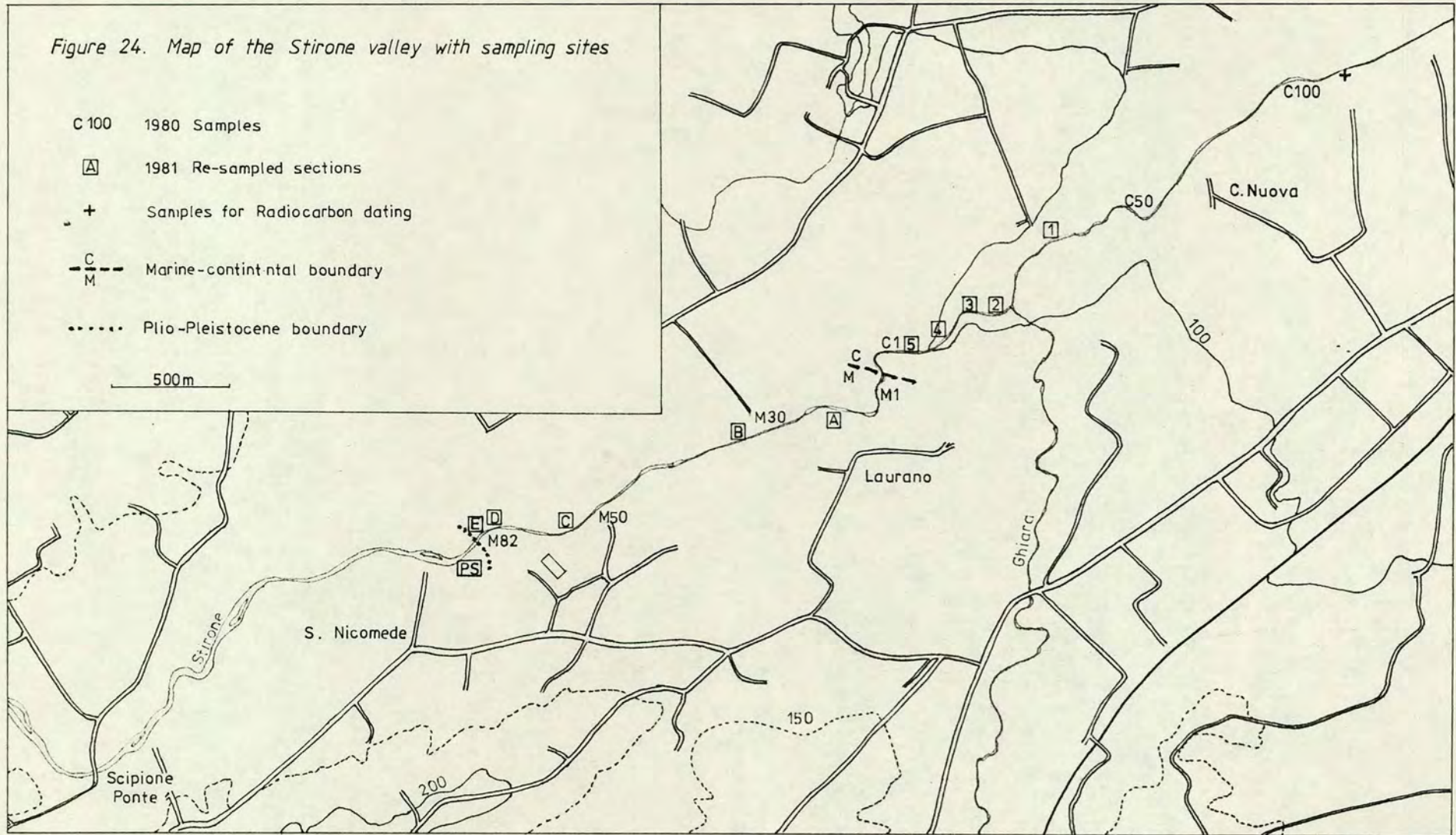
PART 1 STIRONE

GEOLOGY

The Stirone River in northern Italy is a tributary of the Taro River, which is itself a tributary of the Po, the Stirone meeting the Taro 5km south of that river's confluence with the Po. Plio-Pleistocene sediments are exposed between Scipione Ponte and Casa Nuova, 3 to 7km southwest of Fidenza (Map 73 IV S.W.), see Figure 24. The sediments consist of at least 1000m of marine sands, silts, and clays, overlain by 95m of continental fluvial sediments.

The marine sediments exposed in the Stirone valley date from the Lower Pliocene, that is 5.5 m.y. b.p., to approximately 1 M.Y. b.p. The series begins with a transgressive conglomerate, which is followed by silts and clays, becoming coarser upwards, deposited towards the southern margin of the Po gulf. The main source of detritus was the Apennines, to the southeast; however, mineralogical evidence indicates some contribution from the Alps to the north (Bertolani et al, 1979). The uppermost 109m of this series (i.e. between depths of 95 and 204m) from Nicomede to Laurano, has been studied in detail by workers from the Universities of Parma and Bologna (Pelosio and Raffi, 1977; Bertolani et al, 1979; Papani, unpublished). The nature of the deposits of the marine series was controlled by bathymetry: there is a gradual regression which takes place from the Lower Pliocene to the Pleistocene and superimposed on this four 'microcycles' can be seen within the uppermost beds, where fluctuations in depth are chiefly characterized by changes in the

Figure 24. Map of the Stirone valley with sampling sites

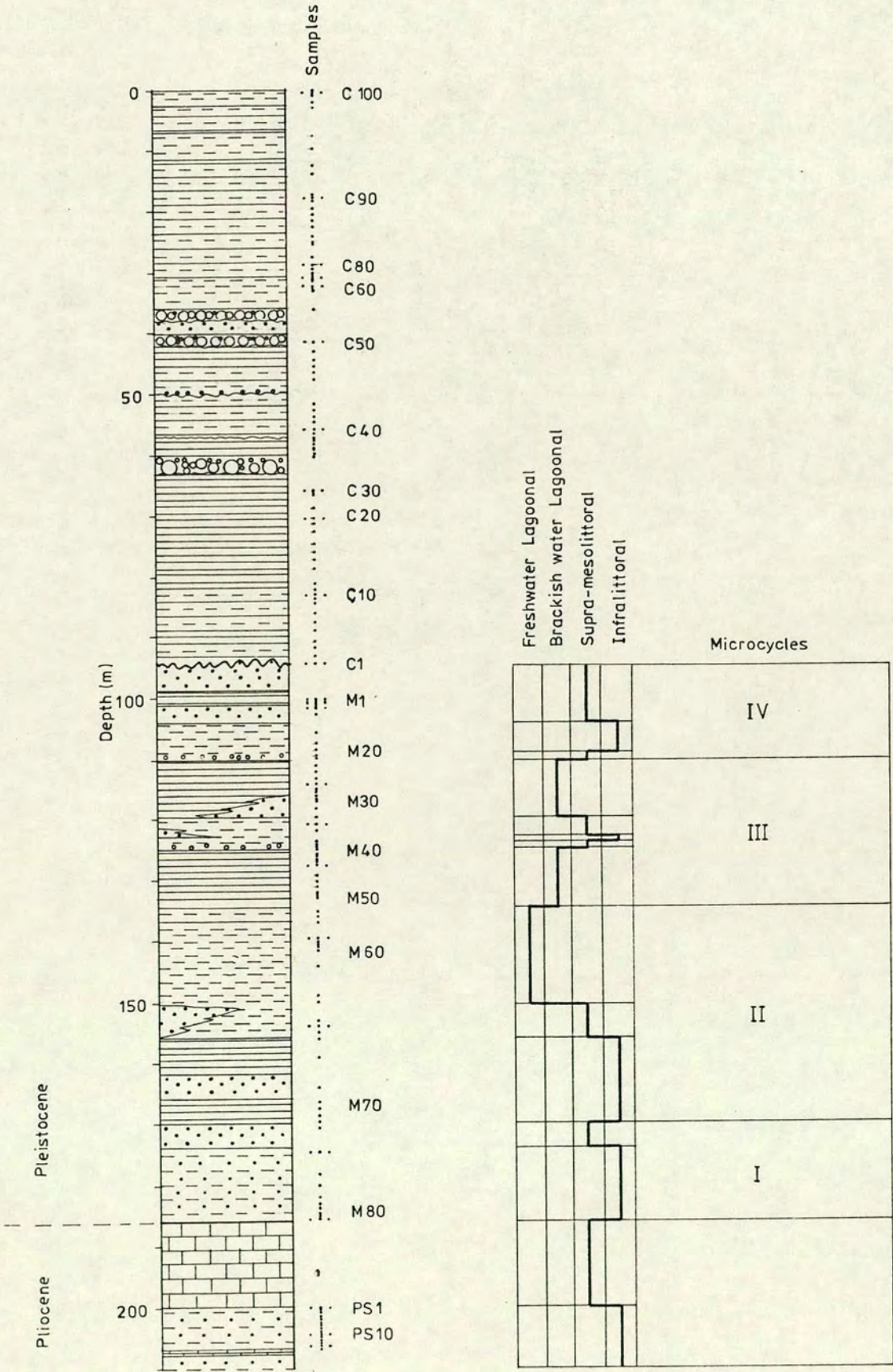


mollusc fauna (Figure 25). Within this part of the series, lithology varies from sand to clay, gradually becoming coarser upwards, with occasional gravel lenses and irregularly cemented bioclastic lenses. The generally abundant macrofossils are characteristic of sandy substrates, sedimentary structures are indicative of wave action, showing that the environment was mostly shallow water infra-littoral.

The lowermost microcycle, between 186m and 170m, consists of only a minor fluctuation in depth: fine infra-littoral sands follow well cemented biosparite at 186m, while above 174m the sands are well-sorted with a supra-mesolittoral fossil assemblage. The conventional Plio-Pleistocene boundary, that is the first appearance of Arctica islandica, is seen at 186m. The second cycle begins at 170m with silty clay and sand containing infra-littoral molluscs such as Venus multilamella, the sediments become coarser upwards, ending in the Dreissena sands between 156 and 150m. The infra-littoral molluscs give way to freshwater molluscs including Unio and Hydrobia between 133m and 150m. Arias et al (1982) suggest this freshwater phase follows a major hiatus in deposition. Green clays are seen in this interval overlying a conglomerate indicative of a lacustrine environment. The first appearance of Hyalinea balthica is seen at 162m.

The third microcycle commences with clays and sands bearing infra-littoral molluscs between 125.5 and 133m. These are followed by a beach sand with gravel and red sand lenses between 121.0 and 125.5m, suggesting a short period of emergence. Plant remains are seen in this interval, but invertebrate macrofossils are rare. A slight unconformity follows this hiatus in deposition, with the formation of an erosional surface. The uppermost microcycle begins at 110m with a rounded pebble bed, above which occur sands with

Figure 25. Sedimentological Column at Stirone with Sampling Levels



infra-littoral fossiles. Between 95 and 104m the sands are coarse with reworked fossils representing the final regression. The top of the marine series is an erosional surface.

The variations in lithology arose from changes in sea level due to local tectonism which has given rise to a northeasterly dip varying from 14° at the Plio-Pleistocene boundary to 3° at the top of the series. Pollen analysis by Bertolani et al (1979) shows that the series can be divided into seven sections on the basis of Sequoia (indicating coastal forest) and Sciadopytis (indicating mountain vegetation favoured by rainy seasons). The general trend through the section is of a gradual warming and drying from the initially cool period coinciding with the first appearance of Arctica islandica to the warm temperate forests immediately preceding the Pleistocene regression. Pelosio and Raffi (1977) note a decrease in mollusc diversity due to climatic oscillation, though this may be partly due to change in environment. Macrofossils in the marine series are both boreal and warm temperate.

The continental series of fluviolacustrine sands and clays follows the marine series, separated in time by a period of emergence represented by erosional hollows, manganiferous laminations, and intense alteration, possibly pedogenesis, in the uppermost marine sandstones (Cigala Fulgosi, 1976). The continental sediments, which lie discordantly on the marine sands, begin with gravel lenses and fossil tree trunks filling the erosional hollows, followed by lacustrine clays and silts containing freshwater molluscs such as Unio. The section consists of fluvial and lacustrine sands and clays, followed by coarse pebbly deposits (Cremaschi, pers comm.). Bones from two rhinoceras (Dicerorhinus hemitoechus) have been found just

above the base of the series. Comparison with an example of D. etruscus found in the Upper Villafranchian sediments in the Arno valley suggest a continual trend of evolution, implying that these lowermost continental deposits are post-Villafranchian (Cigala Fulgosi, 1976). Direct palaeomagnetic correlation with Villafranchian deposits is not, at present, possible (although an excellent opportunity for palaeomagnetic study exists at the type section of Villafranca d'Asti). The lowermost continental sediments can be dated at about 800,000 years or less on the basis of the fossil D. hemitoechus (Cremaschi, pers comm.). Alessio et al (1980) report that material from marsh clay at the top of the series is older than 37,000 years, the limit of C14 dating.

COLLECTION OF SAMPLES

In 1980 the entire section from Casa Nuova to the Plio-Pleistocene boundary at San Nicomede was sampled at intervals of approximately one metre. Previous work by Bucha et al (1975) and Kukla (unpublished) placed the Reunion Event coincident with the first appearance of Arctica islandica, and the Jaramillo Event just below the top of the marine series. Bucha et al placed the Matuyama-Brunhes transition at about 57m in the section, that is near the confluence of the Ghiara river. This would date the D. hemitoechus remains as immediately post-Jaramillo, the oldest reported occurrence of this species.

In 1981 a number of sections along the river were studied in more detail, in an attempt to define the magnetostratigraphy more accurately, and to study the polarity transitions recorded. These sections are shown in Figure 24, they included possible excursions recorded in the continental deposits, however in some cases

re-examination of the outcrop revealed that slumping and faulting had disturbed the beds. A section of the river below the Plio-Pleistocene boundary was also sampled.

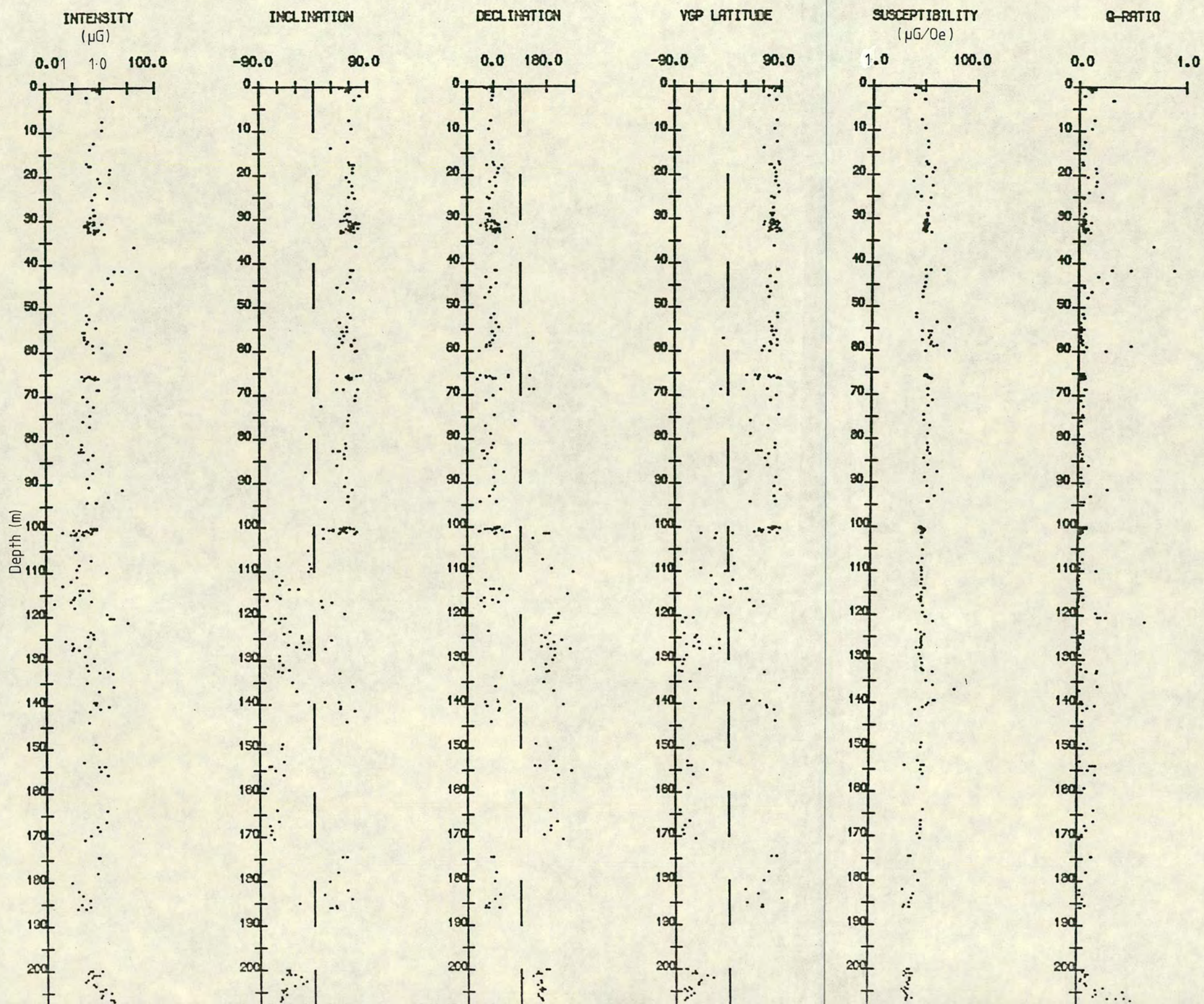
RESULTS

Figure 26 shows NRM intensity, susceptibility, and Q-ratio, together with NRM directions for the whole section (that is the 1980 samples and the samples taken from below the Plio-Pleistocene boundary in 1981). The arithmetic mean intensity is $0.94 \pm 1.97 \mu\text{G}$ throughout the section, variation is high, but there is no systematic deviation from the mean at any particular depth. Susceptibility is more uniform, averaging $10.35 \pm 3.94 \mu\text{G}/\text{Oe}$, giving an average Q-ratio of about 0.1.

The continental deposits are more or less all normally magnetized, whereas the marine deposits (below 95m) show periods of reversed and normal polarity. The directions in the continental deposits all give high latitude, normal VGPs, save for occasional isolated samples such as C52 (33.10m), C36 (57.10m), and C17 (72.50m) which have steep positive inclination and southeasterly declination, and C13 (78.80m) and C6 (87.50m) which have northerly declination but shallow negative inclination.

The uppermost samples of the marine series are normal, but intermediate directions occur below 101.39m. Between this level and 140.00m there is much variation in direction giving normal, reversed, and intermediate pole positions. Inclinations are generally reversed, the variation in pole latitude being mainly the result of declination changes. However a normal interval, with northerly declinations is seen between 116.6m and 119.5m. Below 140m the magnetostratigraphy is better defined, normal polarity occurs between 140.5 and 144.0m and between 174.50 and 186.00m, although the latter interval is split by a

Figure 26 NRM Results For Shirone



single sample with shallow reversed inclination (M80A: 185.00m).

Pilot demagnetization (Figure 27) showed that a large number of the samples were stable, changing little in direction, although median destructive fields varied from 125 Oe (M60: 141.50m) to in excess of 400 Oe (C1: 94.25m, M35: 120.50m, and M70: 166.5m). There is no specific variation in magnetic hardness with depth. Sample C30 (65.50m) displayed a gradual change from a normal direction to an intermediate direction reaching an end point of $D=167.6^\circ$, $I=4.6^\circ$ at 200 Oe. Samples in the marine series between 101.39m and 144.00m often have low intensity, so demagnetization may cause the intensity to drop below the noise level of the instrument. Some samples in this interval are stable (e.g. M35: 120.50m) some show a change in direction, often with an increase in intensity (e.g. M26: 114.00m, in this case from reversed to normal above 200 Oe).

After blanket demagnetization at 150 Oe, intensity has decreased by about 53% to an average of $0.44 \pm 0.97 \mu\text{G}$ (Figure 28). Only in the bioclastic sands below the Plio-Pleistocene boundary is there no appreciable drop in intensity. Directions are similar to the NRM results, apart from the intervals between 57.10 and 77.00m and between 101.39 and 140.50m. In the former interval some inclinations become intermediate and occasionally reversed (C15: 77.00m), but more often declinations become southerly while inclinations remain positive, giving low latitude VGPs. It may be that the samples have not been demagnetized to an end point, although it should be noted that the end point of sample C30 (65.50m) had an intermediate direction. The interval between 101.39 and 140.50m which showed much variation at NRM has been 'cleaned' by demagnetization. Most samples have negative inclination and southerly declination, although low normal VGP latitudes are seen at 108.30 to 109.30m and 118.00 to 119.50m, the

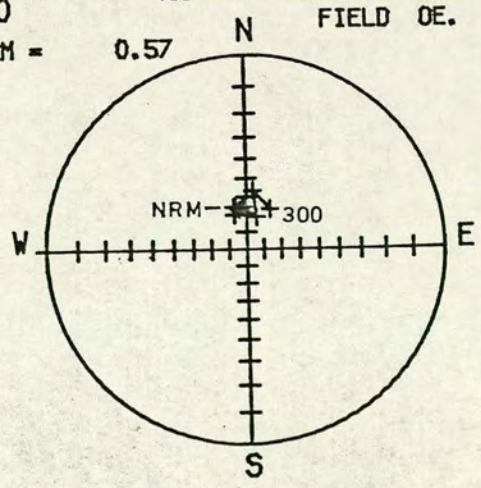
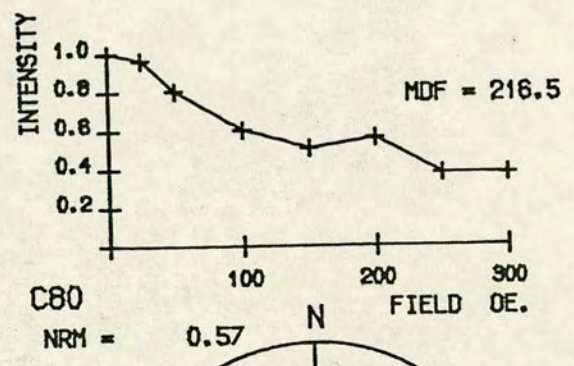
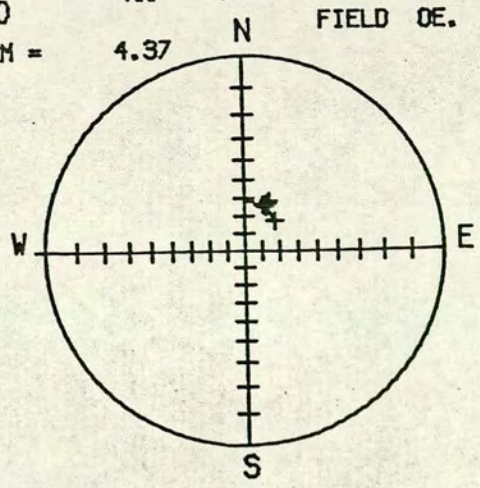
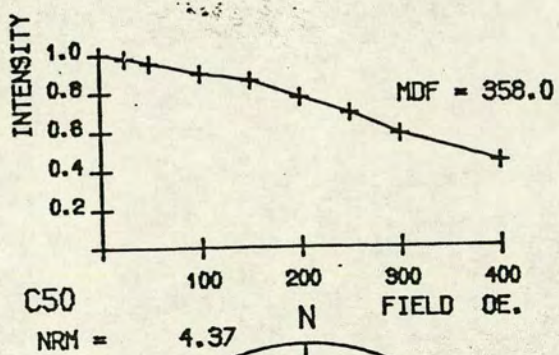
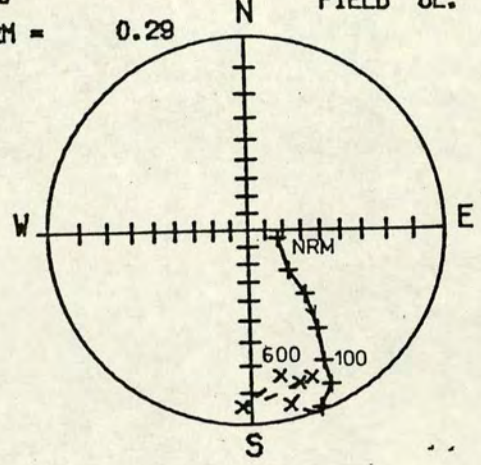
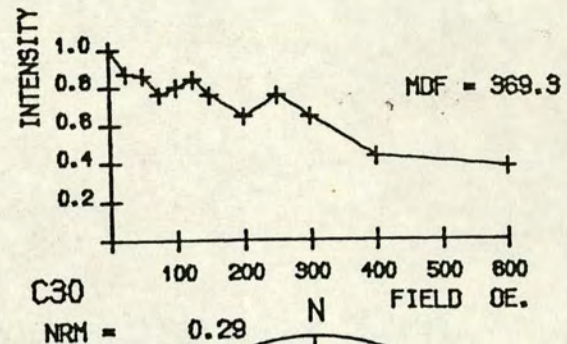
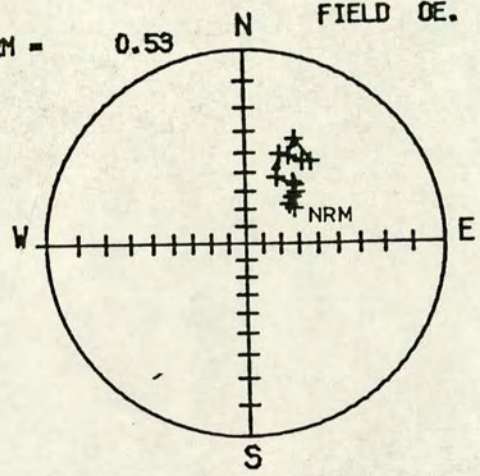
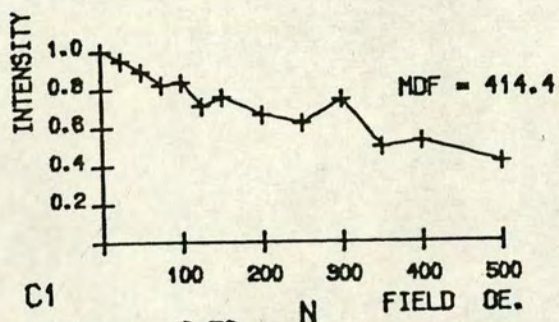


Figure 27. Examples of Demagnetization from Stirone

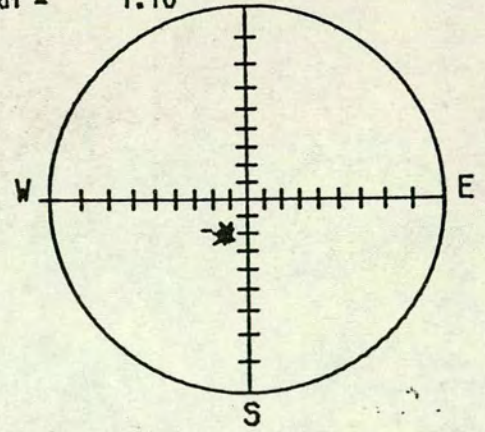
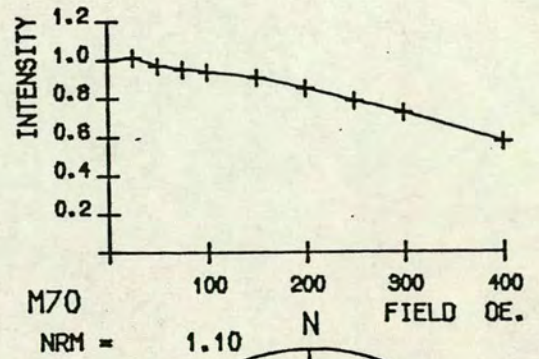
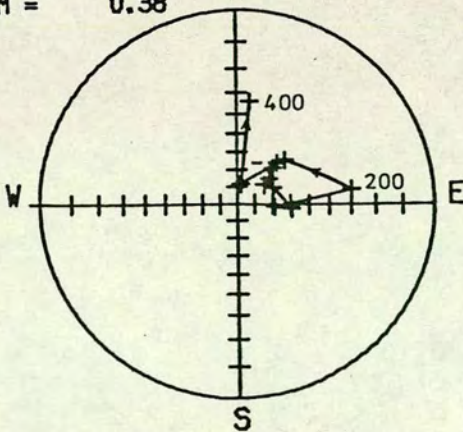
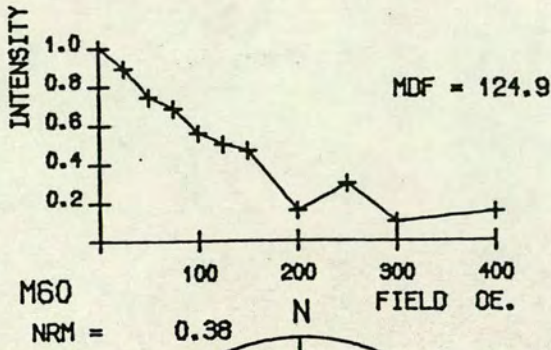
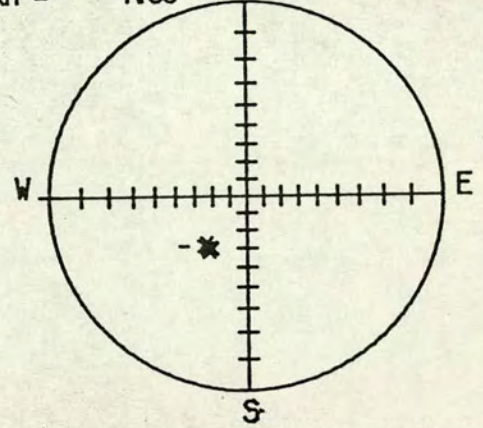
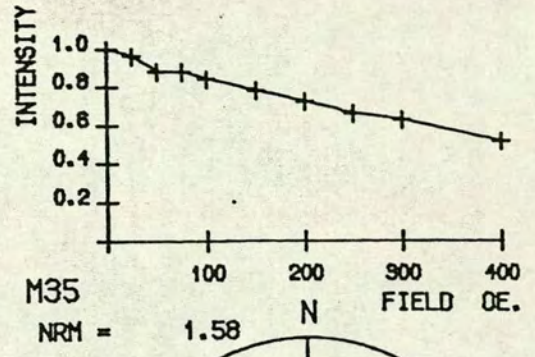
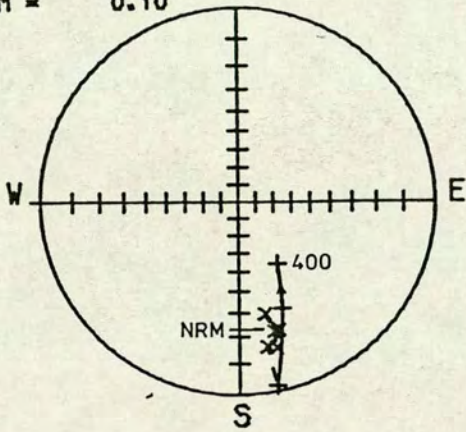
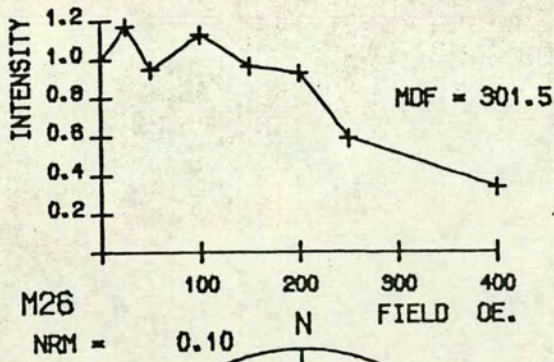
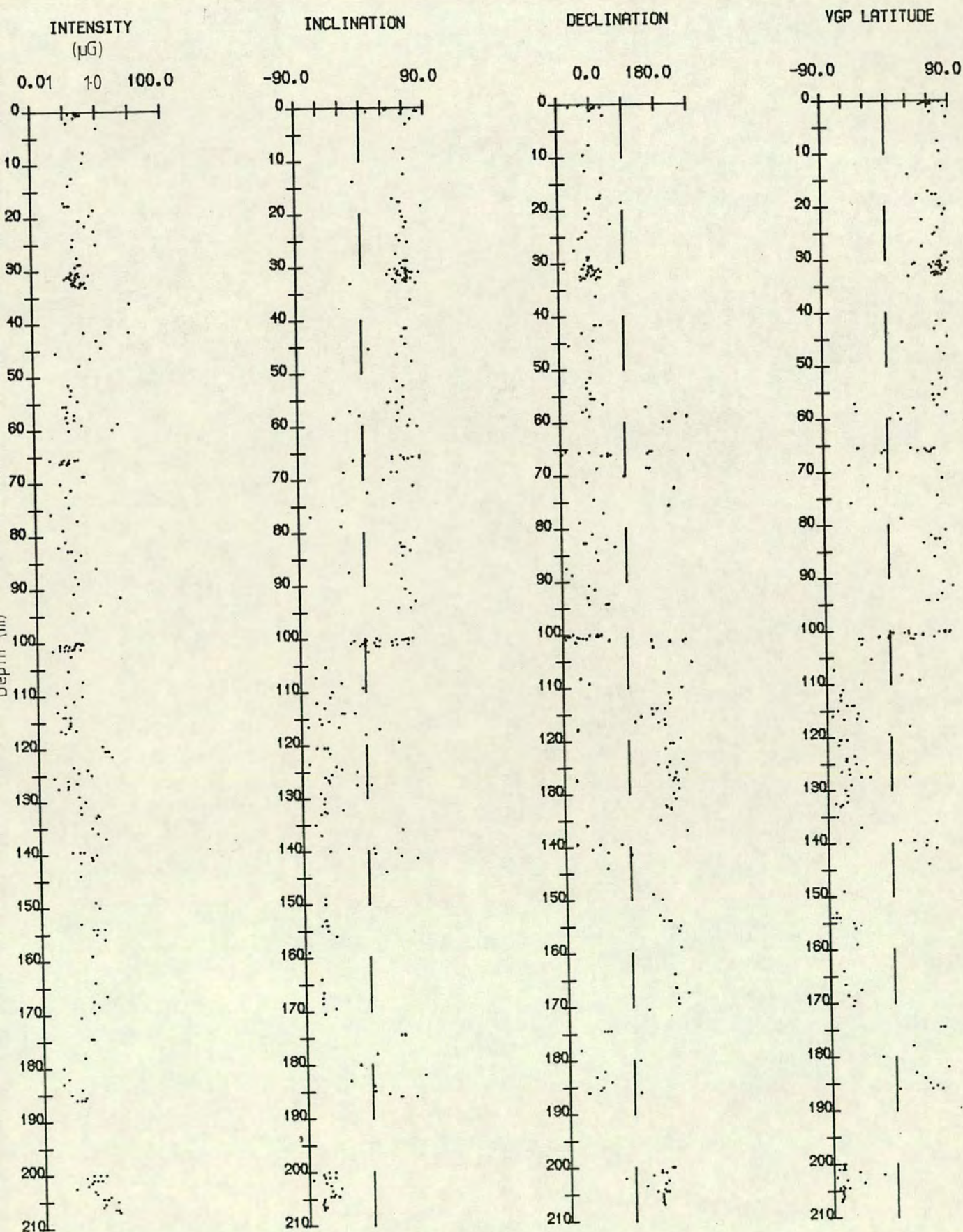


Figure 27 continued

Figure 28 Results for Stirone after Demagnetization



former with northerly declination and shallow negative inclination, the latter with shallow positive inclination and a range of declinations. Demagnetization causes a few of the samples in the normal event just above the Plio-Pleistocene boundary to become more intermediate, emphasizing a split in this event.

Alpha 95 values for groups of three samples at the same level are low (generally less than 20) above 57m and below 144m, whilst between there is much variation. Demagnetization decreases alpha 95 where values are low, but causes much larger values where there is a change in direction with demagnetization, that is between 57 and 77m and between 101 and 140m, probably due to differing effectiveness of demagnetization.

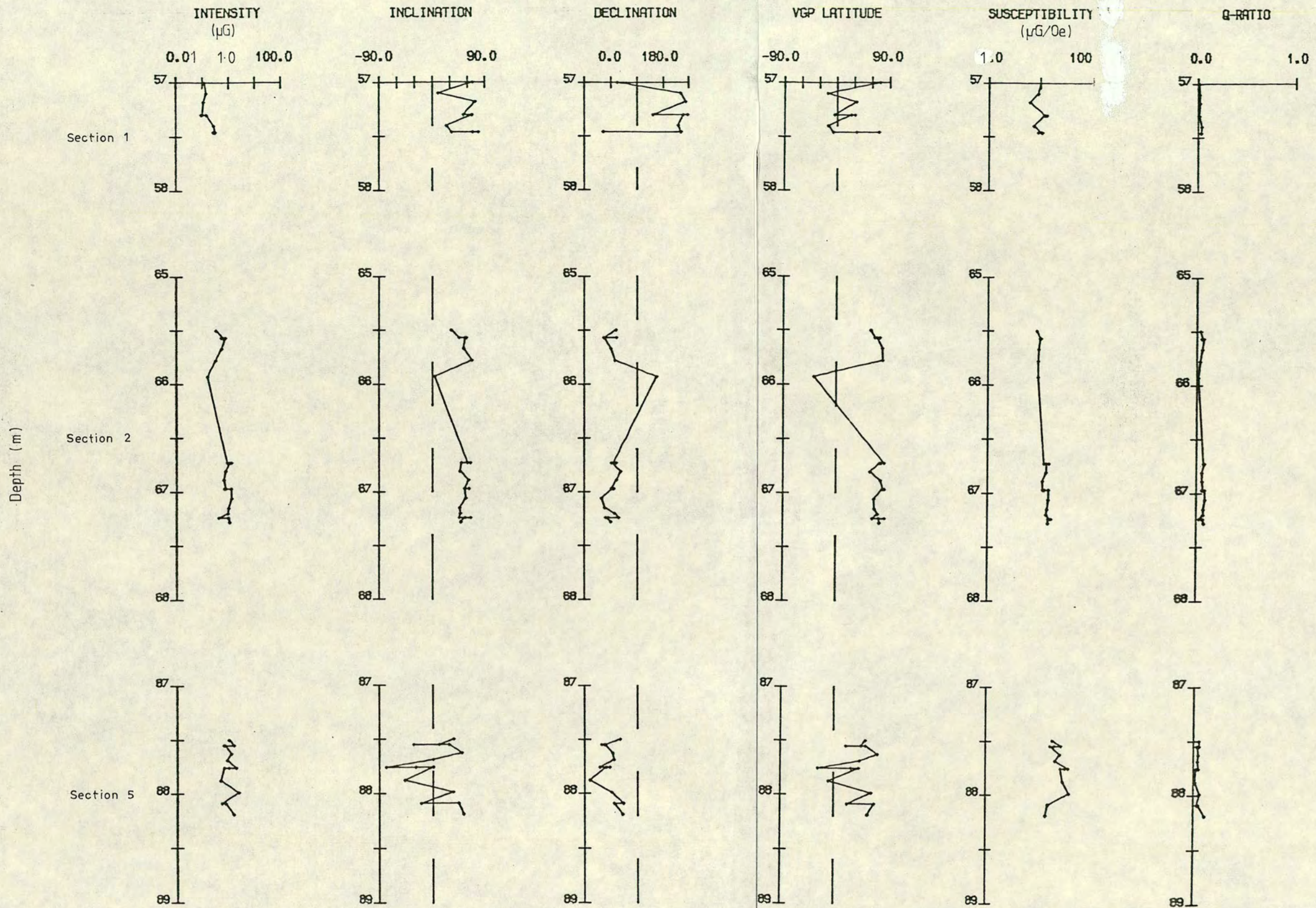
INVESTIGATION OF CONTINENTAL SECTIONS

Five anomalous sections within the continental series were resampled in detail, these being 57-58m, 65-68m, 71-73m, 78-80m, and 87-89m. Of these, two showed evidence of faulting (Sections 3 and 4: 71-73m and 78-80m), and will not be considered here. Figure 29 shows the NRM results for sections 1, 2, and 5, together with susceptibility and Q-ratio.

Section 1, correlating with C36 (57.10m) marks the top of the anomalous interval within the continental series described above. Intensity is low ($0.18 \pm 0.08 \mu\text{G}$) and directions show some variation. Inclination is positive averaging 55.7 ± 22.7 ; however declination is mainly southerly giving intermediate VGPs.

Section 2 correlates approximately with samples C20 and C30 (68.65 to 65.50m) which represent a detailed section in the original investigation. The original section had positive inclination, but a few samples had southerly declinations which persisted after

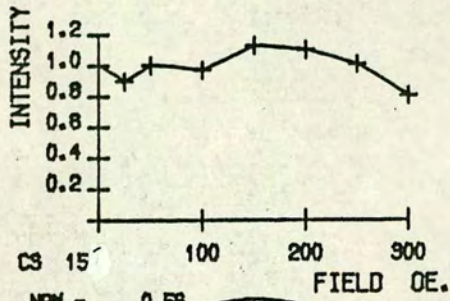
Figure 29. NRM results for Detailed Continental Sections



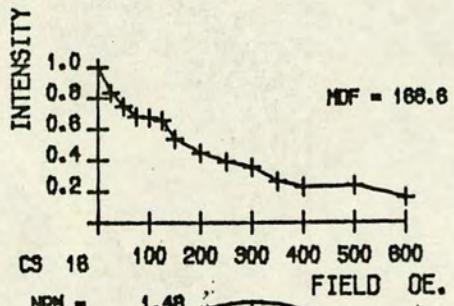
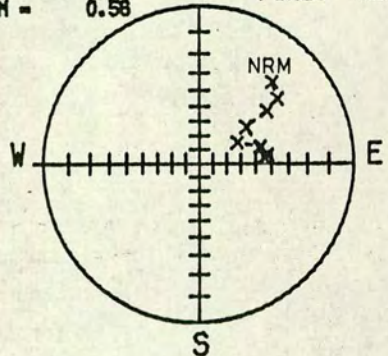
demagnetization. Intensity in the 1981 section averages $0.77 \pm 0.31 \mu\text{G}$ at NRM. Most of the directions are normal apart from CS42 (65.93m) which has southerly declination and low inclination, this sample has a lower intensity than the others ($0.15 \mu\text{G}$).

Section 5 between 87 and 89m is equivalent to sample C6 (87.50m). Intensity is relatively high ($1.03 \pm 0.53 \mu\text{G}$) and susceptibility is much higher than in the rest of the continental series ($25.2 \pm 8.1 \mu\text{G}/\text{Oe}$). All the samples have a more or less northerly declination, however inclination varies between -79.0° and $+52.0^\circ$, giving intermediate VGP latitudes between 87.76 and 88.09m.

Pilot demagnetization of samples from section 1 show that in many cases there is a soft normal component superimposed on an intermediate component (for example CS46' at 57.30m; see Figure 30). Median destructive fields vary from 53 Oe to over 600 Oe depending on the size of the overprint, the primary component generally being quite hard. Samples CS29' and CS29" (both 66.73m in section 2) show no large change in direction with demagnetization, but vary around their original direction, probably due to low intensity. On the other hand CS30 (66.81m) shows behaviour similar to C30 (65.50m), that is, a soft normal component superimposed on an intermediate component. These samples have low median destructive fields (49 to 60 Oe), however C30 is quite hard (343 Oe). The samples from section 5 which were demagnetized stepwise show large variation between steps, even though intensity is relatively high. Some samples show changes in direction, although there is no definite trend to these changes, sample CS15' (88.09m) becomes more reversed with demagnetization. Sample CS16 (88.19m) however shows gradual decrease in intensity with no change in direction. In none of these continental sections do the demagnetization paths show uniform behaviour, however this may be the

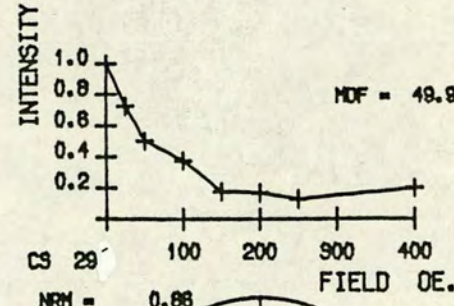
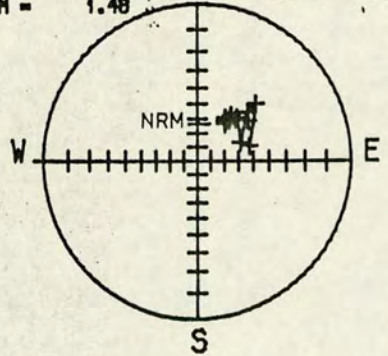


NRM = 0.58



MDF = 168.6

NRM = 1.48



MDF = 49.9

NRM = 0.86

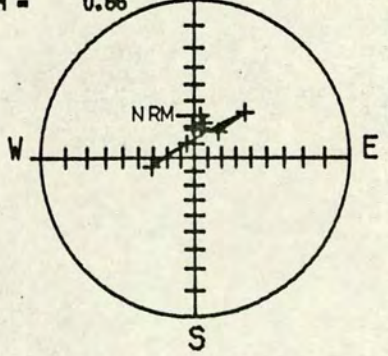
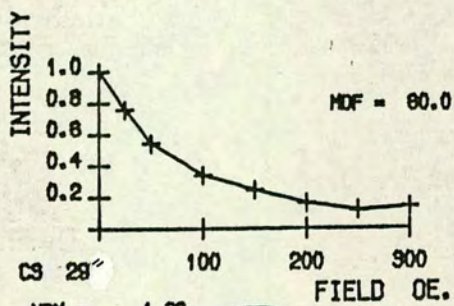
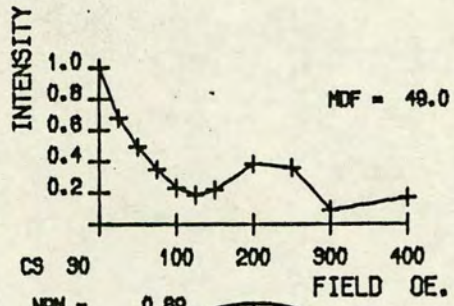
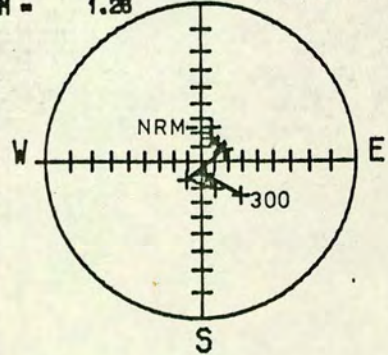


Figure 30: Examples of Pilot Demagnetization from the Continental Sections



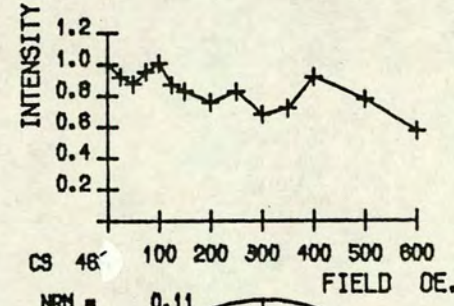
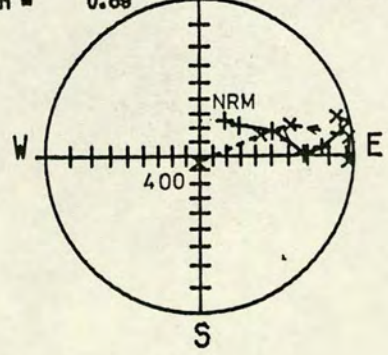
MDF = 80.0

NRM = 1.28

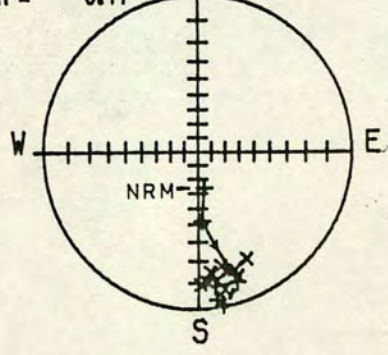


MDF = 48.0

NRM = 0.89



NRM = 0.11



result of variation in lithology. There are samples in all three sections which show the definite presence of an anomalous primary magnetization. CS46A and CS15A reach endpoints by 150 Oe, but CS30 continues to become more reversed above 300 Oe.

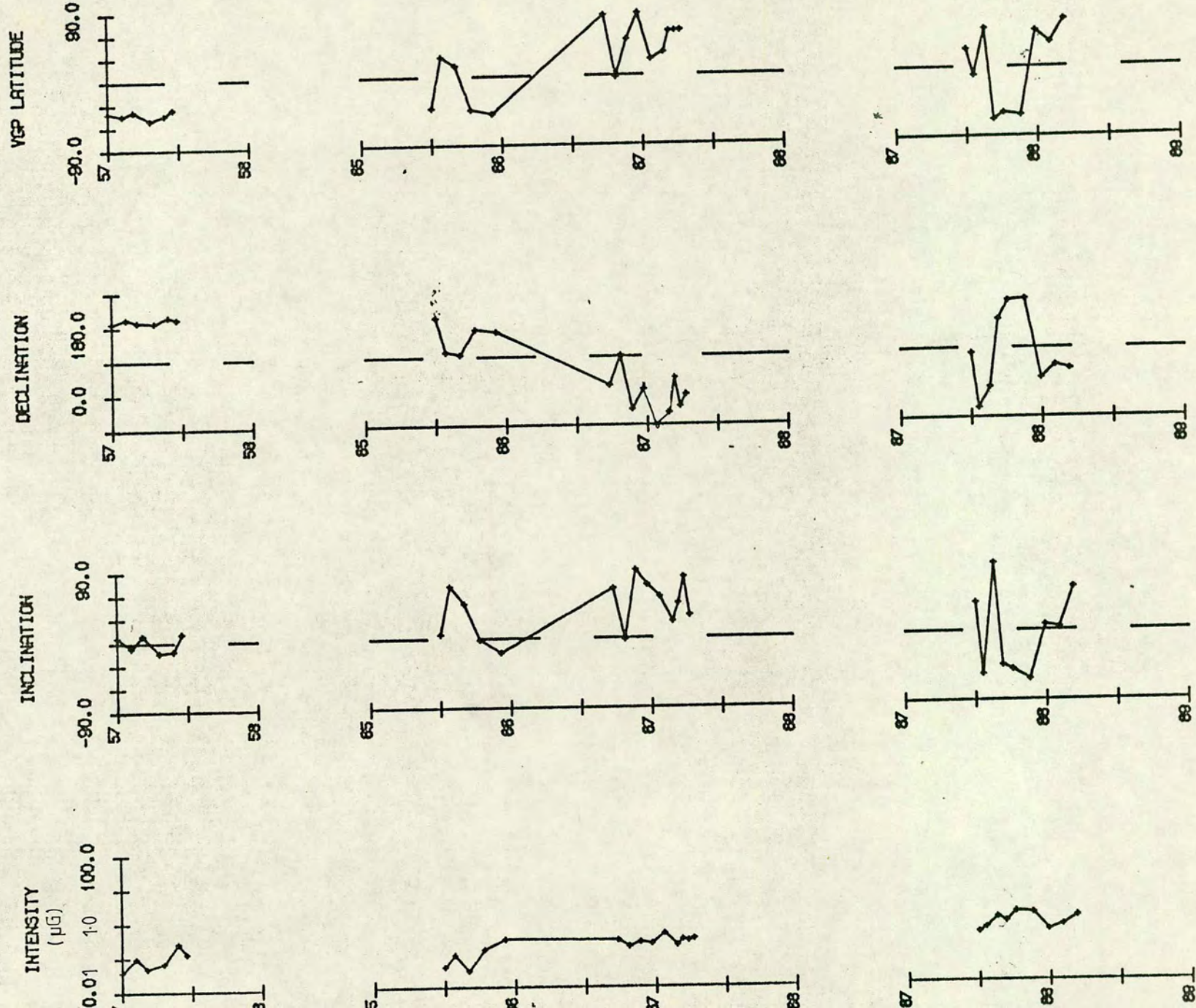
The results of blanket demagnetization of these sections at 150 Oe are shown in Figure 31¹. Intensity in section 1 decreased by about 40% to $0.11 \pm 0.07 \mu\text{G}$, inclination became more intermediate, and declination more southerly giving VGPs with a latitude of around 40S. This direction is similar to that reached by samples C33 (58.50m) and C36 (57.10m), however samples C34 and C35 show normal directions. It is not possible to correlate the 1980 and 1981 samples exactly, but this part of the section definitely records anomalous directions.

Section 2 shows a large (75%) decrease in intensity to an average of $0.18 \pm 0.08 \mu\text{G}$ (although CS42 at 65.93m increases to $0.25 \mu\text{G}$). Inclinations become more scattered, but mainly remain normal. Declination of the upper samples (above 66m) becomes southeasterly while in lower samples it remains northerly but shows more scatter. The alpha 95 values for groups of three samples from the same level increase from 10-20° at NRM to 70-120° with demagnetization demonstrating the increased scatter after demagnetization. VGPs are in low southerly latitudes at the top of section 2 gradually becoming more northerly downward. It is possible that the anomalous directions seen in section 1 are continuous with those seen at the top of section 2.

Intensity in section 5 decreases by about 40% to an average of $0.64 \pm 0.46 \mu\text{G}$ with demagnetization. Inclination is more scattered than at NRM, samples having both normal and reversed inclinations. Declination, which was mainly northerly at NRM, becomes southerly between 87.69 and 87.88m, giving rise to an excursion of the pole to

1 All blanket demagnetization diagrams include results for samples demagnetized stepwise. In these cases the result shown is the most stable endpoint.

Figure 31. Continental Sections after Demagnetization



southerly latitudes between these depths. VGP latitude is northerly elsewhere in the section, although latitude is by no means high. No intermediate poles are seen either side of the excursion (Figure 32).

MARINE SECTION A

Ninety six samples were taken from a section of the river corresponding to, and about 50m upstream from, the 1980 section at the top of the marine series where a reversed to normal transition was observed. Figure 33 shows the detail of the 1980 samples after demagnetization at 150 Oe. Inclination changes from negative to positive with a large number of intermediate values. Declination is mainly southerly below 101.00m, but with much variation, above 101m declinations are northerly.

NRM directions for the 1981 section with intensity, susceptibility and Q-ratio are shown in Figure 34. Intensity averages $0.77 \pm 1.15 \mu\text{G}$, the uppermost metre of the section has lower than average intensity (about $0.1 \mu\text{G}$) while samples from either side of the bioclastic rudite which splits the section between 103.57 and 104.20m have higher than average intensities (3.0 to $6.0 \mu\text{G}$). The environment in which these sediments were deposited was shallow, water infra-littoral, causing sands and clays to alternate in rapid succession. A number of small erosional surfaces are seen, the major one occurring beneath the bioclastic rudite at 104.20m. These erosional breaks probably represent only minor gaps in deposition. No variation in intensity or susceptibility with respect to the sediment type is seen. Susceptibility is more or less constant in the section at $9.94 \pm 1.65 \mu\text{G}/\text{Oe}$ so Q-ratio reflects variation in intensity.

NRM directions are scattered: above the bioclastic rudite

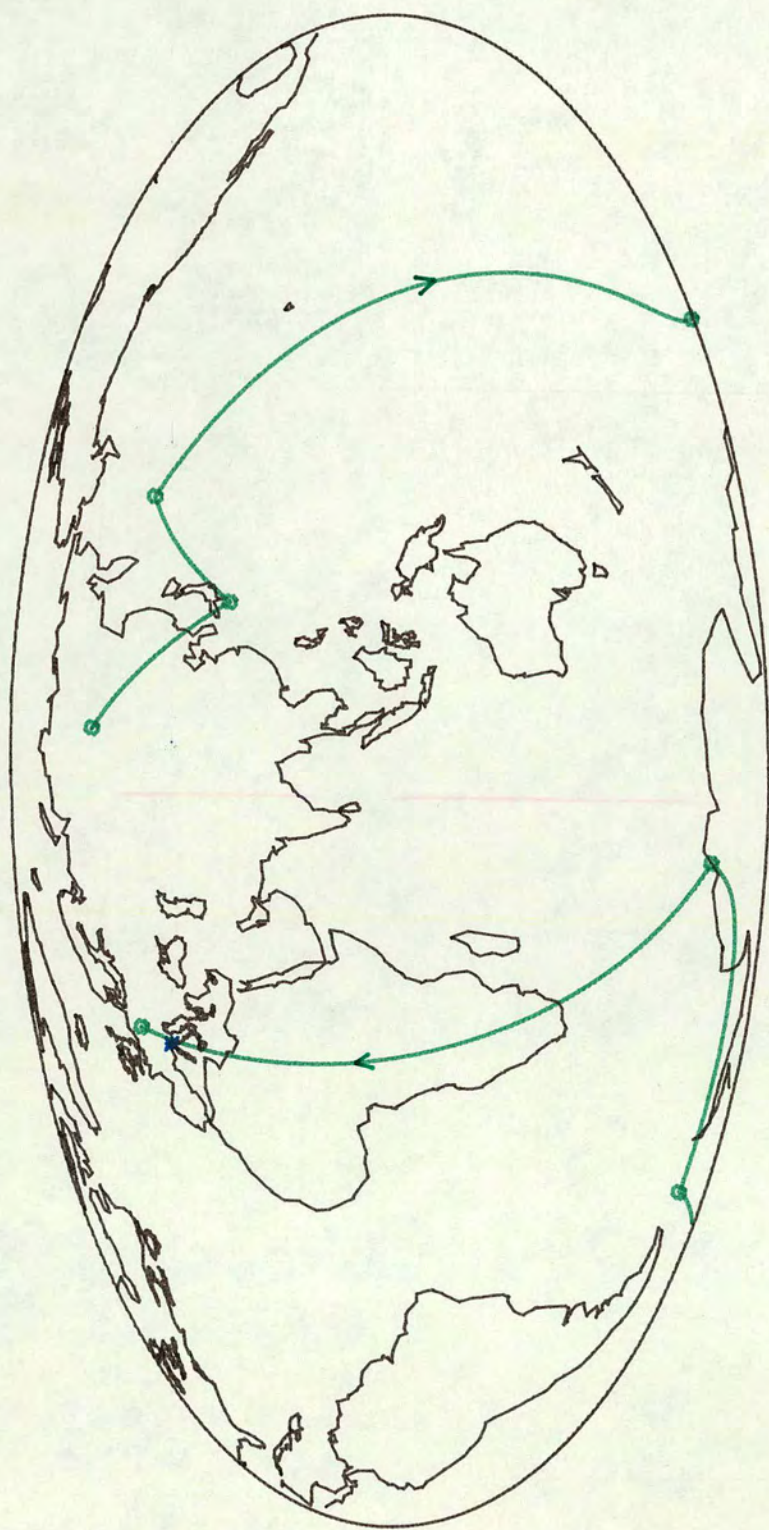


Figure 32. Excursion recorded at 88m at Stirone

Figure 33. Detail of the Transition at 100-106m

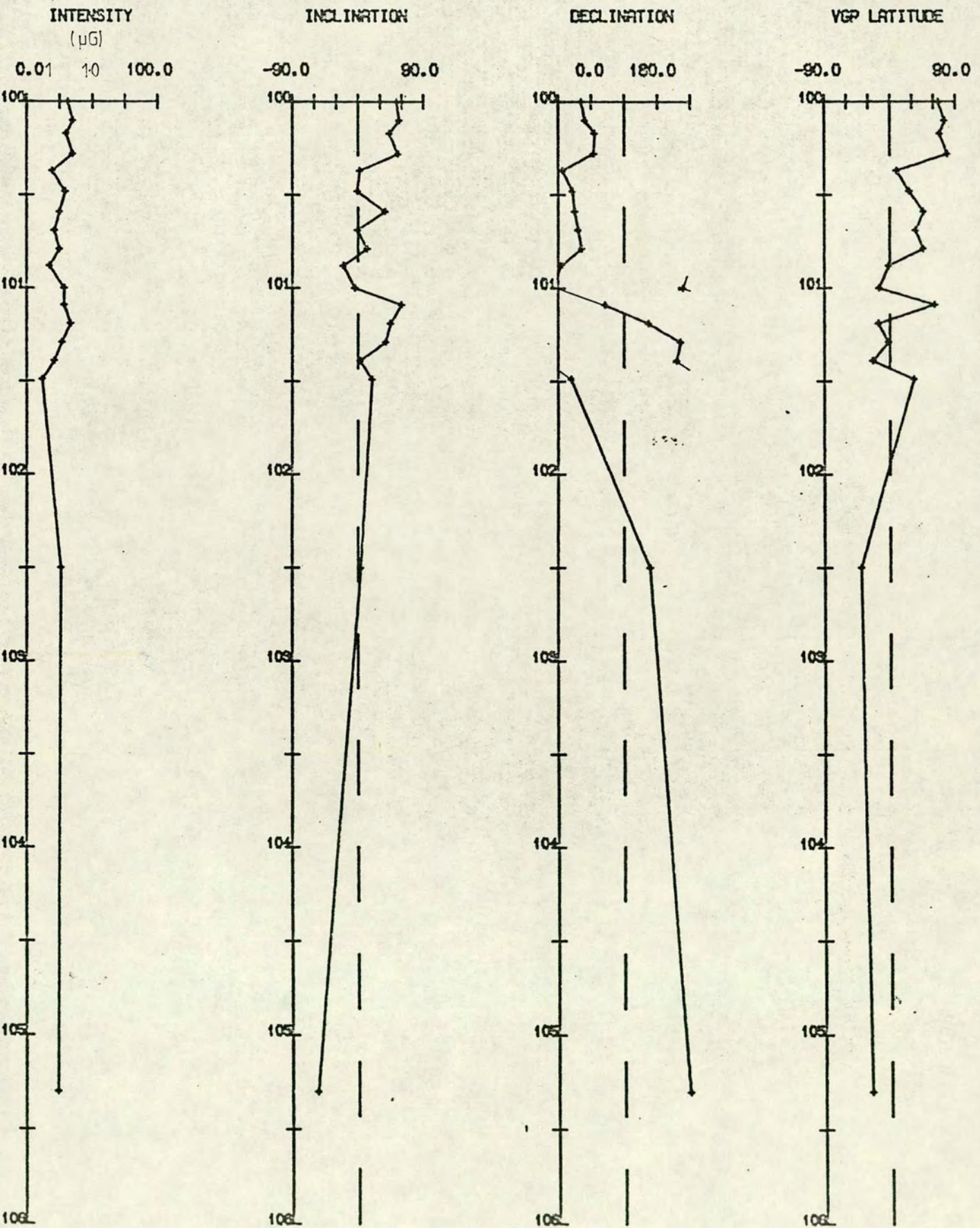
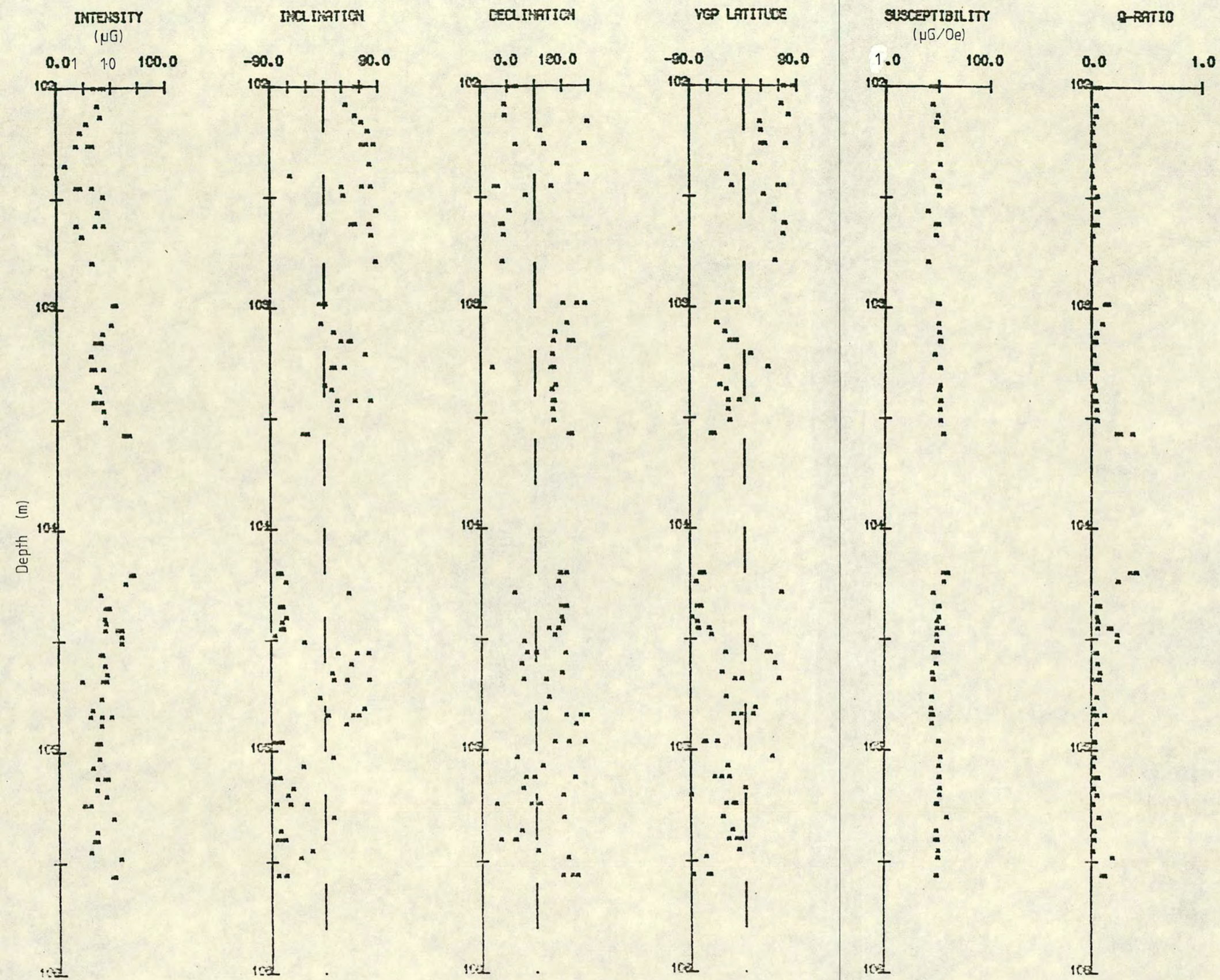


Figure 34. NRM Results For Marine Section A at Strone



inclinations are mainly normal, becoming intermediate below 102.98m. Declinations are more or less northerly above 102.98m, but show much variation, below this level declinations are mainly southerly. VGPs are in high northerly latitudes at the top of the section and in low latitudes of the southern hemisphere between 102.98 and 103.57m. Below the bioclastic rudite directions are variable, however inclinations are mainly negative with a normal interval between 104.56 and 104.88m. Declinations show much variation between 90° and 270°, but are mainly biased towards the south.

Examples of the pilot demagnetization of section A are shown in Figure 35. Some of the normal samples at the top of the section show a tendency to move toward more intermediate directions (for example MS320', 102.45m), others such as MS312" (102.00m) are stable in their normal direction. Intermediate samples below these also tend to be stable (MS328: 103.11m), or show movement towards more intermediate directions (MS329": 103.15m). These samples remain at the intermediate endpoints above 150 Oe. Median destructive fields range from 50 Oe to over 400 Oe. Most of the reversed samples below 104.20m are stable, all showing the removal of a normal overprint (for example MS282': 104.20M, and MS311': 105.56m). Even allowing for this overprint, the MDF of these samples is around 400 Oe. Samples among the sandstones between 104.56 and 104.88 are much less stable, showing erratic changes in intensity and direction (for example MS293: 104.65m). The removal of a normal overprint occasionally leads to a change in direction, for example the declination of MS301 (105.07m) changes from 101.7° at NRM to 162.5° at Oe, giving a definitely reversed direction.

The results after blanket demagnetization at 150 Oe are shown in Figure 36. Intensity decreases by 52% to $0.37 \pm 0.68 \mu\text{G}$, the

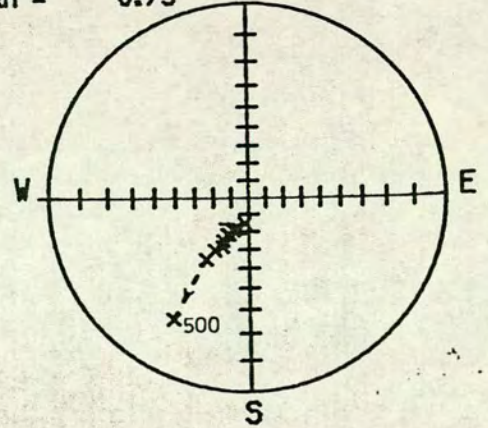
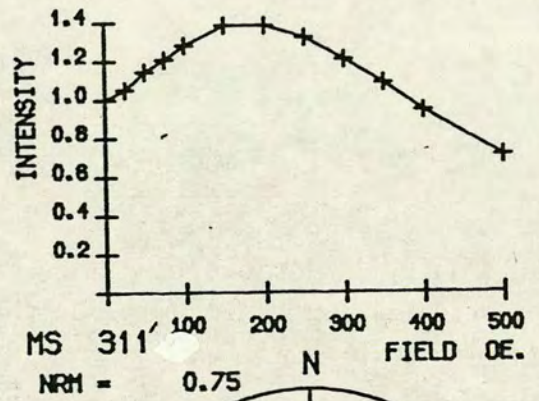
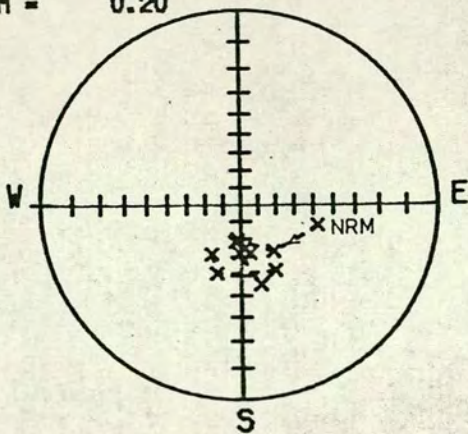
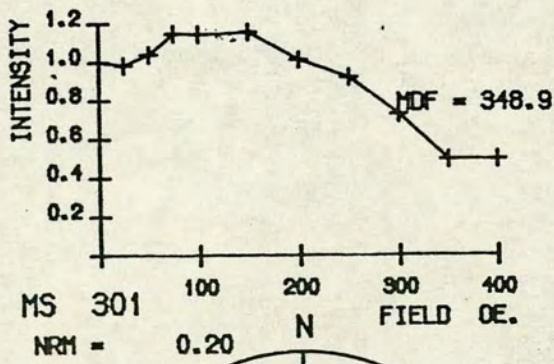
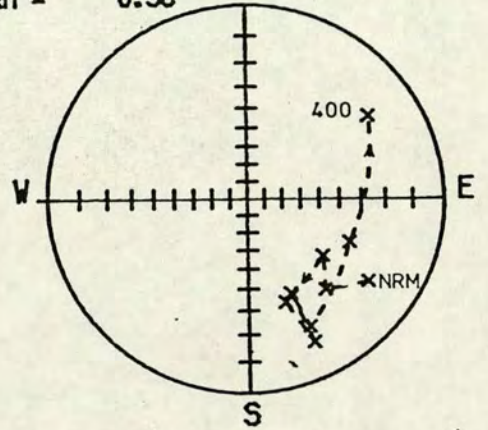
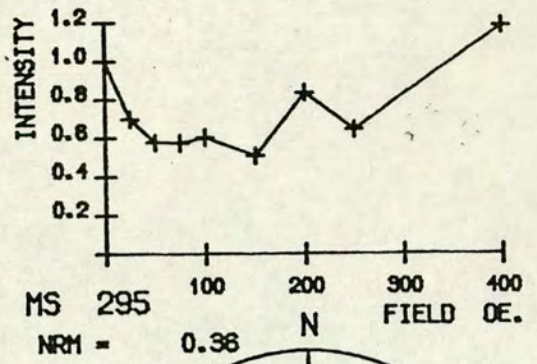
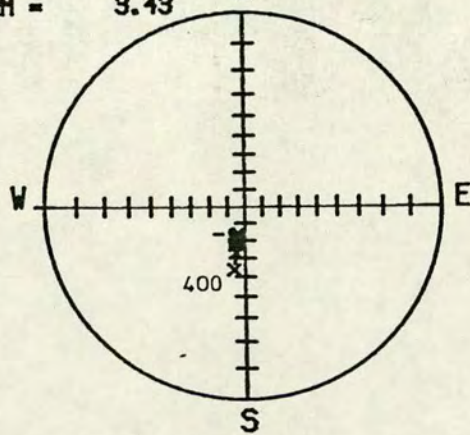
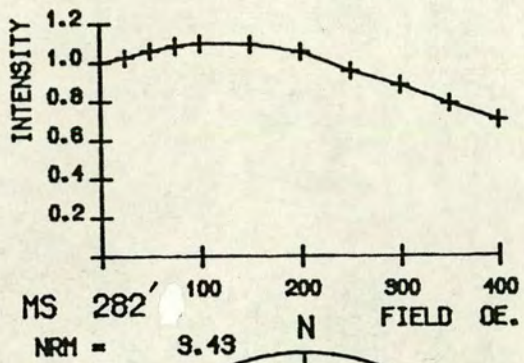


Figure 35. Examples of Pilot Demagnetization from Section A

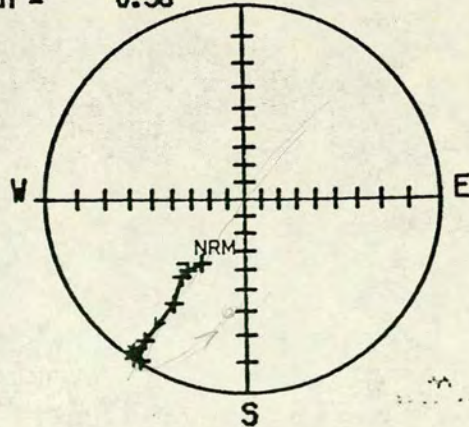
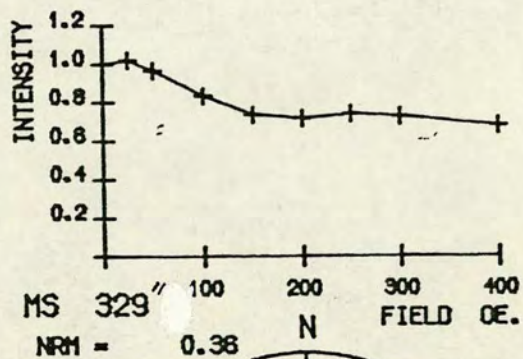
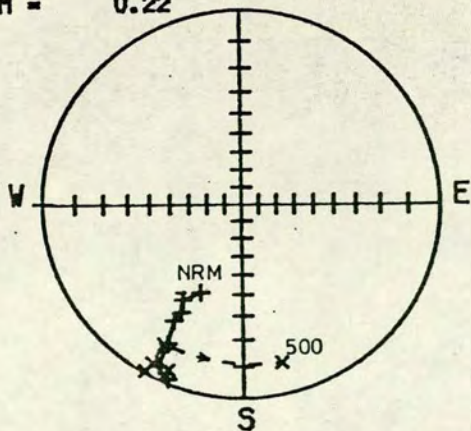
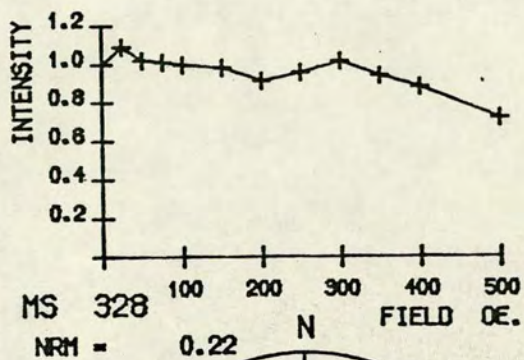
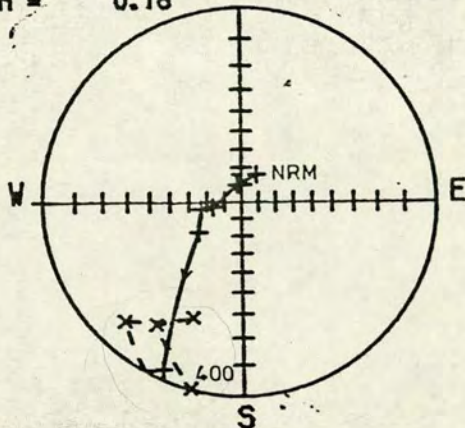
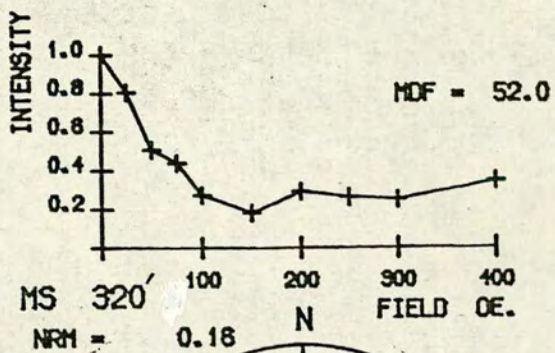
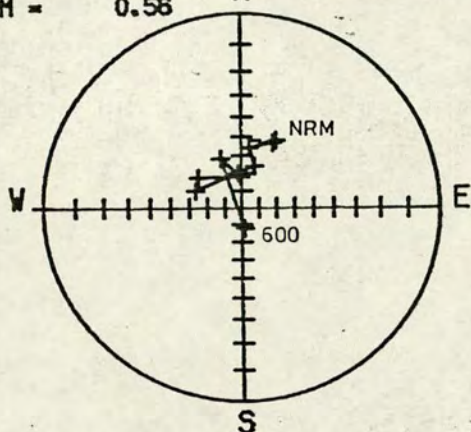
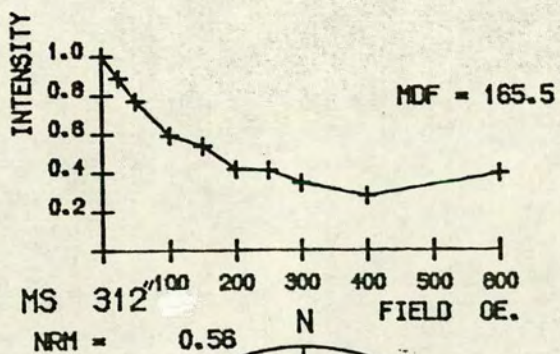


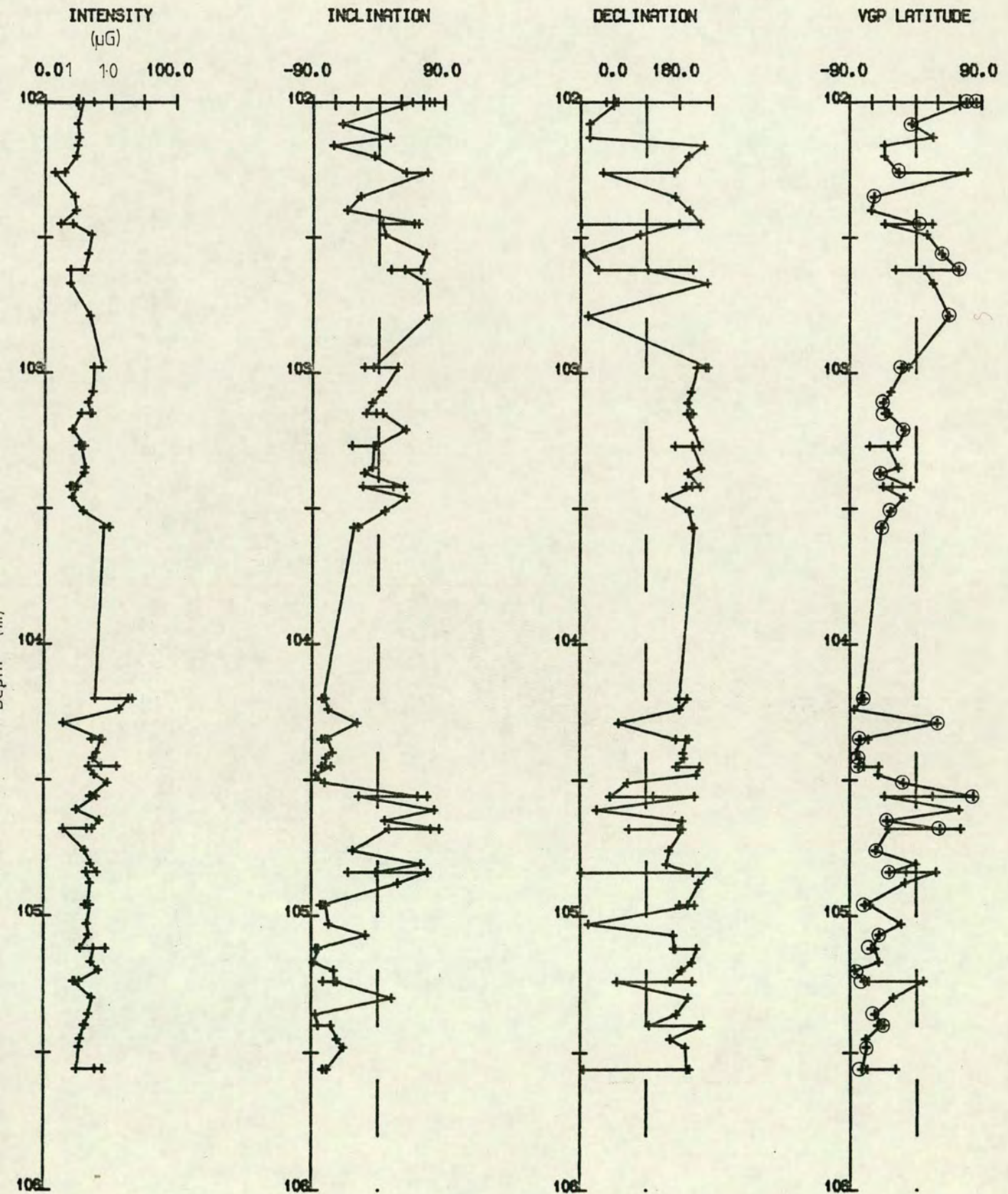
Figure 35 continued

decrease being more marked in the upper part of the section (the softer components in the lower part of the section carried normal overprints, so the removal of these softer components often led to a slight increase in intensity). Inclination in the lower part of the section remains more or less the same, although some isolated samples with shallow inclinations become more negative. The declinations of this lower set of samples become more consistent, the majority are close to 180° . This gives VGPs near the south pole, except for an excursion coinciding with the sand. The sands showed erratic behaviour during demagnetization, and isolated samples taken from the sands have anomalous directions (including MS284: 104.29m, and MS306: 105.30m). There must be some doubt about the accuracy of the samples from the sand between 104.56 and 104.88m, although the suggestion of an excursion is supported by low latitude VGPs in samples MS289 and MS290 (104.48 and 104.51m), both of which were taken from clay.

Above the bioclastic rudite, demagnetization leads to a shallowing of inclination, and a drift in declination towards the south. Between 102.98 and 103.57m directions are consistently intermediate with inclination about zero, and declination about 190° , giving VGP latitudes of around 30° S. The uppermost samples show variation in inclination and in declination, directions do not become completely normal until 102.00m.

Alpha 95 values reinforce the theory that sands are poor recorders of the palaeomagnetic field, at least in the Stirone valley. In the lower half of the section, alpha 95 rises from $10-20^\circ$ in the clays to over 90° in the sands. The top of the section also shows large alpha 95 values, possibly due to the lower intensity. Demagnetization causes alpha 95 to increase in the sands, while in the clays

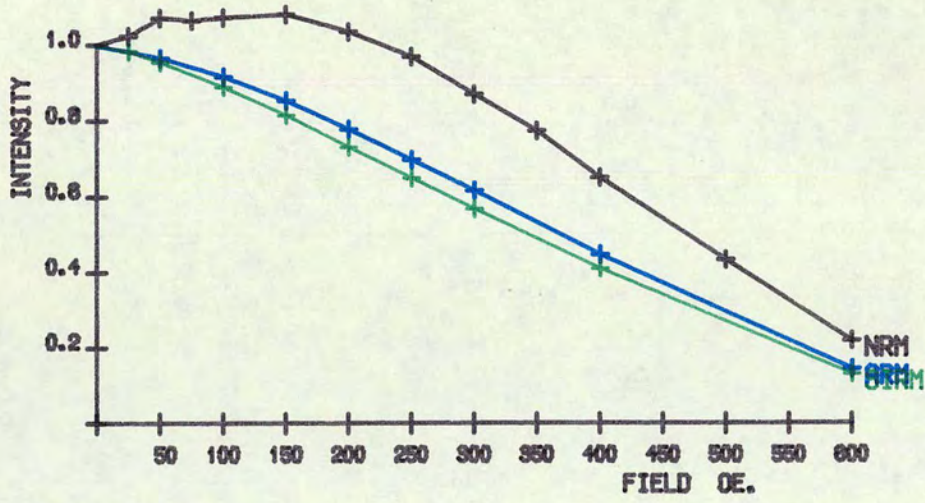
Figure 36. Results for Section A after Demagnetization



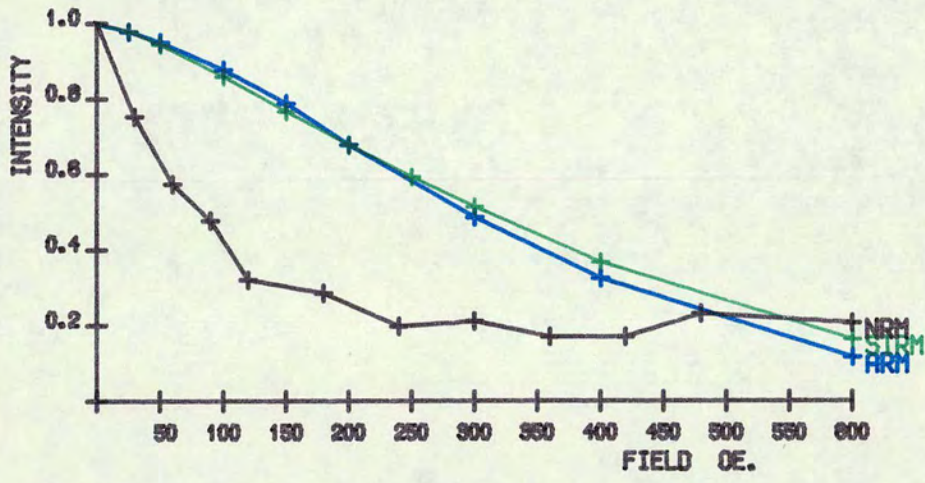
it remains more or less the same.

Twelve samples from section A were given ARMs and SIRMs, each time the samples were demagnetized stepwise (Figure 37). There are slight differences in the relative hardnesses of the synthetic magnetizations in individual samples but no systematic difference with respect to depth or lithology. Median destructive fields range from 250 to 350 Oe for both types of remanence. The demagnetization curve for NRM varies considerably from sample to sample, suggesting that although the total magnetic mineral content is consistent throughout the section, the carriers of the natural remanence vary greatly. In many cases the demagnetization curve is complicated by normal overprints. Another possible cause of variation in demagnetization behaviour is the variety of lithologies, representing environments of differing energies. High energy environments such as those represented by the sands will give rise to a dominance of current forces over magnetic forces as the particles settle. This is manifested in the poor palaeomagnetic fidelity of the sands, that is, the coarser sediments have a larger scatter in directions. The amount of magnetic alignment within a sediment will be controlled by the amount of current or wave action, so that two different deposits with similar magnetic mineral content may have different intensities. In most cases, the remanent direction will be true, as the individual grain moments are distributed about the ambient field direction. The pattern of variation of ARM and SIRM with respect to depth is in some way similar to that of the intensity curve. However differences in normalized intensity probably occur due to differences in current strength rather than ambient field strength.

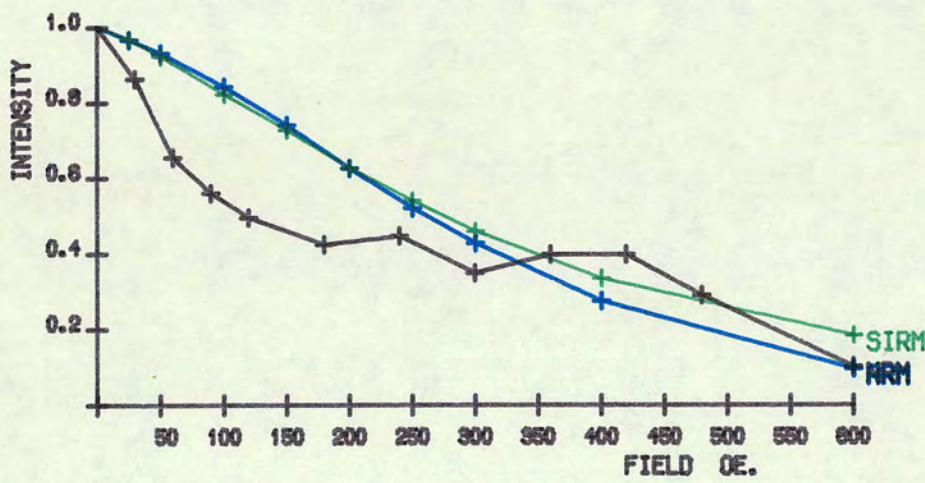
Hysteresis curves for samples from this section (Figure 38) show that the dominant mineral is magnetite, although some haematite is



MS 310



MS 313



MS 336

Figure 37. Demagnetization of NRM, ARM, & SIRM at Section A

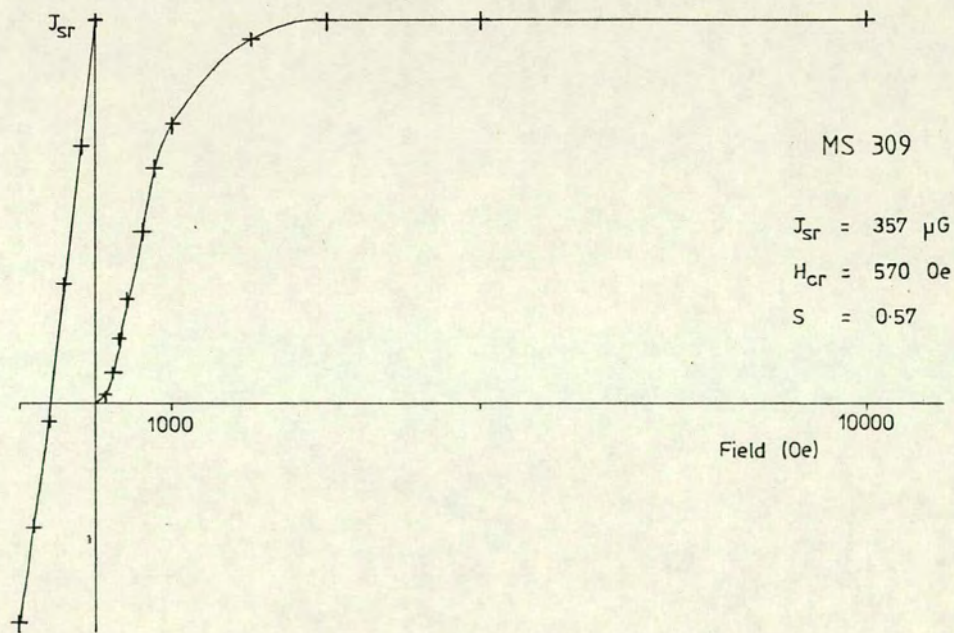
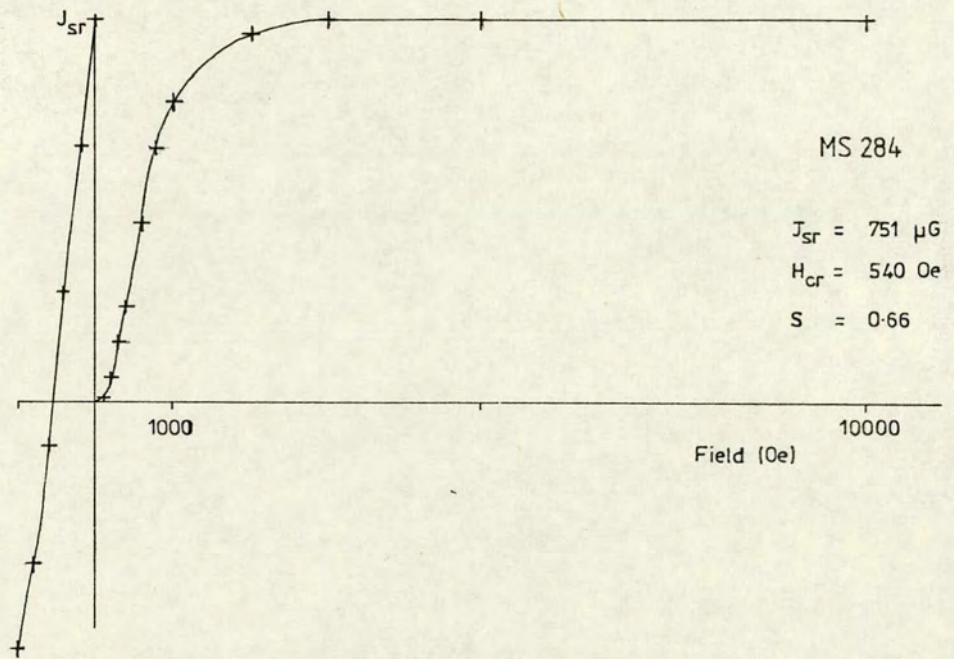
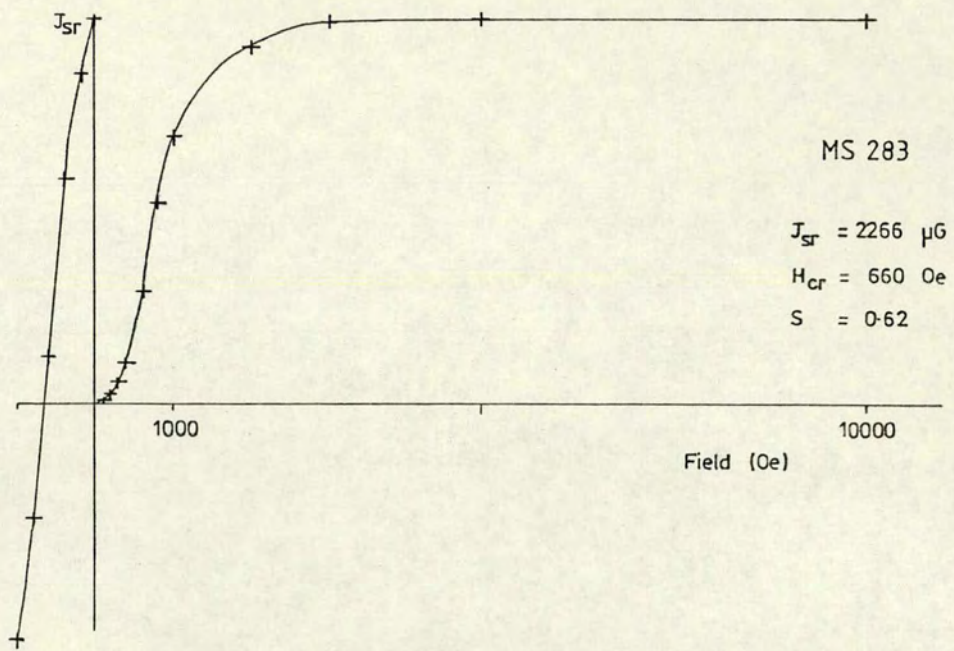


Figure 38 Examples of Hysteresis loops from Stirone

present. Most samples reach saturation between 2000 and 3000 Oe, with coercivities of remanence of 500 to 660 Oe. The ratio of IRM (1000) to SIRM is over 0.6 in most of the cases. There is no difference in the curves between clays (e.g. MS283) and sands (e.g. MS284) indicating that the source of magnetic grains was constant, even if the environment of deposition was not.

Figure 39 shows the transitional path - the first part shows all intermediate poles many of which are grouped in the South Atlantic, and nearly all of which are in the quadrant between 0 and 90 west of the site. Smoothing the path shows that there is a clockwise loop about the Atlantic and Africa before transition via America, which is 90 west of the site. Figure 40 shows a smoothed path for the 1980 section (about 100m downstream). Many of the VGPs are situated in the northern hemisphere about 100 west of the site. However the transition path is similar to the 1981 section, but shows an anti-clockwise loop part way through the transition. It may be that the loops were caused by delayed acquisition of remanence giving a different direction in each case. The poles which give the loops are scattered and another possibility is that at this point in the reversal the direction fluctuated rapidly.

MARINE SECTION B

The section between 115 and 122m is equivalent to the larger of the two excursions in the upper part of the marine series. Preliminary investigation showed that three samples gave a normal, albeit shallow, inclinations compared with the usual reversed inclinations. Further investigation was necessary to discover whether this excursion was real, and to find out if it included complete reversal of the field. NRM directions, intensity, susceptibility, and Q-ratio are shown in Figure 41. Intensity averages $0.18 \pm 0.32 \mu\text{G}$ in the upper

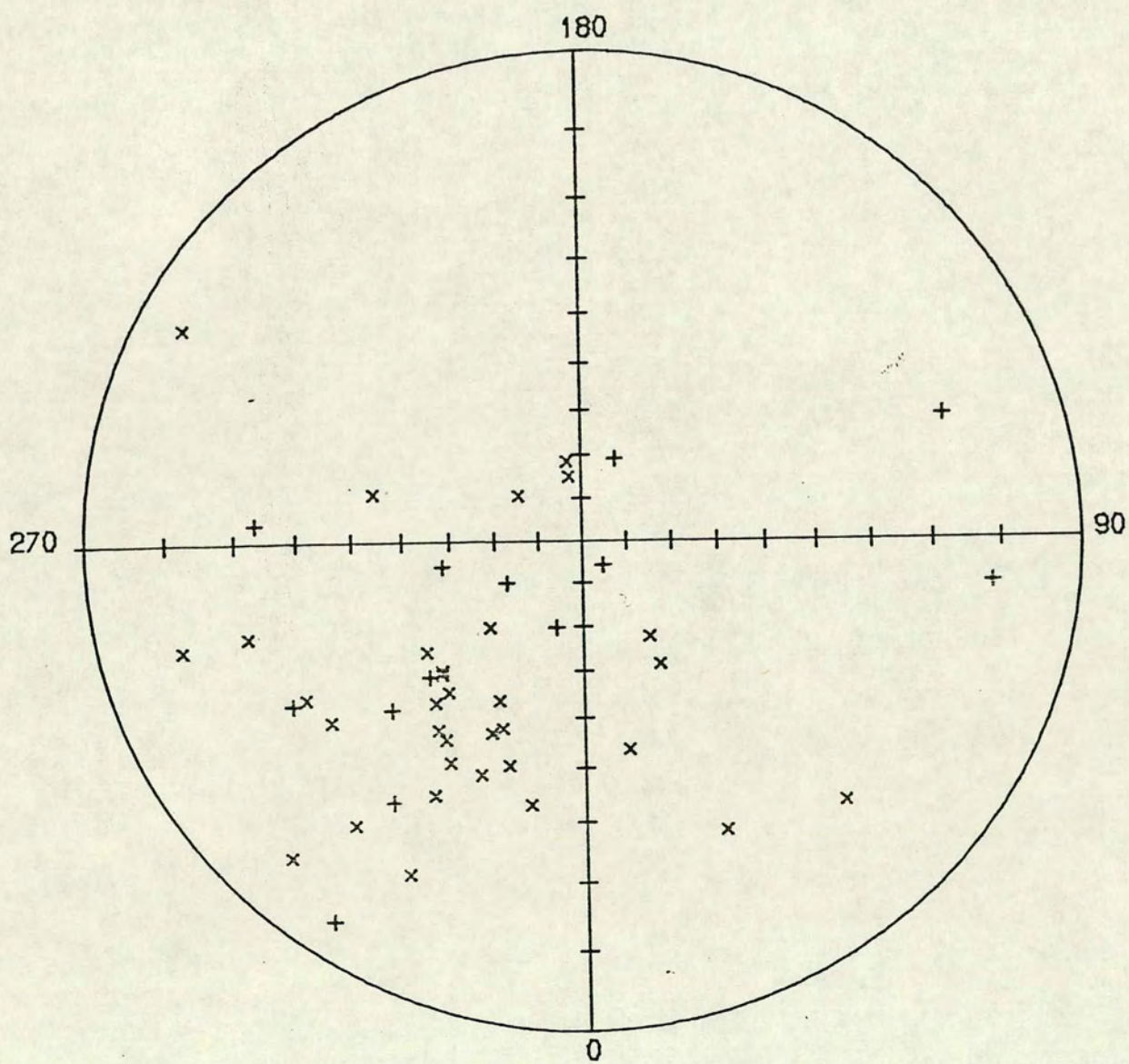


Figure 39a. Intermediate poles at Section A

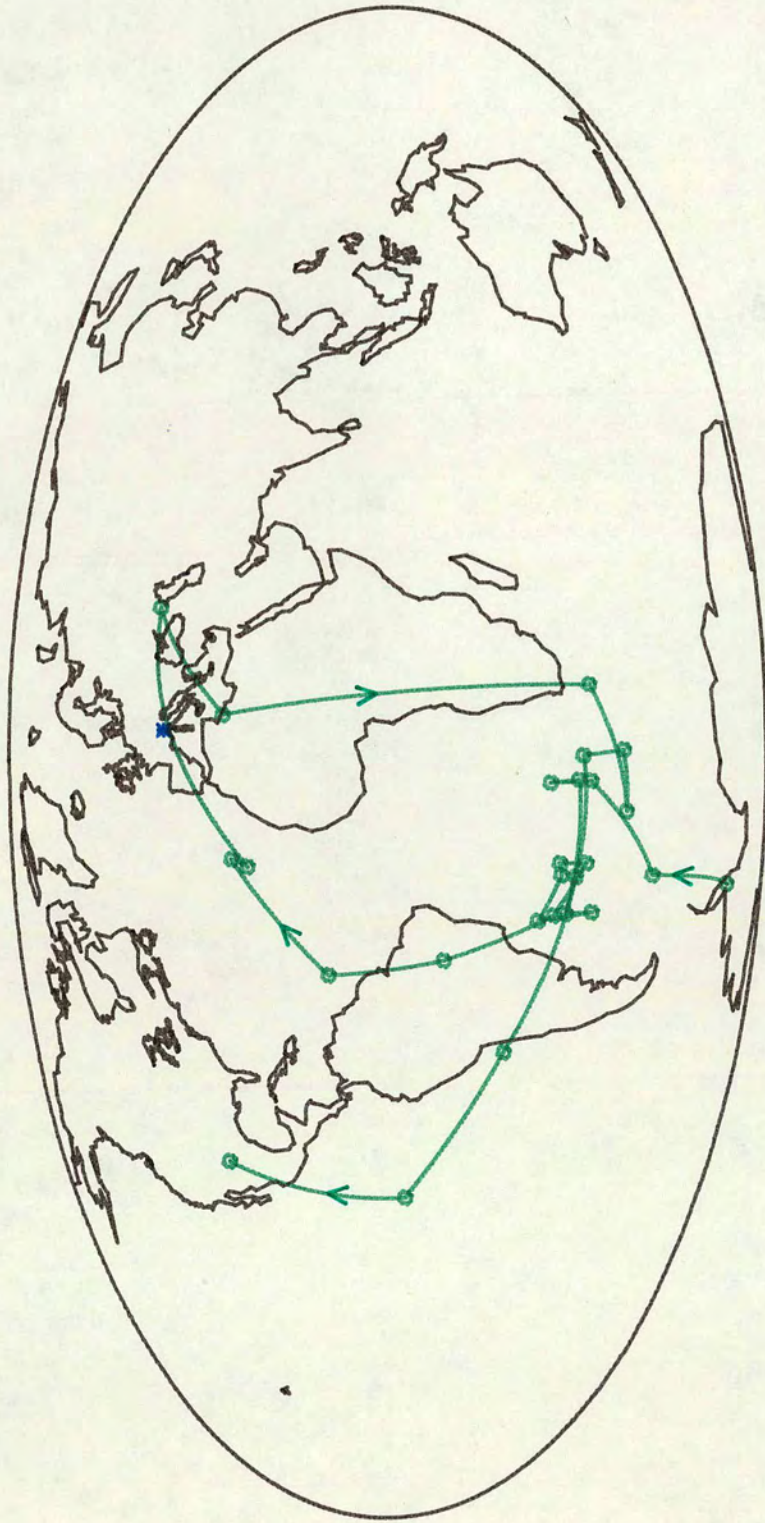


Figure 39b. VGP Path at Section A

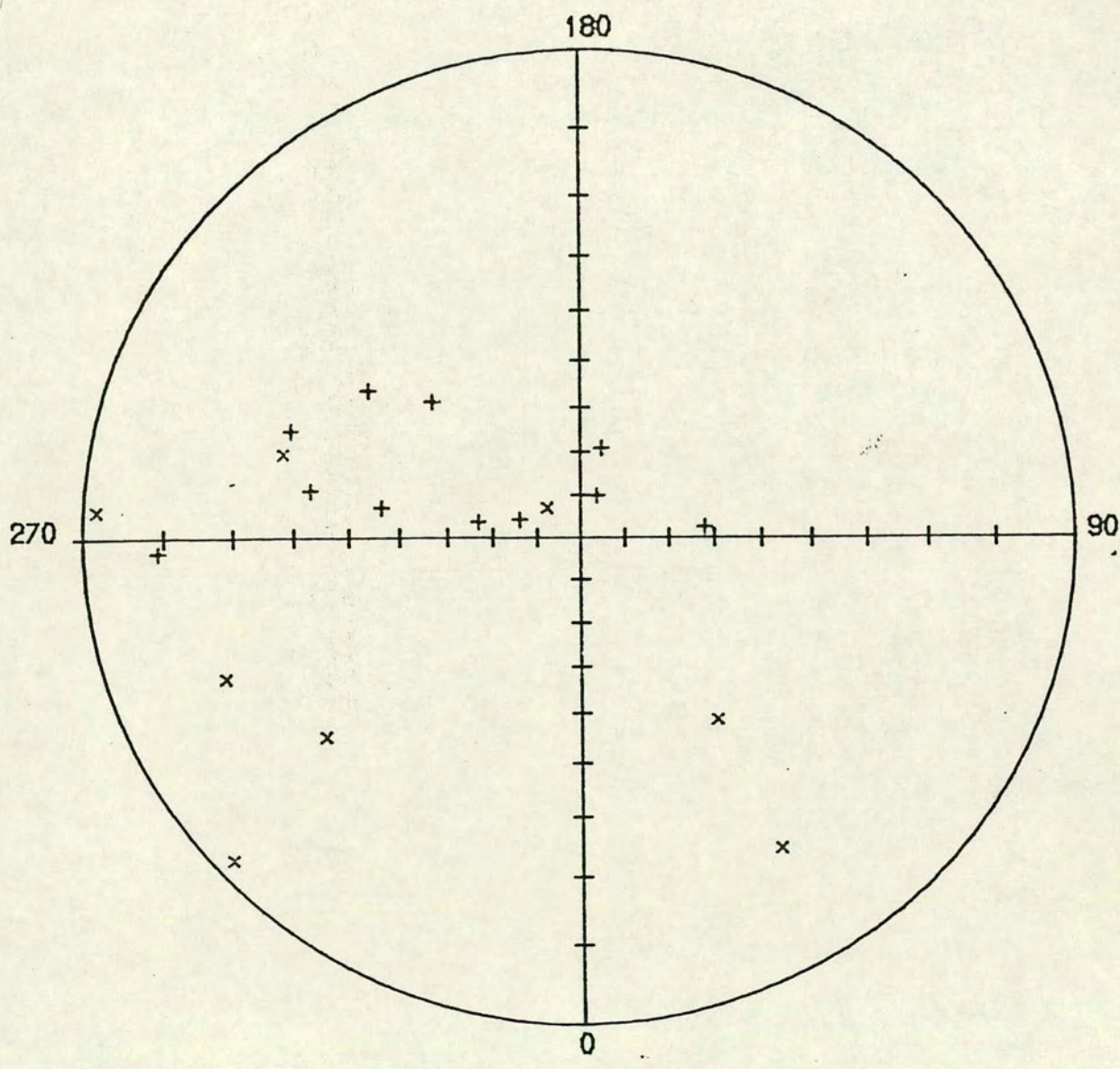


Figure 40a. VGPs for 1980 Section

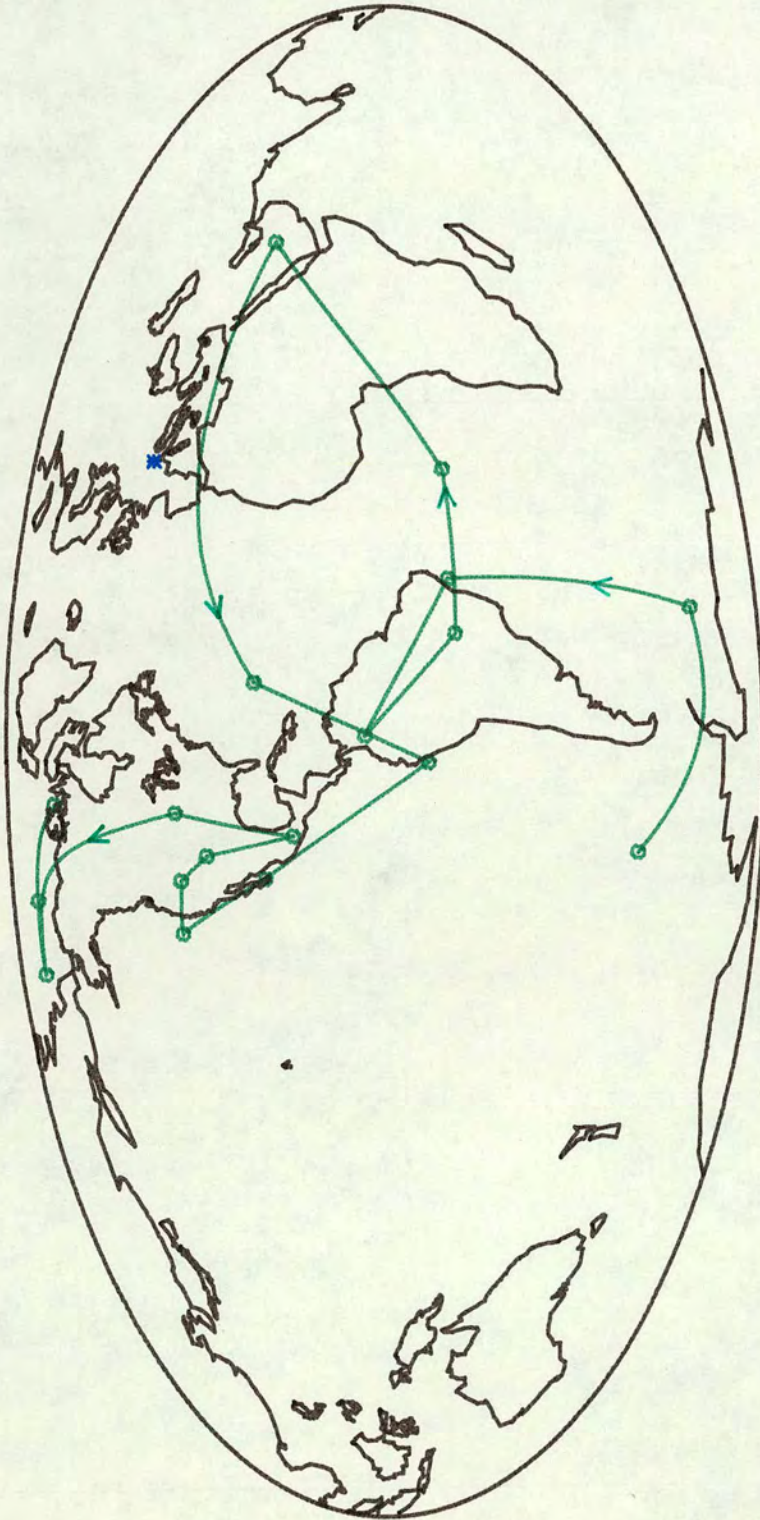
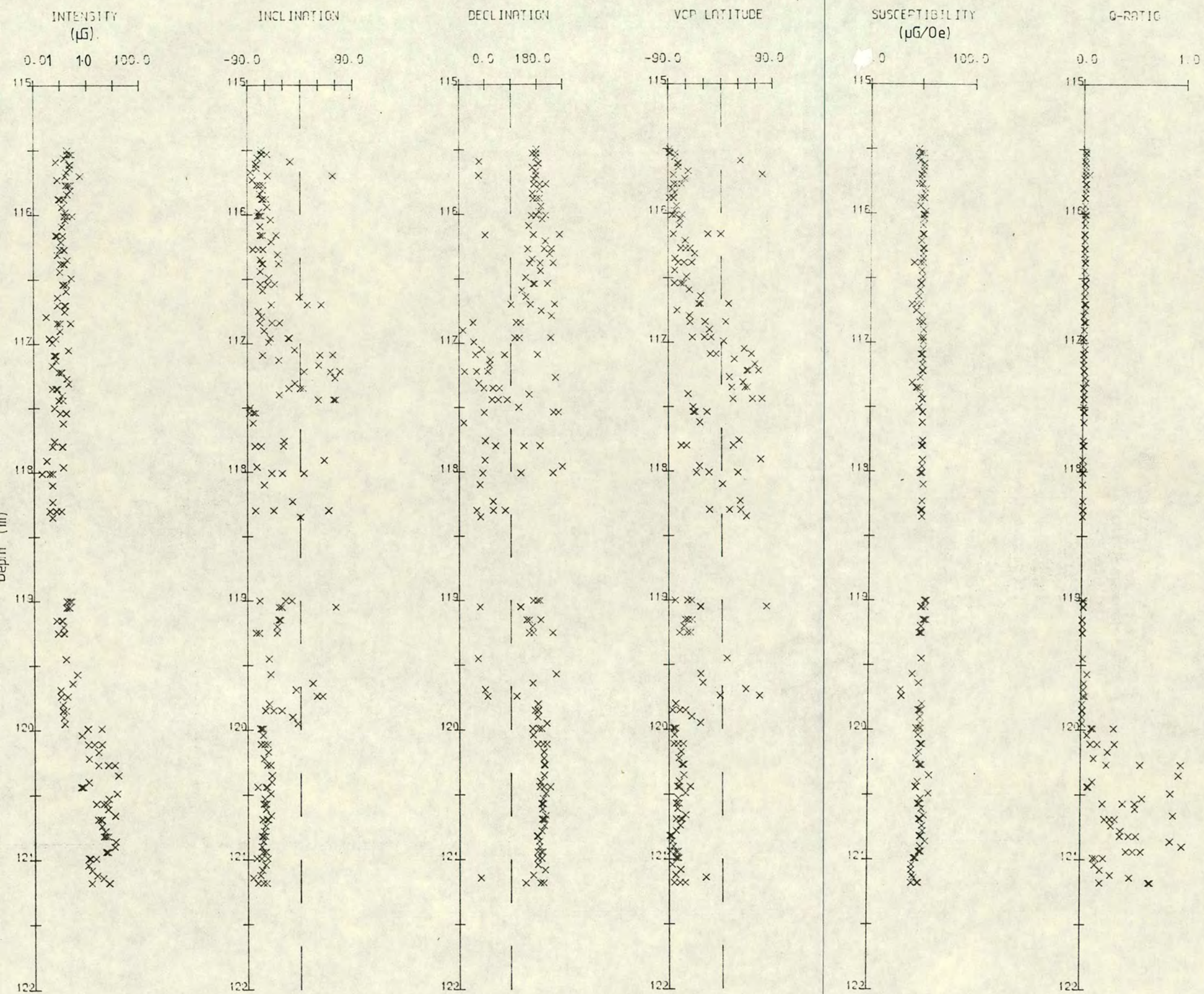


Figure 40b. VGP Path for 1980 Section

Figure 41 NRM Results for Stratum Section B



part of the section above 120m, and $4.39 \pm 3.53 \mu\text{G}$ in the lower part. The lithology in this section is more or less uniform; however a short sand interval occurs between 119.57 and 119.69m. There is little change in susceptibility within the section, the average being $9.85 \pm 1.46 \mu\text{G}/\text{Oe}$. Q-ratios show a marked increase from about 0.02 above 120m to around 0.4 below. Apart from the lowermost samples which record consistently reversed polarity, there is much variation in the directions of magnetization. Above 116.7m, the majority of the samples are reversed, but between 116.70 and 120.00m directions are very scattered.

Examples of pilot demagnetization of samples from section B are shown in Figure 42. Samples which are initially reversed such as MS189' (120.11m) and MS212 (121.14m) show no change in direction with demagnetization. All of these samples have a large normal overprint which is usually removed by 100 Oe. Median destructive fields for these samples are high, generally between 300 and 350 Oe. Other samples with lower intensities show more change in direction between steps, and often unusual changes in intensity. In general the pattern is for normal or intermediate samples to become reversed (e.g. MS250: 117.05m and MS254': 117.22m) and for reversed samples to stay reversed (e.g. MS177': 119.25m). Very occasionally, samples change from reversed to intermediate (MS243": 116.70m).

Figure 43 shows the results for section B after blanket demagnetization at 150 Oe. Intensity decreases slightly in both parts of the section, however the step in values at 120m is still present ($0.14 \pm 0.16 \mu\text{G}$ above compared with $1.79 \pm 1.73 \mu\text{G}$ below). The directions become much more consistently reversed; in fact only three samples have positive inclinations. In addition, a number of samples have northerly declinations giving two intervals of low VGP latitude:

Figure 42 Examples of Pilot Demagnetization from Section B

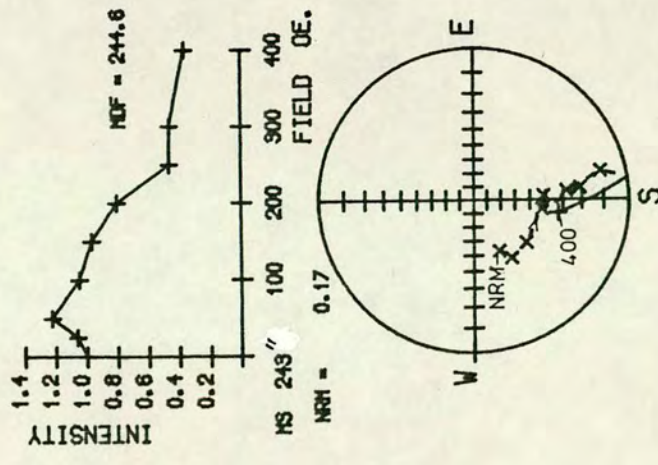
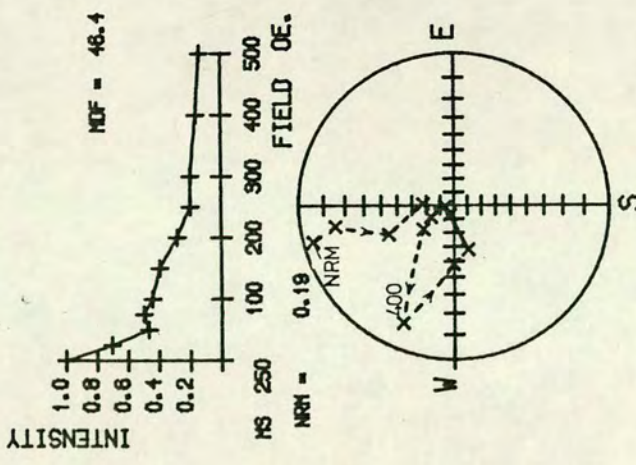
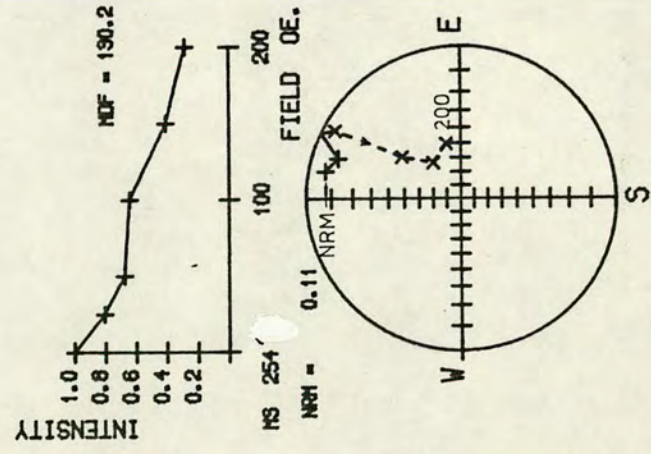
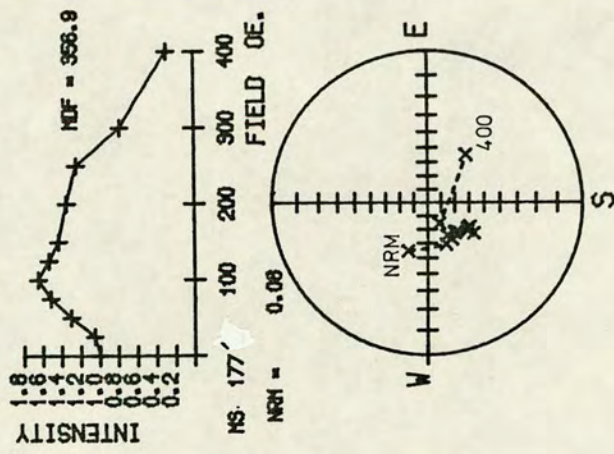
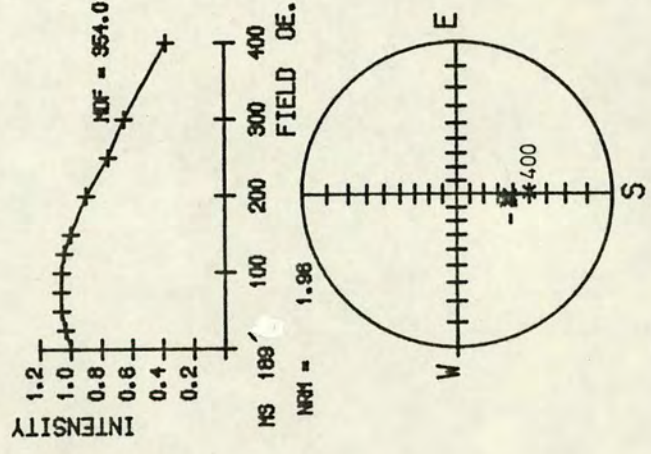
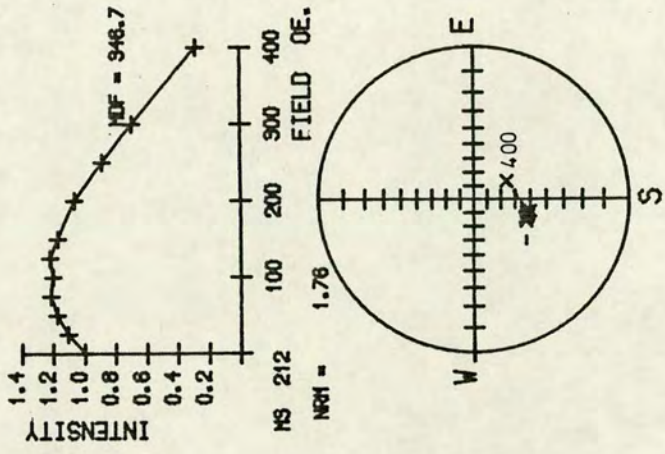
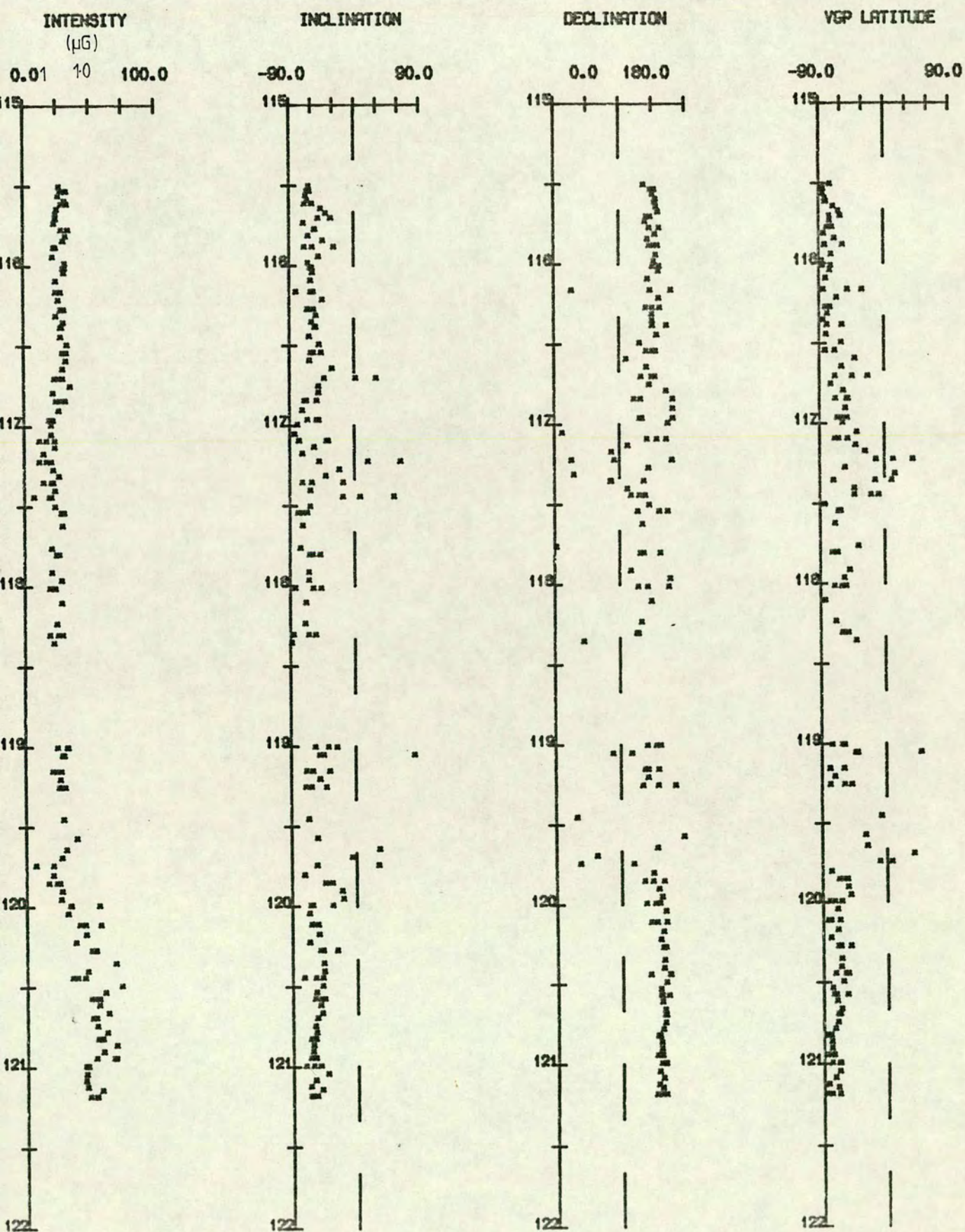


Figure 43. Results for Section B after Demagnetization at 150 Oe



between 117.17 and 117.44m and between 119.45 and 119.74m. Clearly, this section does not record a completely reversed event. The upper excursion is recorded in sediments with low intensity, so the anomalous directions may result from relatively high noise (only MS256 at 117.31m has an intensity greater than $0.1\mu\text{G}$; nevertheless this sample records a stable intermediate direction giving a VGP near Hawaii, see Figure 44). The lower excursion is more probably real; intensities are greater than $0.1\mu\text{G}$, and the directions are similar to those seen in the preliminary survey. However a number of samples were taken from sand, so there must still be some doubt about the reality of this excursion. The lower excursion consists of a transition to near Japan, then a long westward drift through south Africa and southern America to the Mid Pacific before returning to the South Pole (Figure 44).

Alpha 95 values are high in the upper part of the section, reflecting the large variation due to low intensity. Demagnetization improves the grouping, reducing alpha 95 from $40^\circ - >90^\circ$ down to between 20° and 60° . Below 120m, alpha 95 values are low, usually less than 20° .

As with Section A, laboratory induced magnetizations showed little change within the section. ARM and SIRM have similar ranges of coercivity, with median destructive fields between 250 and 350 Oe. NRM is always harder, although the pattern is complicated by normal overprints (Figure 45). The jump in intensity below 120m is also seen in the laboratory induced magnetizations, however the effect is smaller for SIRM. Both SIRM and susceptibility are more constant within the section, suggesting that the increase in intensity below 120m is due to increase in the smaller grained fraction. Intensity normalized by ARM shows a smaller increase below 120m (Figure 46).

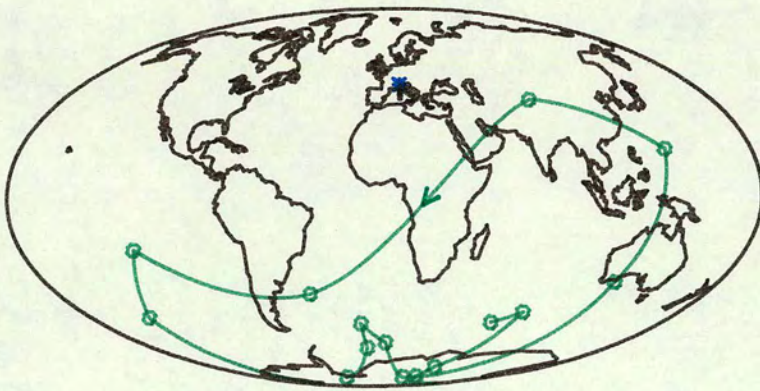
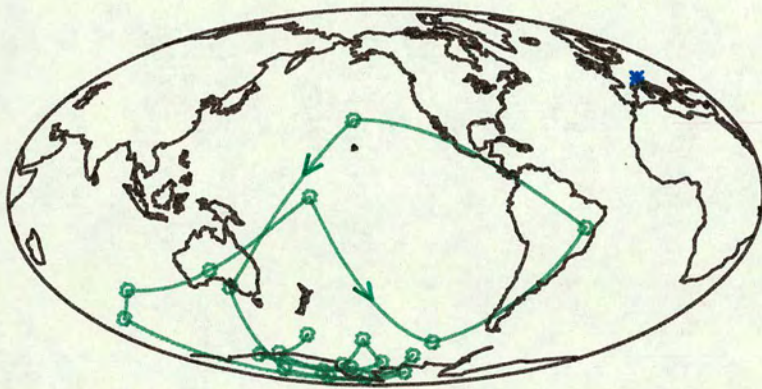
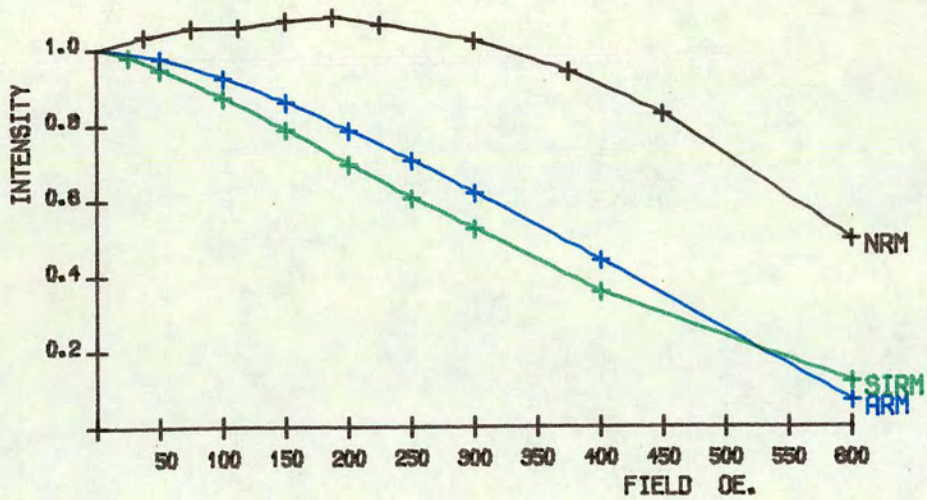
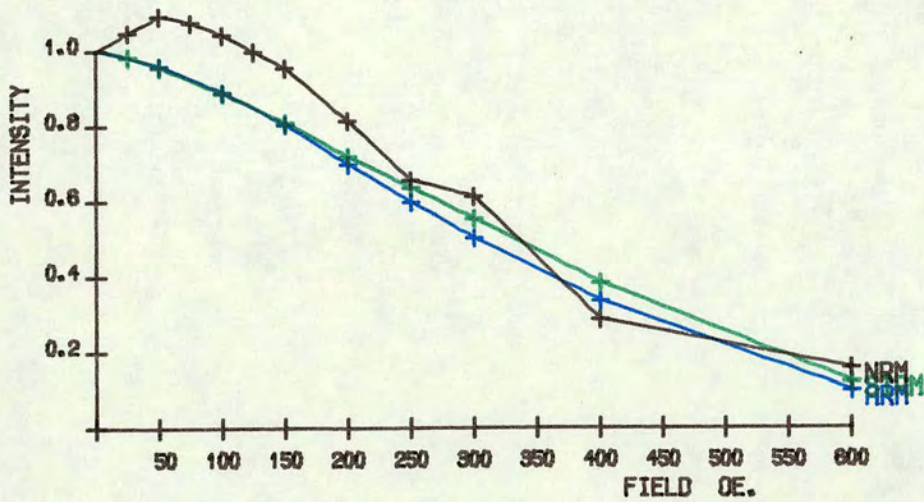


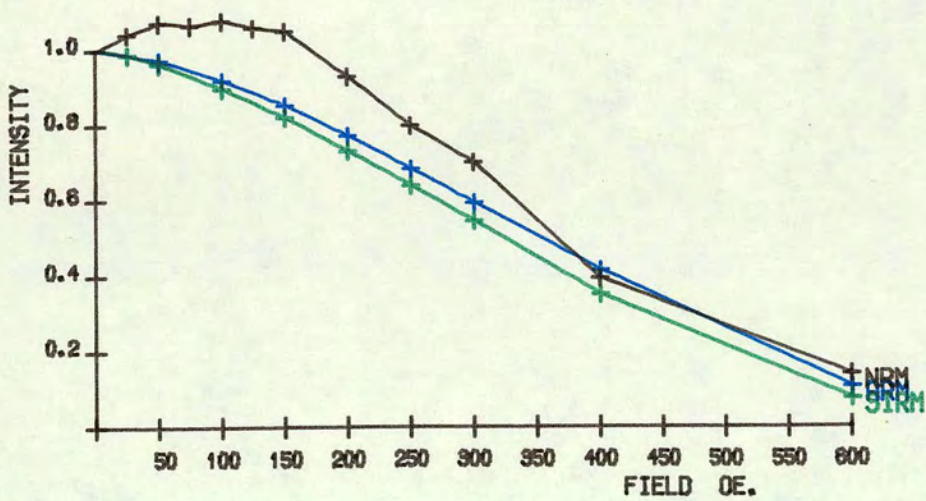
Figure 44. Excursions at Stirone Section B



MS 187A



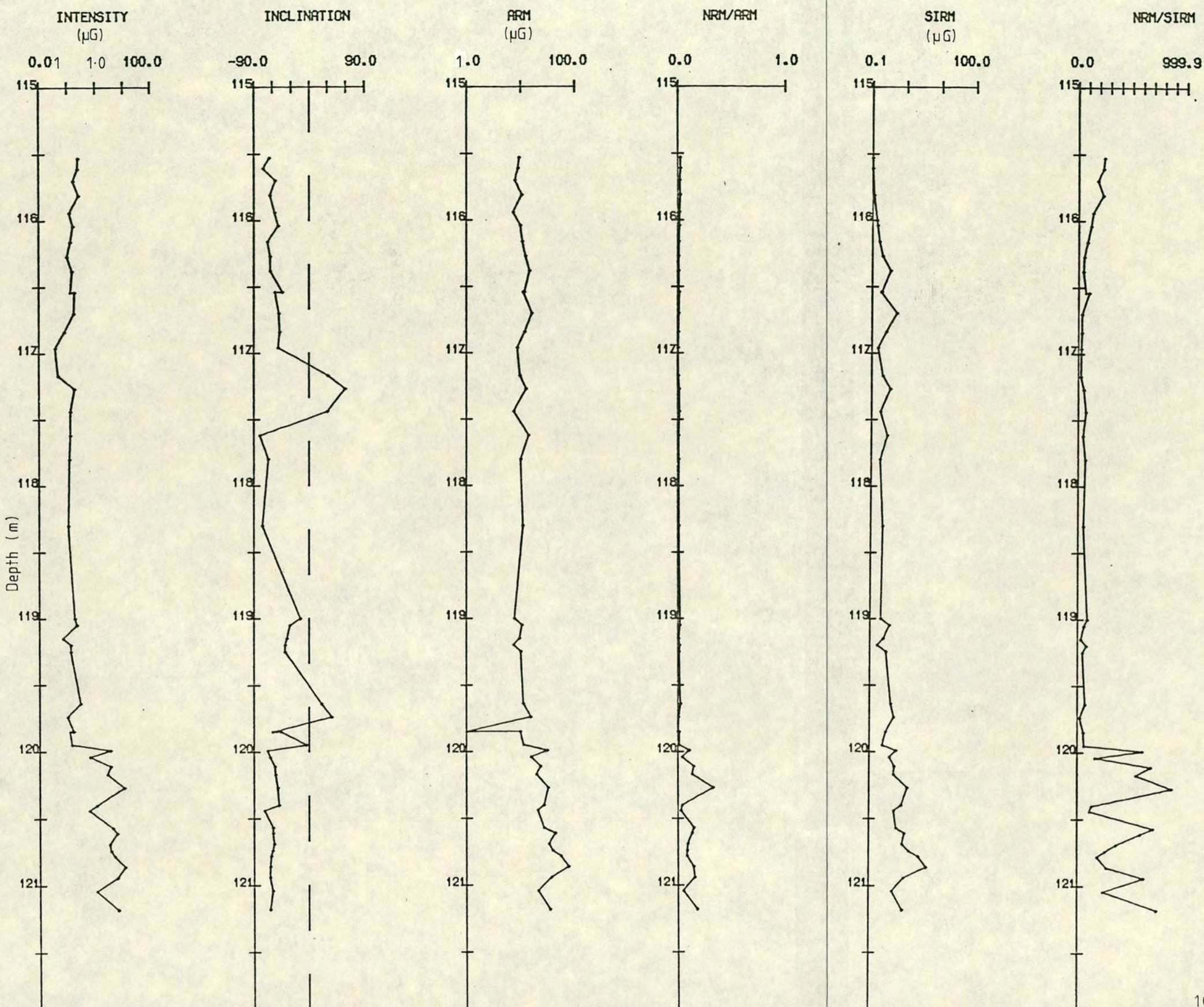
MS 201A



MS 203

Figure 45. Demagnetization of NRM, ARM, SIRM at Section B

Figure 46 Normalization of intensity for Section B

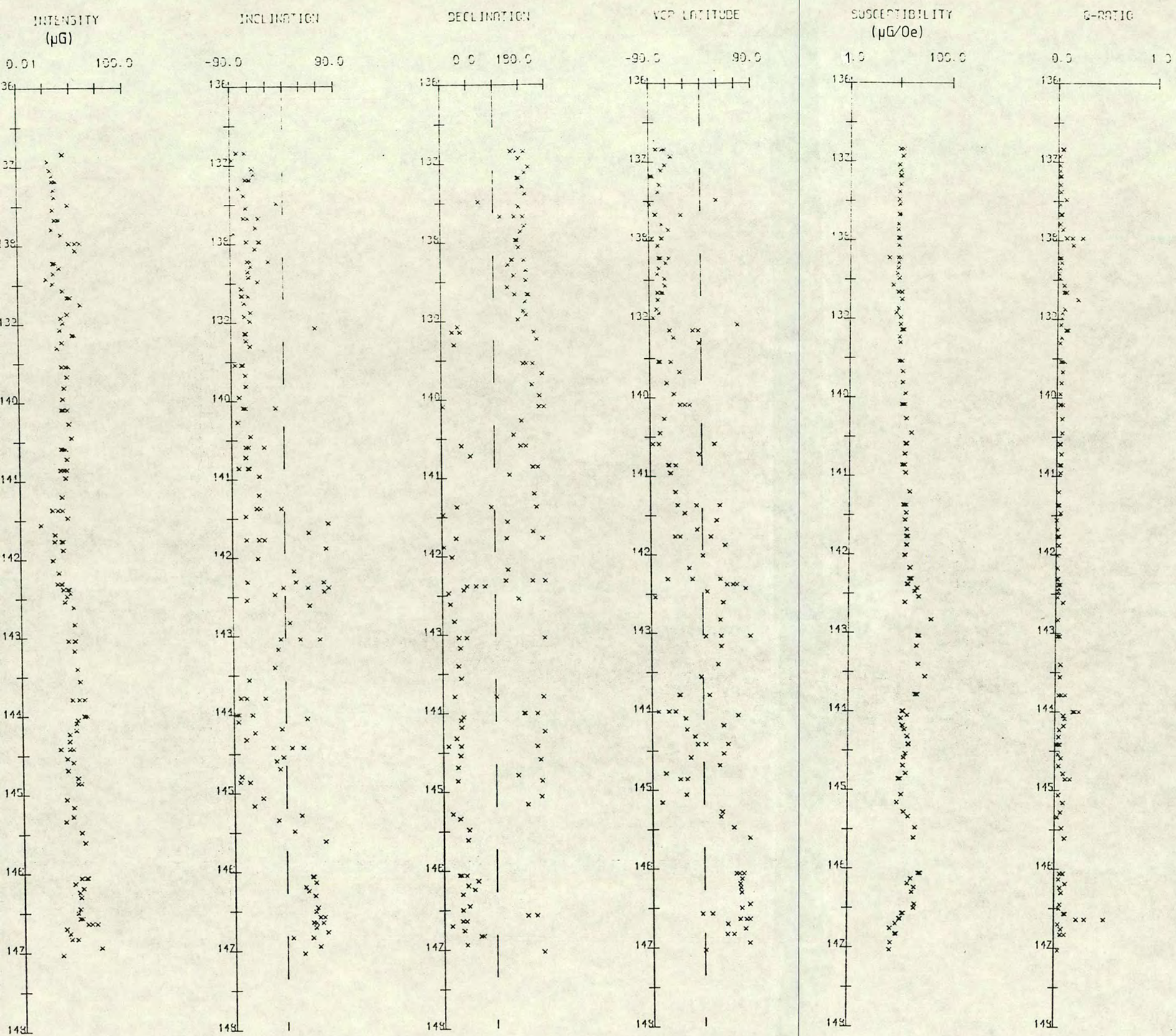


MARINE SECTION C

Section C covers 12m of sediment just above the Dreissena sands, corresponding to samples M55 (137.00m) to M62 (149.00m). The deposits are freshwater sands and clays. Initial investigation showed that these sediments recorded a normal event, the upper limit of which occurred between 135 and 140m. The lower limit was not seen, due to the difficulty of sampling the Dreissena sands. NRM measurements for section C are shown in Figure 47. NRM intensity is more or less the same throughout the section, averaging $0.88 \pm 0.96 \mu\text{G}$. Susceptibility is slightly higher than in other sections from this river: $13.7 \pm 5.4 \mu\text{G}/\text{Oe}$, and Q-ratio is fairly constant at 0.07. NRM directions show much variation, below 145.48m inclinations are normal and declinations northerly giving normal VGP latitudes, between 145.48 and 141.56m both inclination and declination show much variation giving rise to a wide range of pole positions. Further up the section inclination is definitely negative, and although declination is occasionally northerly, the majority of the VGPs lie in high southern latitudes.

Demagnetization (Figure 48) shows that samples from the top of the section are stable, for example MS171''' (137.97m) and MS143' (140.86m), with median destructive fields of around 250 Oe. Samples between 141.56 and 145.48m become more reversed, for example MS121' (143.79m) changes declination from 81.7° at NRM to 180.6° at 300 Oe, however some samples become normal (e.g. MS112", 142.38m). The normal samples below 145m tend to become more reversed (e.g. MS110: 146.94m) and no stable normal samples are seen. Where there is a change in direction with demagnetization median destructive fields range from 170 to 470 Oe, depending on the effect of the soft overprint.

Figure 47 NRM Results For Section C at St. Inge



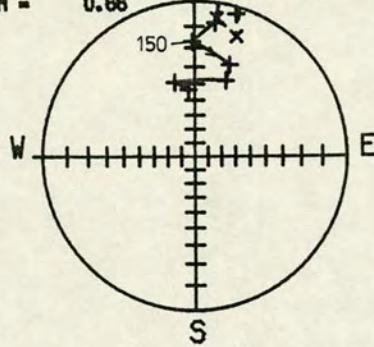
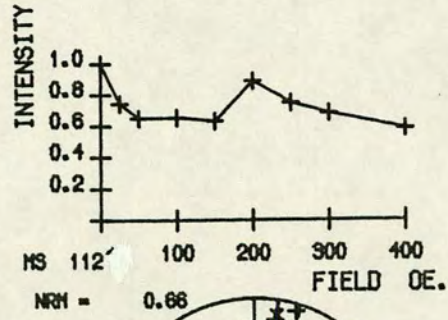
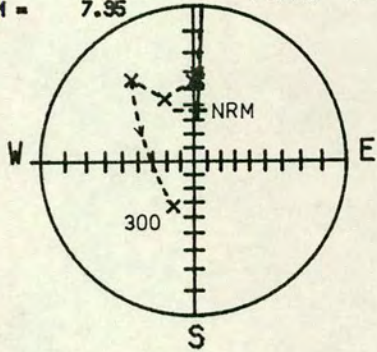
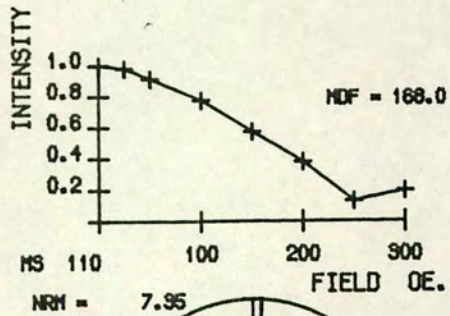
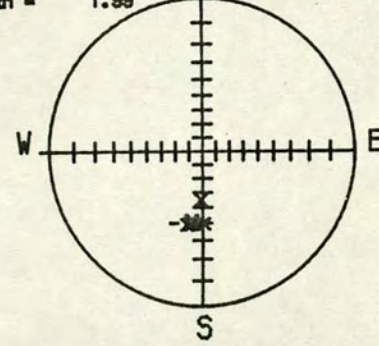
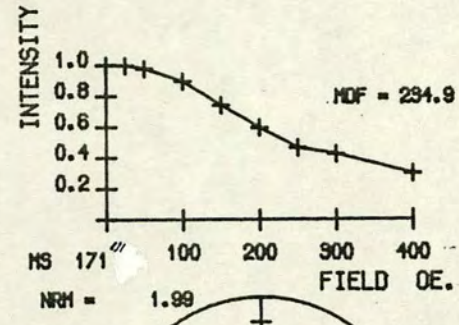
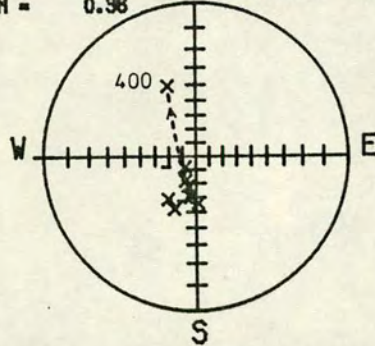
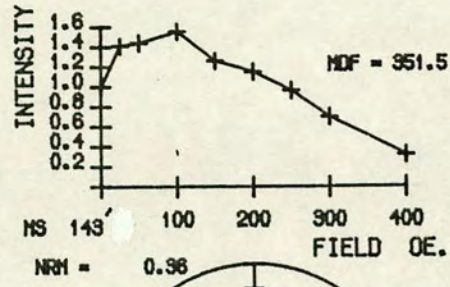
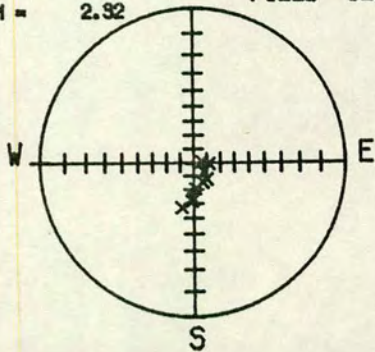
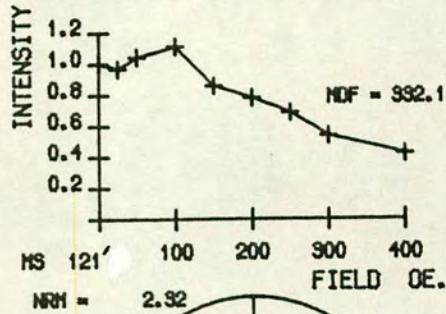


Figure 48 Examples of Plot Demagnetization
from Section C



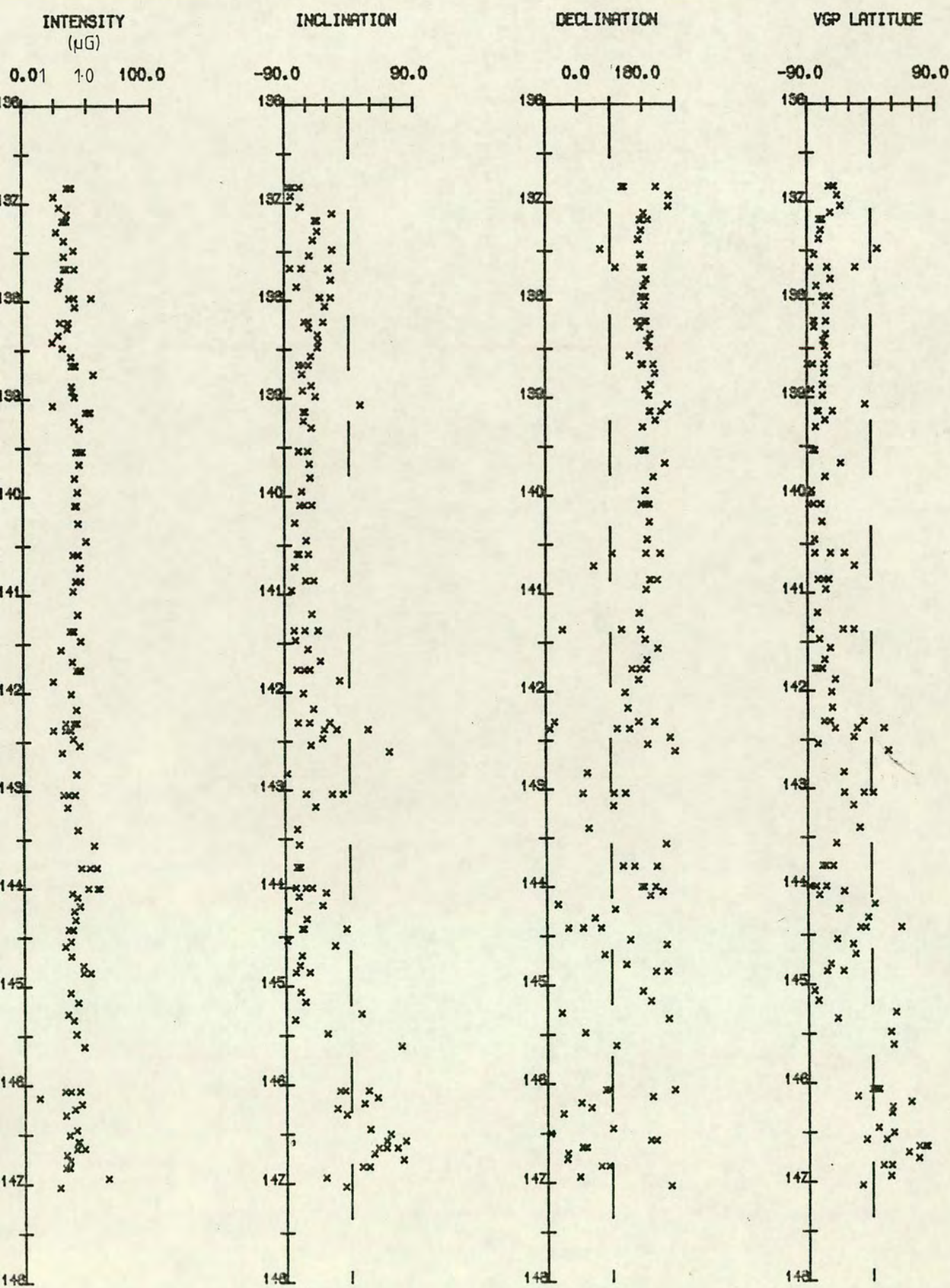
The results after blanket demagnetization of section C are shown in Figure 49. Intensity decreases by about 40% to $0.51(\pm 0.50)\mu\text{G}$, the greater decrease being shown by samples toward the bottom of the section. Apart from the lowermost 1.5m, inclination is consistently negative. Declination in the upper part of the section is more or less southerly apart from anomalous directions below 142.83m. Below 145.50m inclination is positive or intermediate, and declination varies considerably, giving VGPs in low northerly latitudes. The section records a normal to reversed transition, however the base of the section does not quite reach the stable directions of the normal event. In addition there may be two excursions caused by variations in declination above the transition at 142.3 to 143.56m and 144.00 to 144.86m. The younger one is recorded in coarser grained sediments and may thus represent scatter, but the older one being recorded by clay may be real, forming part of the transition. Alpha 95 values are less than 45° in the upper part of the section (above 141m), but values increase to $>90^\circ$ below this. Demagnetization causes an increase in the scatter in the lowermost transition zone.

Figure 50a shows pole positions in the transition zone (i.e. below 144m). These are slightly biased towards the far-side, although there is a large amount of scatter. The smoothed plot for the transition path (Figure 50b) shows a far-sided path, with an initial swing to India from the Aleutians then a swing back to Hawaii. Following the normal to reversed transition is a far-sided excursion around the southern Pacific.

MARINE SECTION D

Section D is approximately equivalent to samples M74 and M75 (170.50 to 174.50m), which recorded a normal to reversed transition.

Figure 49 Results for Section C after Demagnetization



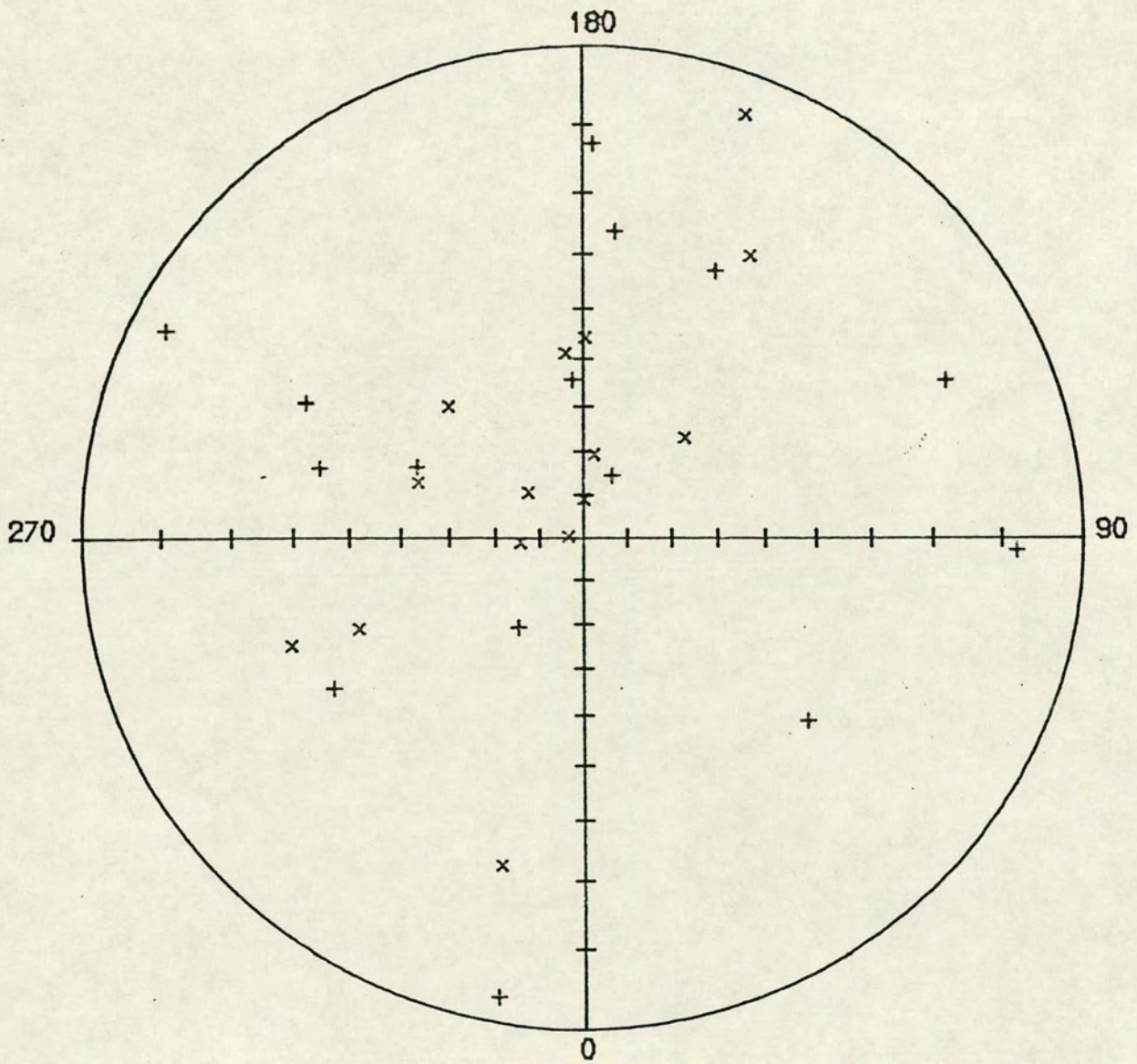


Figure 50a. All intermediate VGPs at Section C

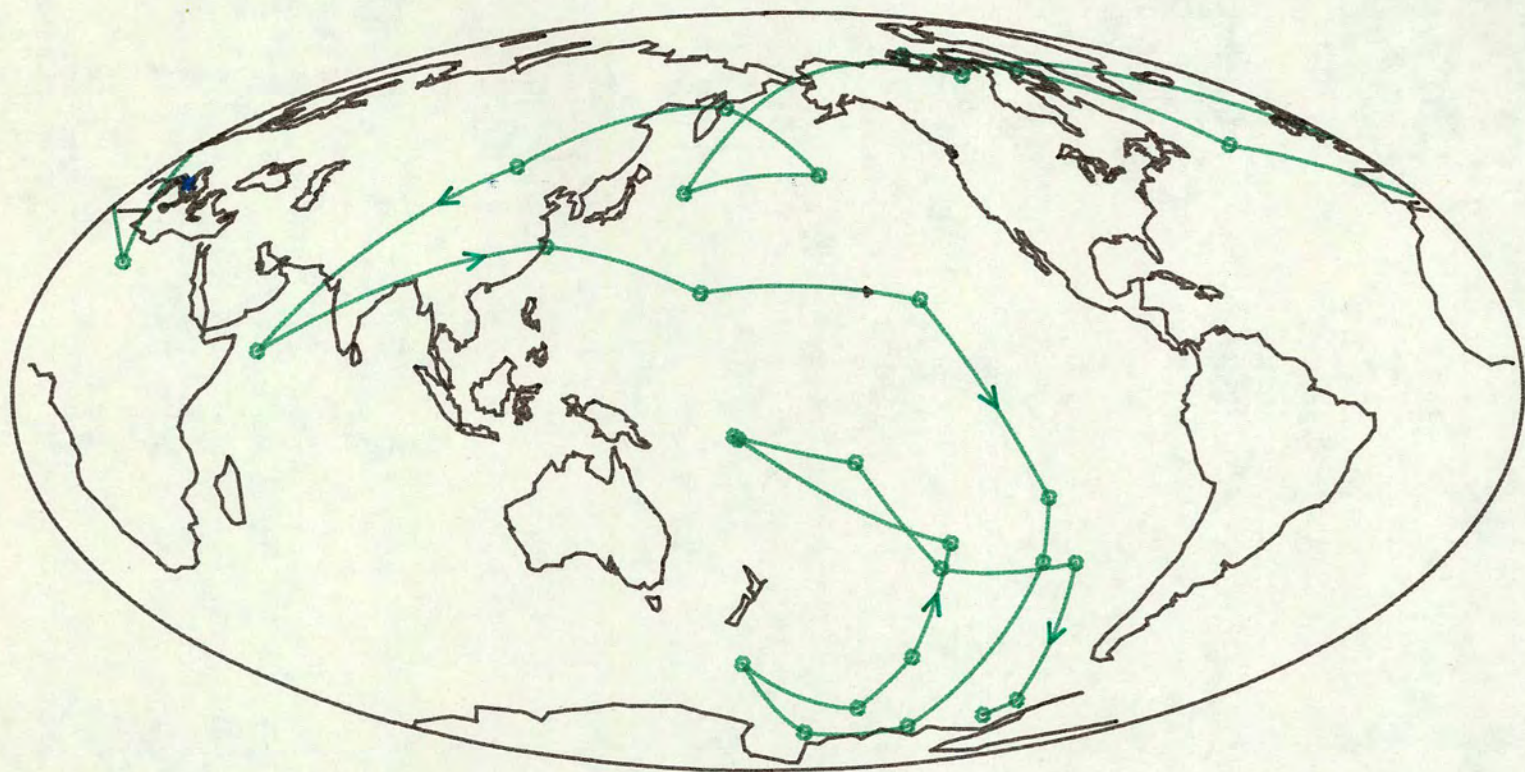


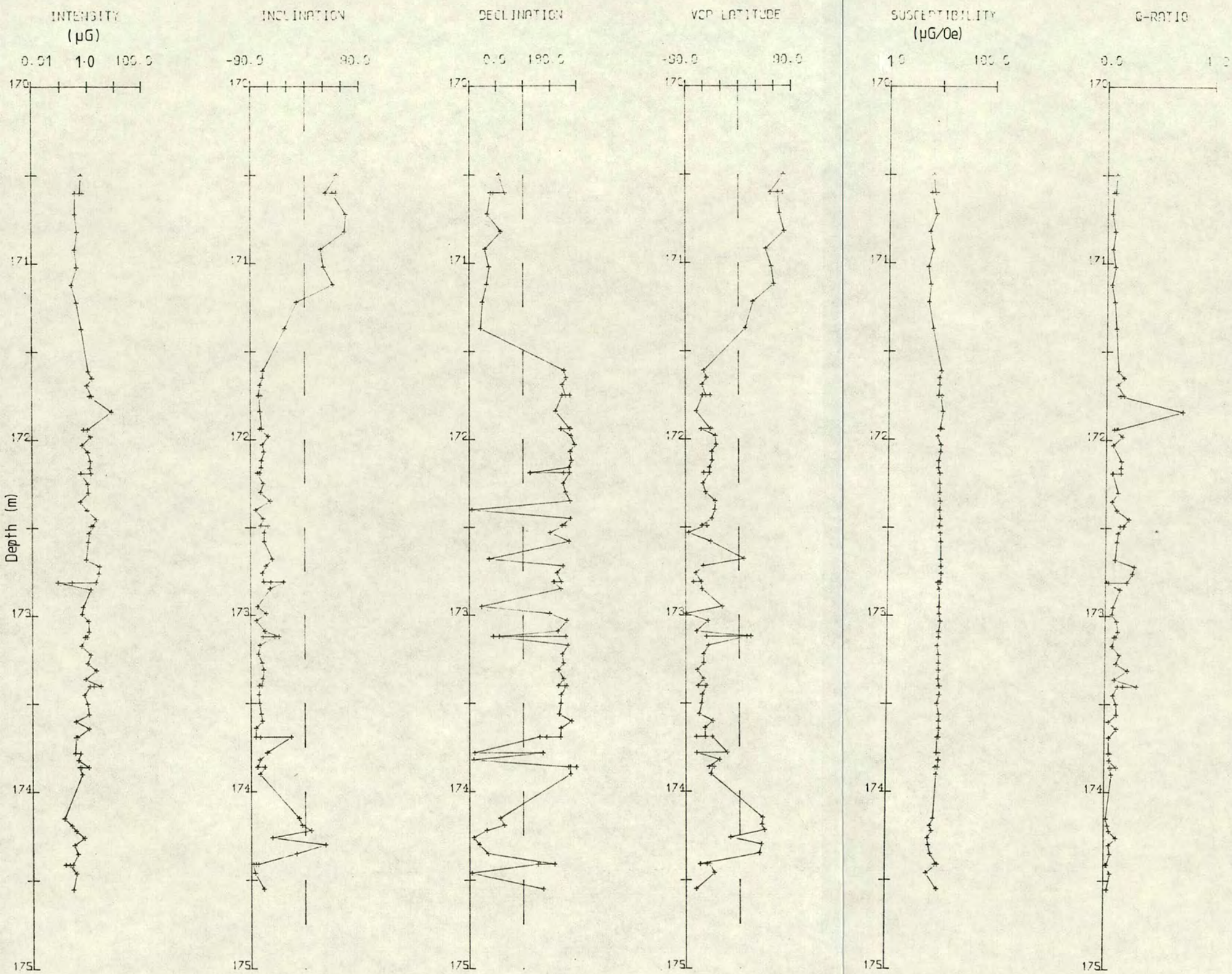
Figure 50b. VGP Path at Section C

Initial sampling in this interval was sparse, so a number of samples were taken to redefine magnetostratigraphy. NRM results are shown in Figure 51. Intensity averages $0.94 \pm 0.89 \mu\text{G}$ throughout the section, with slightly larger values occurring in the centre, and lower intensities above 171.5m and below 173.5m. Susceptibility is more or less constant at $8.79 \pm 1.12 \mu\text{G}$ giving a Q-ratio of 0.1, again with larger values between 171.5 and 173.5m. Directions are opposite to those that were expected: a reversed to normal transition occurs between 171.6 and 170.82m. Most of the values outside this transition zone are clearly normal or clearly reversed, however shallow inclinations and northerly declinations are seen between 174.15 and 174.35m giving VGPs in low northern latitudes.

Examples of pilot demagnetization are shown in Figure 52. Most samples are stable (e.g. MS22: 171.65m and MS54: 173.31m), with MDFs of 300 to 350 Oe. Normal samples from the top of the section show little change in direction until they develop an ARM above 300 Oe, however MDFs are lower (e.g. MS13' at 170.60m which has a MDF of 246 Oe). Intermediate samples at the bottom of the section may change sign, but they remain intermediate. MDFs are low (MS75 at 174.46m has a MDF of 130 Oe). The difference in MDFs between normal and reversed samples is due to the soft normal overprint.

After blanket demagnetization at 150 Oe there is little change in direction except in the lowest metre of the section (Figure 53). Inclination between 174.15 and 174.35m remains more or less the same but declinations change to become more southerly, causing VGP latitudes to be lower, and to lie both sides of the equator. Average intensity drops by an average of 50% to $0.48 \pm 0.39 \mu\text{G}$, with the greater change occurring in the stable central part of the section. Alpha 95 values are generally low (10-30°) even in the excursion recorded at the

Figure 51. NRM Results for Section D at Stirone



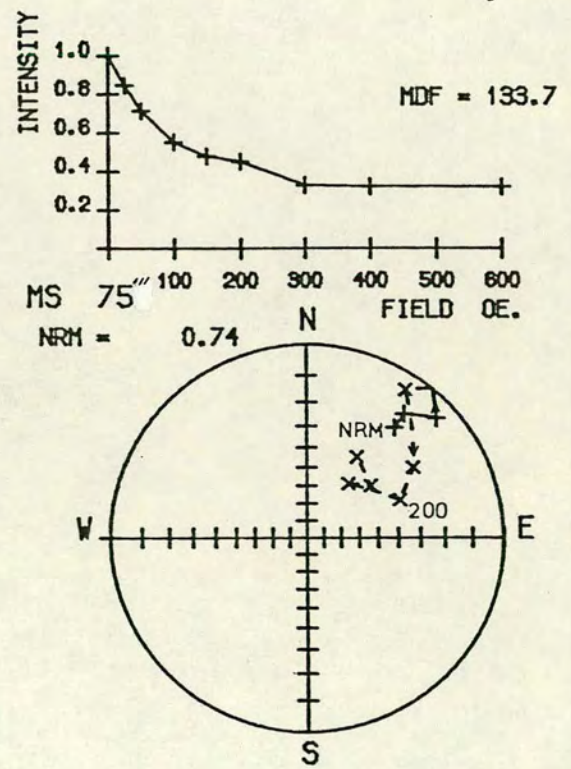
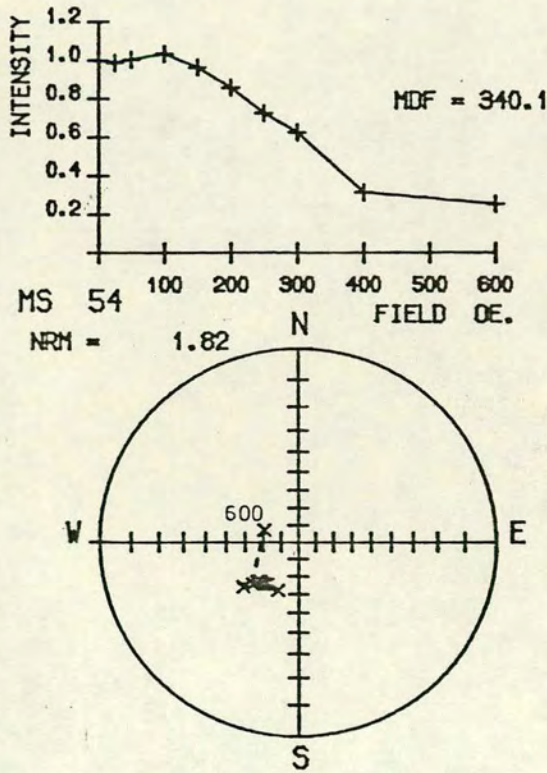
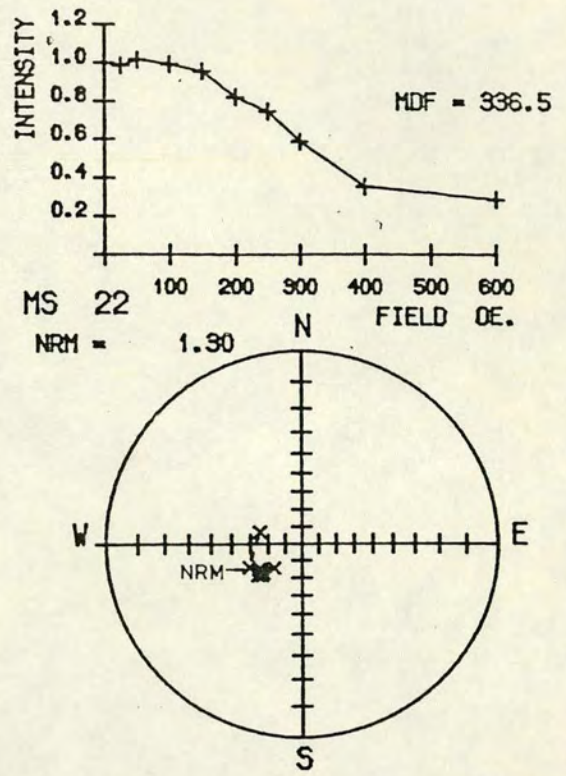
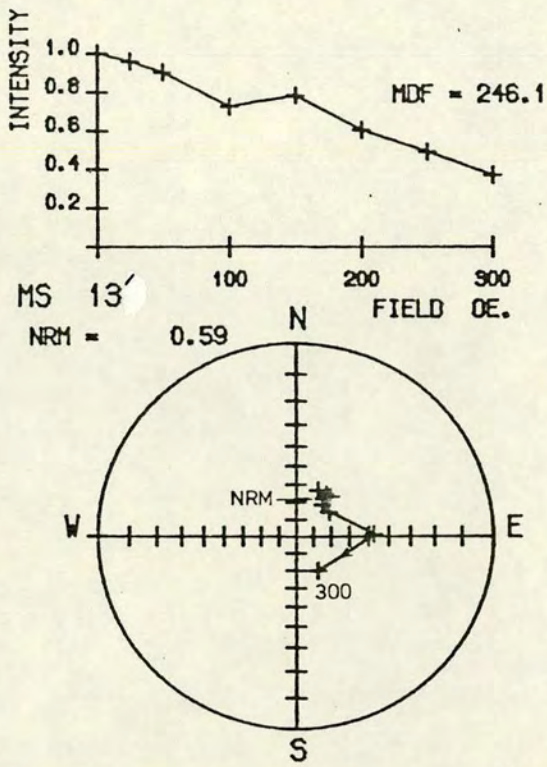
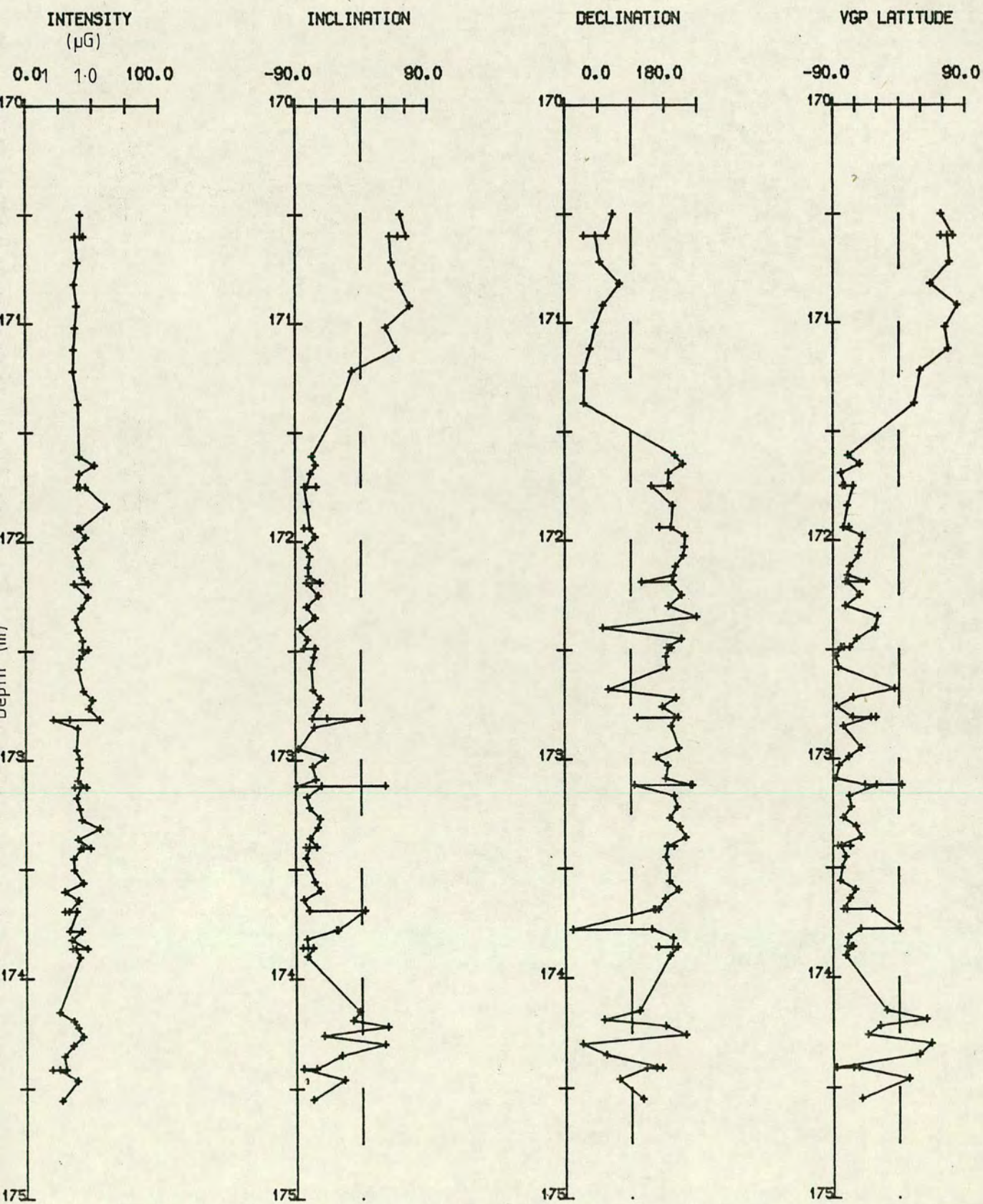


Figure 52. Examples of Pilot Demagnetization from Section D

Figure 53 Results for Section D after Demagnetization



bottom of the section; however demagnetization causes a slight increase in alpha 95.

These results seem to conflict with the initial investigation; however originally sampling was sparse, so the upper normal interval may represent a short event which was not seen due to gaps in the first set of samples. This upper section is recorded in sands; however the close grouping of all directions and the stable behaviour during demagnetization suggests that the palaeomagnetic record of the field is accurate. There are at least 20m of sediment between this section and Section C, which yield consistently reversed directions, so that the event at the top of section D is not the same as that seen at the base of Section C. The excursion at the base of Section D is apparently part of a normal to reversed transition, as below this section there are a number of normal, or intermediate samples. This lowermost normal event in the marine series is often interrupted by samples of reversed polarity. If intensity can be normalized by susceptibility the two events or excursions in Section D appear to have taken place when field intensity was slightly lower, compared with the stable reversed period between 171.5 and 173.5m.

The transition at 171.50m gives a far-sided path which passes between Mexico and Hawaii (Figure 54). The linear path is confined to 135°W of the site. VGP positions in the interval 174-175m show large amounts of variation and may be inaccurately recorded.

MARINE SECTION E

Section E was sampled about 1m above the Plio-Pleistocene boundary to study a reversed interval within the lowermost normal event of the marine series which occurs between 174.5m and 186m. The NRM directions for Section E (Figure 55) show northerly declination,

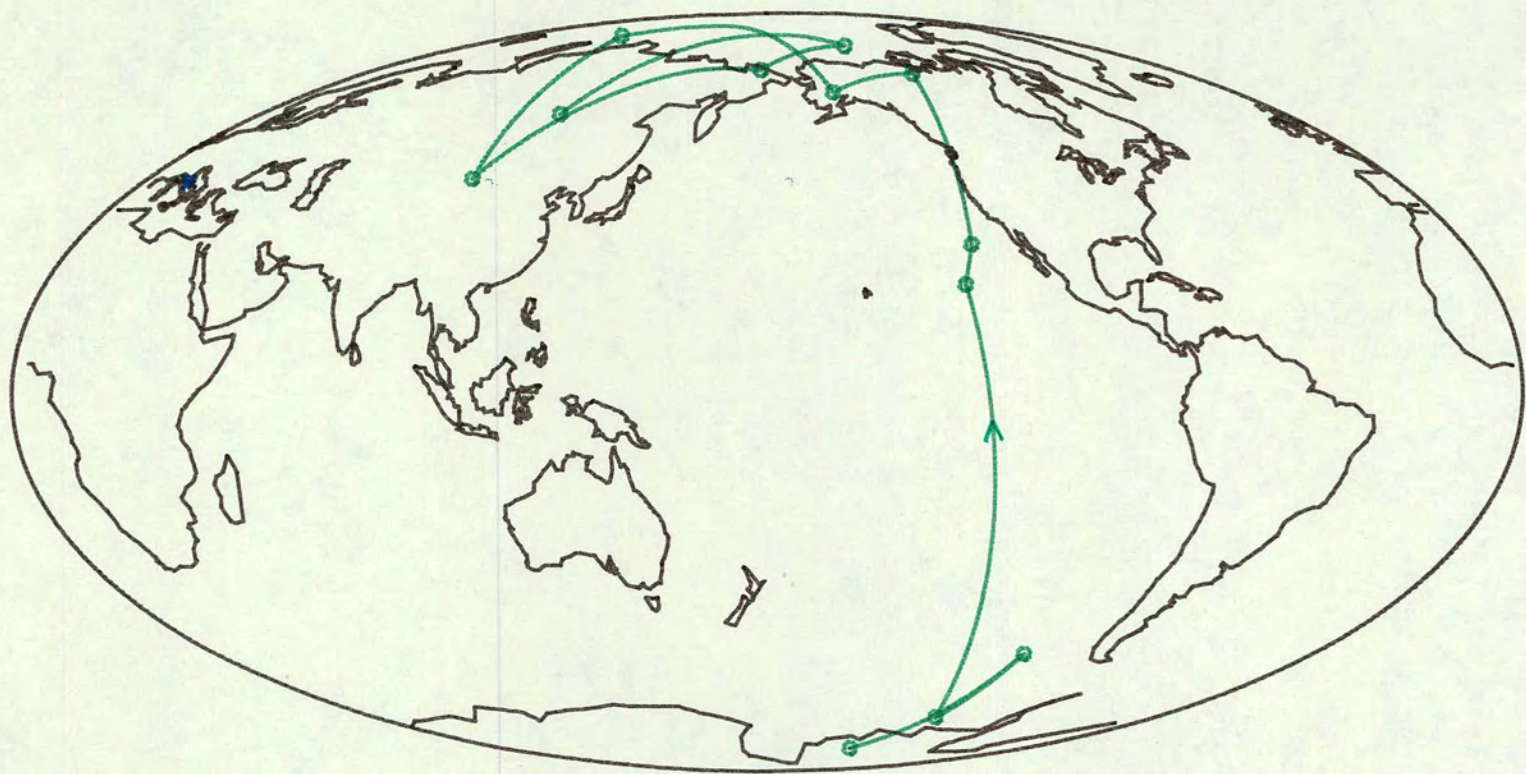
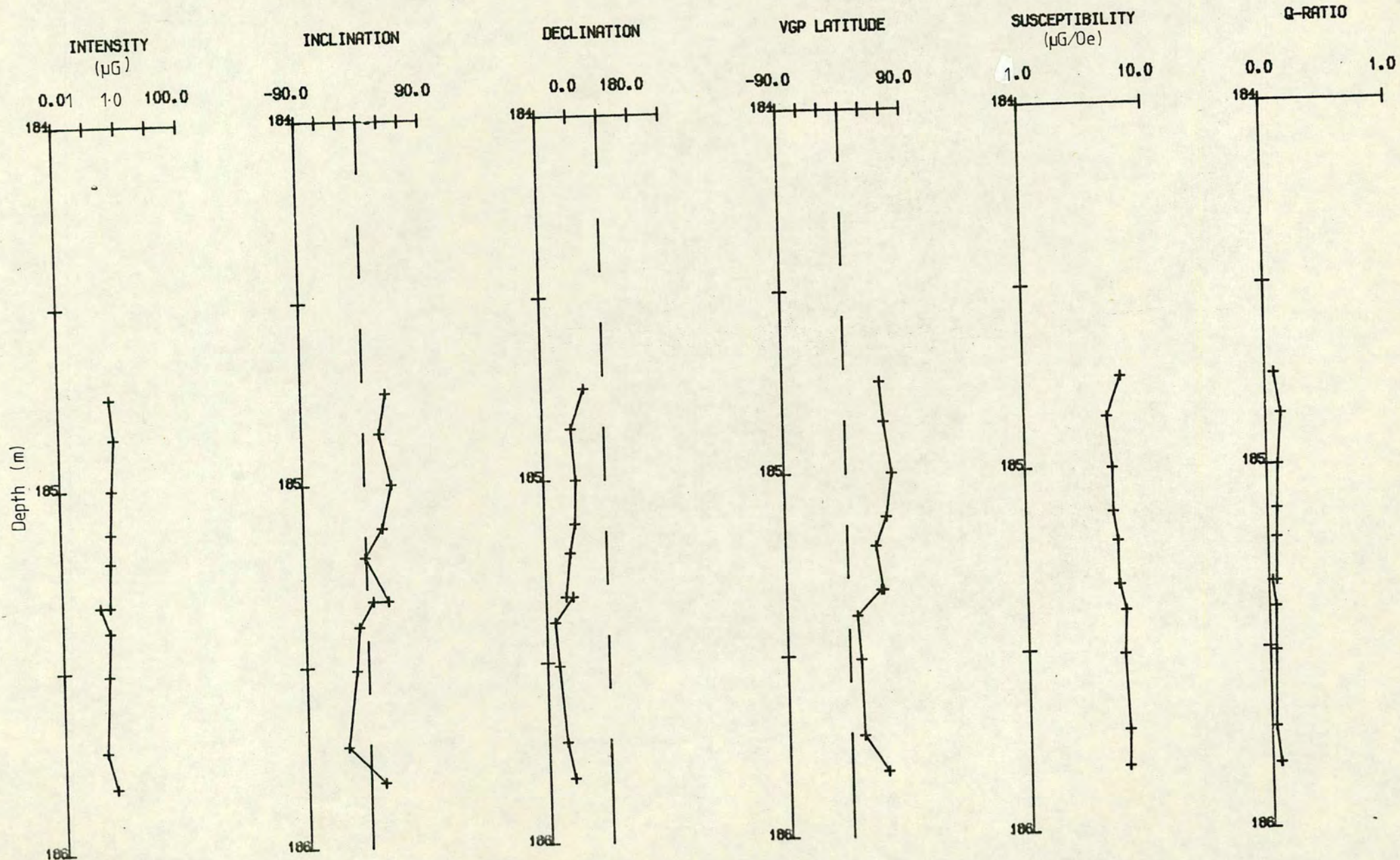


Figure 54. VGP Path for Transition at Section D



but shallow inclination, positive above 185.32m, and mainly negative below, (apart from the lowermost sample at 185.82m). VGP latitude is about 15°N between 185.72 and 185.39m and 40 to 60°N either side of this excursion. Intensity averages $0.36 \pm 0.11 \mu\text{G}$ and shows a slight decrease down the section. Susceptibility which averages $5.7 \pm 0.5 \mu\text{G}/\text{Oe}$ shows the opposite trend, becoming larger downwards giving an increase in Q-ratio from 0.04 within the excursion to about 0.1 at the top of the section.

Pilot demagnetization of some samples is shown in Figure 56. The uppermost sample (MS1: 184.75m) does not change in direction, and MS5 (185.20m) changes only slightly, moving from a low positive inclination to a low negative inclination. On the other hand MS10 (185.72) shows a large amount of variation, especially at higher fields. Median destructive fields are between 130 and 300 Oe.

Blanket demagnetization at 150 Oe leads to a decrease of 50% in intensity to $0.16 \pm 0.06 \mu\text{G}$ (Figure 57), however the same basic trend to lower values near the base is maintained. The excursion is more pronounced due to a change in declination to about 180° between 185.72 and 185.39m. Inclination becomes more negative in this interval and more positive either side of it. VGP latitudes now change from 60°N to 50°S within the excursion. The low Q-ratios within this interval suggest that the field strength was low during this excursion, however there are very few normal samples to enable comparison.

The beginning of the excursion is abrupt, however the end consists of a gradual change from negative inclination to positive inclination giving a path through the eastern Pacific about 90° west of the site (Figure 58).

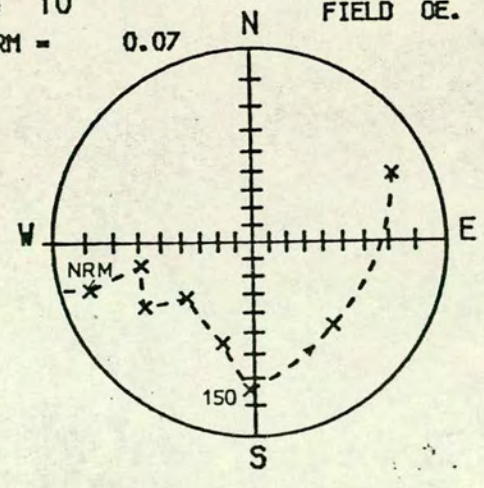
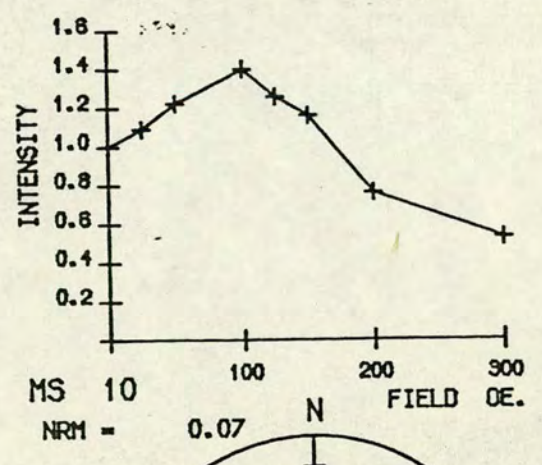
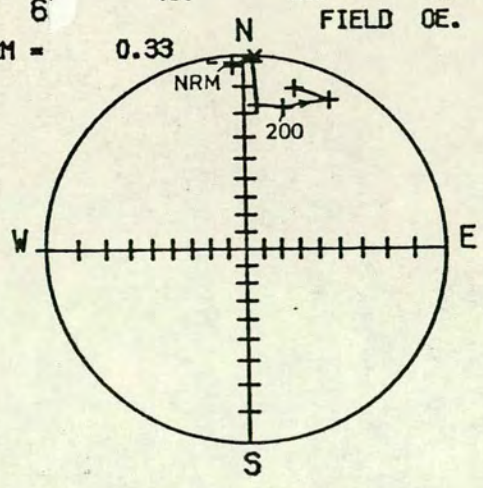
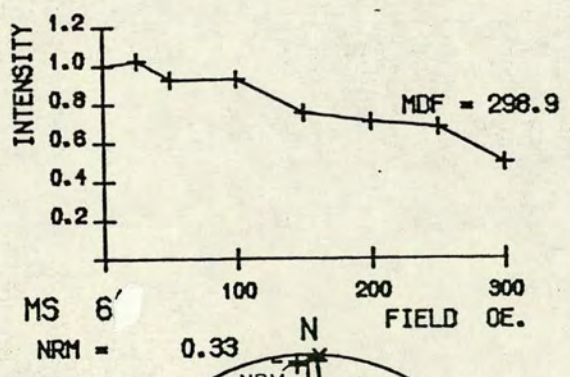
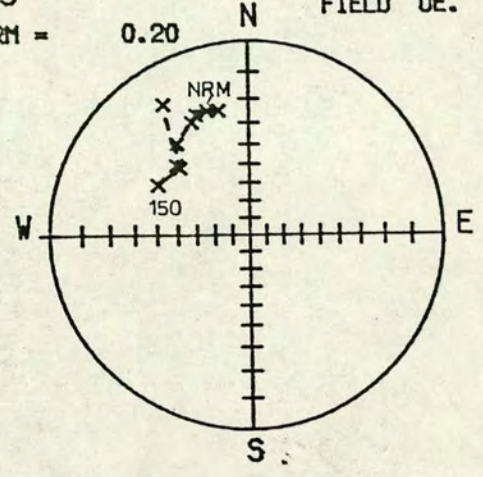
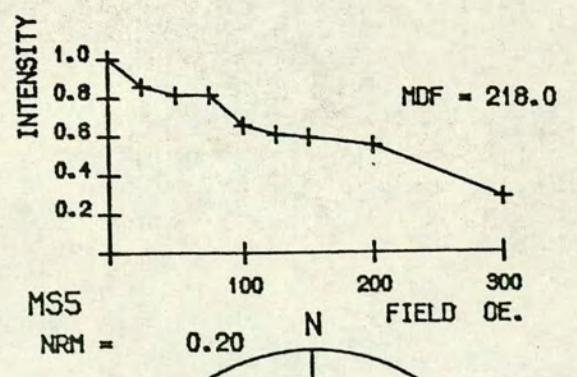
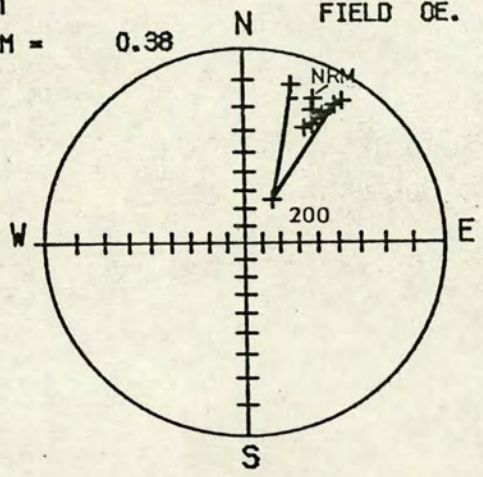
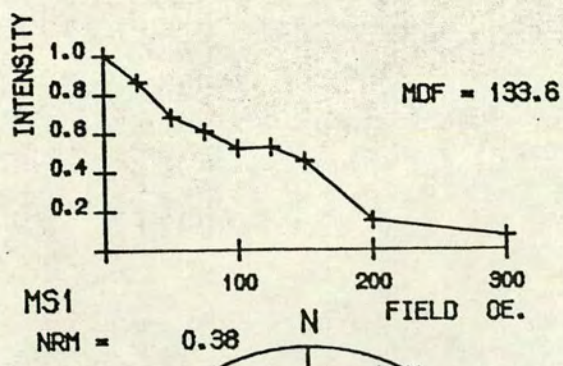
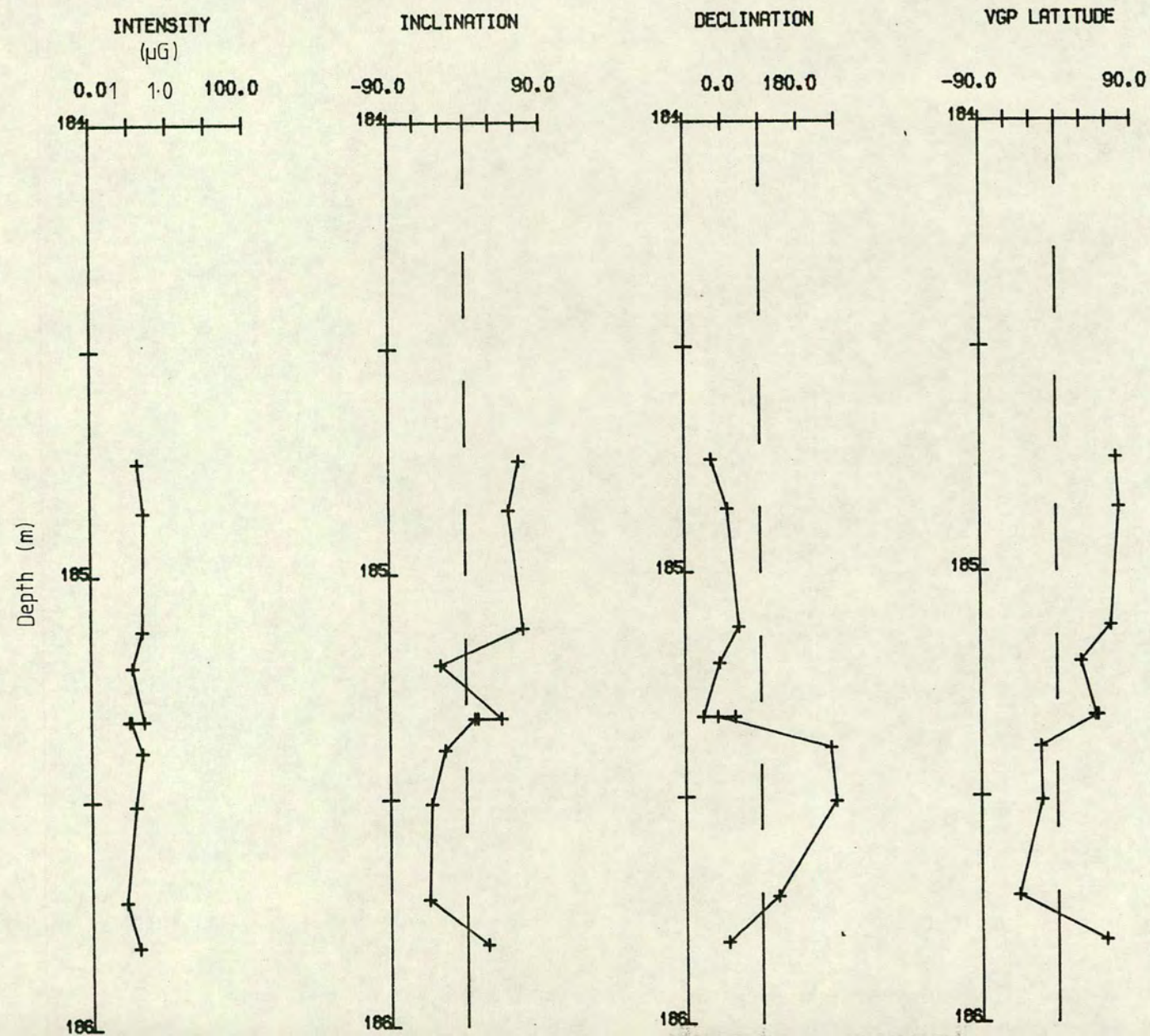


Figure 56 Examples of Pilot Demagnetization from Section E

Figure 57. Results for Section E after Demagnetization



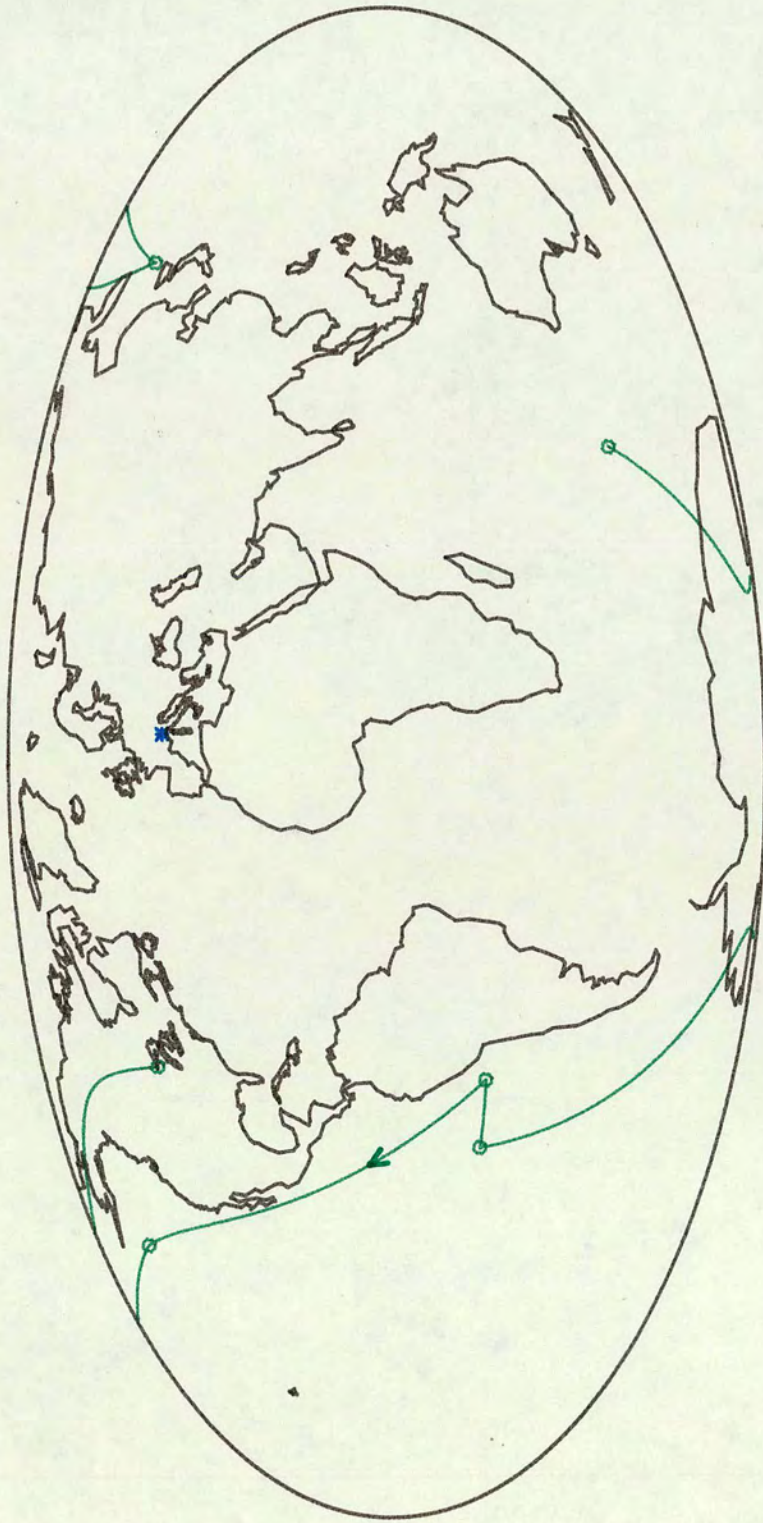


Figure 58 VGP Path for Transition at Section E

GEOLOGY

The River Crostolo flows northeast from the Appennines, 30km east of Stirone, and like that river flows towards the Po. During the past ten years erosion of the valley has cut through recent alluvium to reveal a sequence of about 75m of continental deposits overlying at least 1700m of marine sediments. The continental series crops out between Rivalentella and Puianello, between 5 and 11km south of Reggio Emilia (maps 86 IV NE and NW), with the marine series cropping out further to the south (Figure 59).

The whole succession has been studied by Barbieri and Petrucci (1967). About 1700m of sediment are present in this area dating from the Upper Miocene to the present. At the base of the succession are Messinian gypsum and anhydrite evaporites which indicate shallow water deposition. These are followed by almost 1000m of Pliocene grey-blue clays and silts deposited in a neritic environment. The Calabrian deposits are initially similar to those below, but upwards they represent shallower water, eventually becoming continental. Deposition during the marine series was more or less continuous the deposits can be sub-divided on the basis of foraminifera. The marine series was studied between Puianello and the Vendina confluence (see Figure 60), this interval includes the Calabrian identified by the presence of H. balthica and A. islandica to a depth of 125m. The remaining sediments all belong to the C. inflata zone. The Vendina confluence occurs about 300m above the base of the Piancenzian which Labrecque et al (1977) place in the Gauss below the Mammoth Event.

The close of the marine series is marked by a coastal sand deposit overlain by a gravel layer. The gravel layer consists of pebbles imbricated towards the Appennines, indicating deposition from a

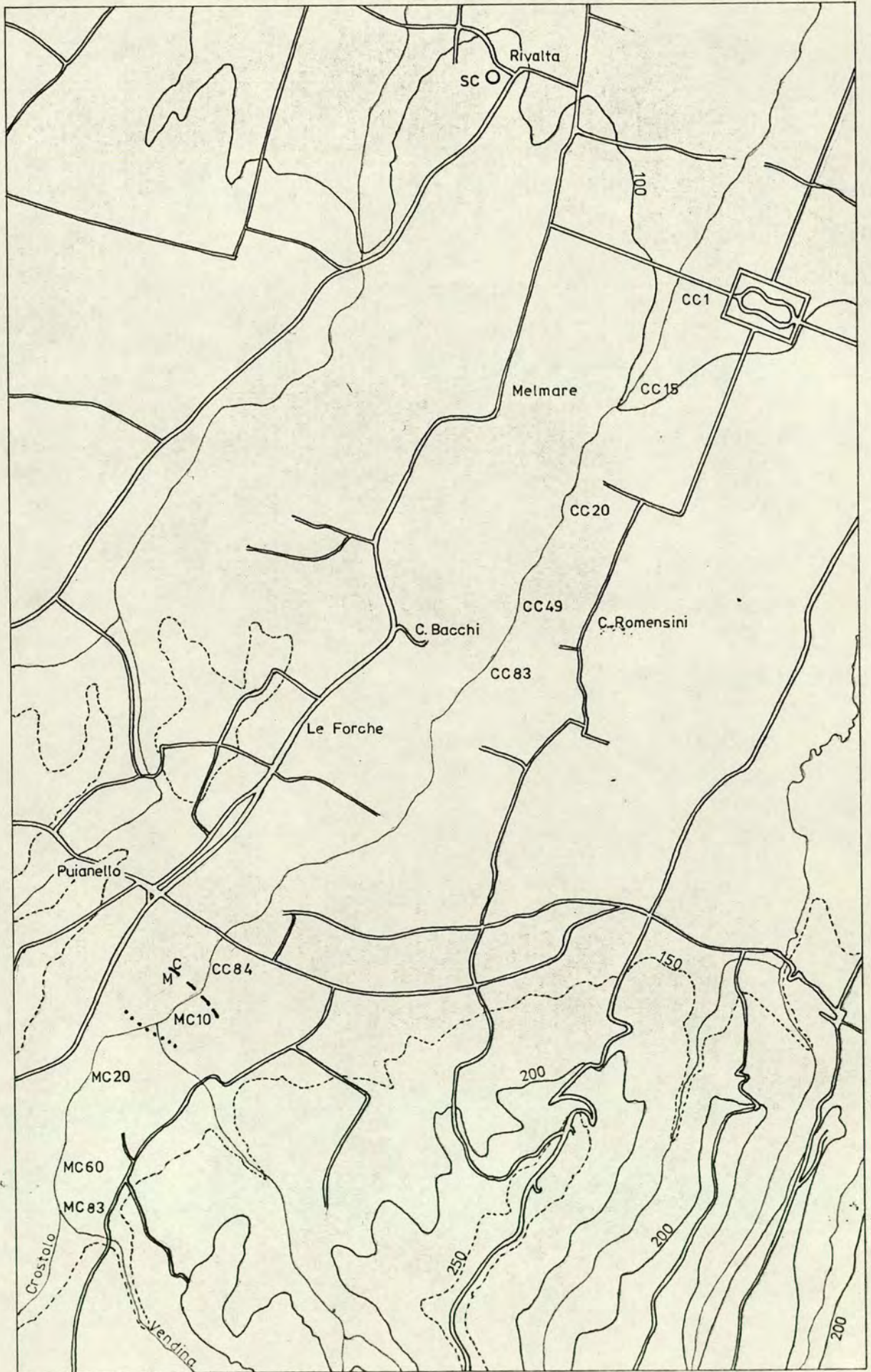


Figure 59 Map of Crostolo with Sampling Sites

500 m

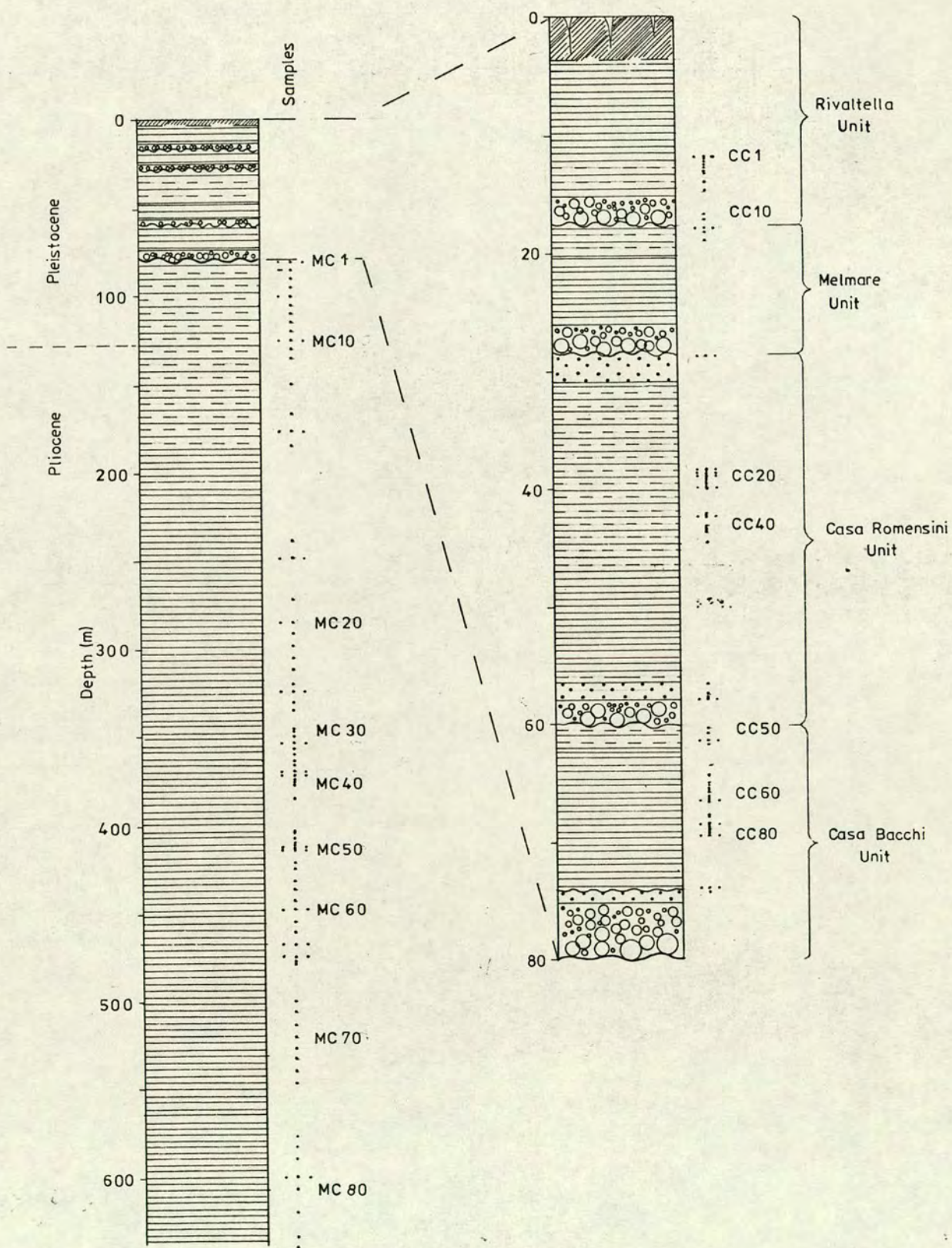


Figure 60. Sedimentary Column for Crostolo with Sampling Levels

river flowing from the hills. Above this four units can be recognised, each separated by an erosional surface (Ambrosetti and Cremaschi, 1976). The first unit (the Casa Bacchi Unit) consists mainly of yellow-brown lacustrine clay in which freshwater molluscs and bones are seen. Above this is a grey-blue clay with sandy lenses. The Casa Romensisi Unit which follows begins with fluvial gravel filling in meander hollows of the erosion surface which terminates the preceding unit. Flood plain channel and bar sand deposits alternate, the flood plain deposits containing organic detritus including tree trunks. These sediments give way to grey-blue freshwater lacustrine clays. This unit is truncated by an erosion surface with meander channels. The Melmare Unit is similar to the preceding unit in that it begins with yellow fluvial sands and gravels before passing upwards into grey-blue lacustrine clays. The uppermost unit, The Rivalentella Unit is wholly fluvial, consisting of bar and channel sands with gravel lenses. A red decalcified palaeosol is formed on gravel at the top of this unit, which can be correlated with other soils belonging to the Mindel-Riss interglacial.

Each unit seems to represent a cycle of drying up of a lake, fluvial deposition, and flooding to form a lake. It is not possible to say whether the cycles represent local tectonism or global climatic variations. Nor is it possible to say whether the cycles represent long periods of time, or isolated intervals.

Study of mammal remains recovered from the deposits suggest that the cycles all belong to the Upper Villafranchian B or zone 5-6 (based on Hippopotamus amphibus and Libralces gallicus). This fauna is considered to be older than 900,000 years (Cremaschi, pers comm.). The Hippopotamus was found at the base of the Casa Bacchi Unit, but the Libralces found in the Rivalentella Unit is probably either reworked or

wrongly identified.

The continental series is folded into an anticline, dipping about 4° towards the north between Le Forche and Rivalentella, and dipping by the same amount to the south between Le Forche and Puianello. The marine sediments are much more steeply dipping, angled at $40-60^\circ$ towards the north, implying the existence of a syncline south of Puianello. The sharp increase in dip may be due to a fault with an Appennine trend beneath the deposits.

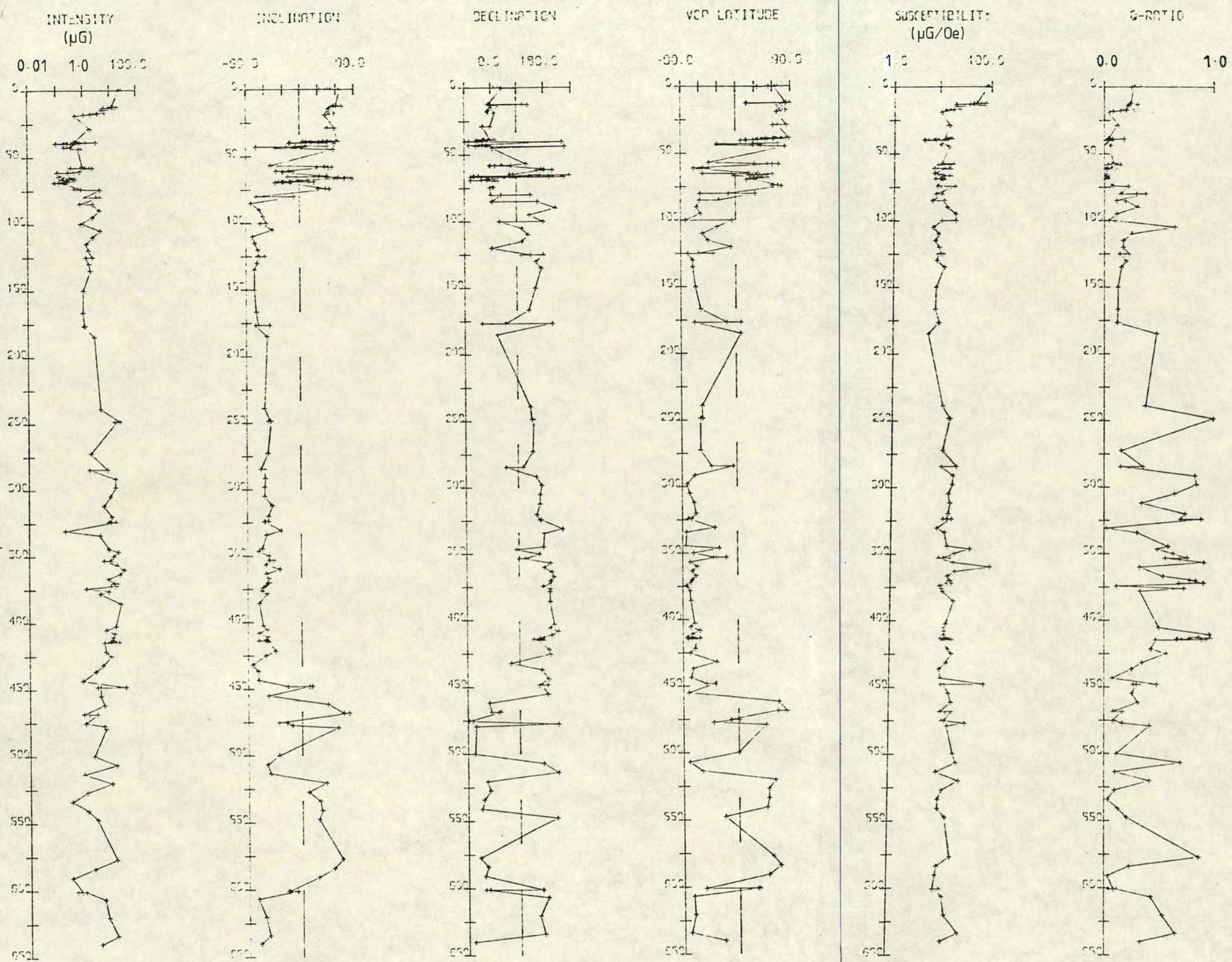
SAMPLING

Recent attempts by local Italian farmers to slow down the erosion of the Crostolo valley have resulted in the construction of a number of dams downstream from Puianello. While being successful in their environmental application, these dams have seriously hindered geological investigation by creating large lakes which have drowned up to 50% of the exposure. It was only possible to sample the continental series in gaps, as shown by the geological column (Figure 60), for example only 3 samples were taken from the Melmare Unit. This, added to the probably intermittent sedimentation, creates difficulties in interpretation. Samples were also taken from the marine series at more regular intervals, along the river bank.

RESULTS

The NRM results for samples from Crostolo are shown in Figure 61. Overall intensity averages $5.07(\pm 6.74)\mu\text{G}$, the marine clays have intensities distributed evenly about this mean; whereas in the continental series there is a gradual decrease from top to bottom. The palaeosol at the top of the Rivalentella Unit has a remanent intensity of about $20\mu\text{G}$, and the rest of this unit has intensities of around $10\mu\text{G}$. The samples from the Melmare Unit are slightly weaker, and the lowest

Figure 61. NRM Results for Crostolo

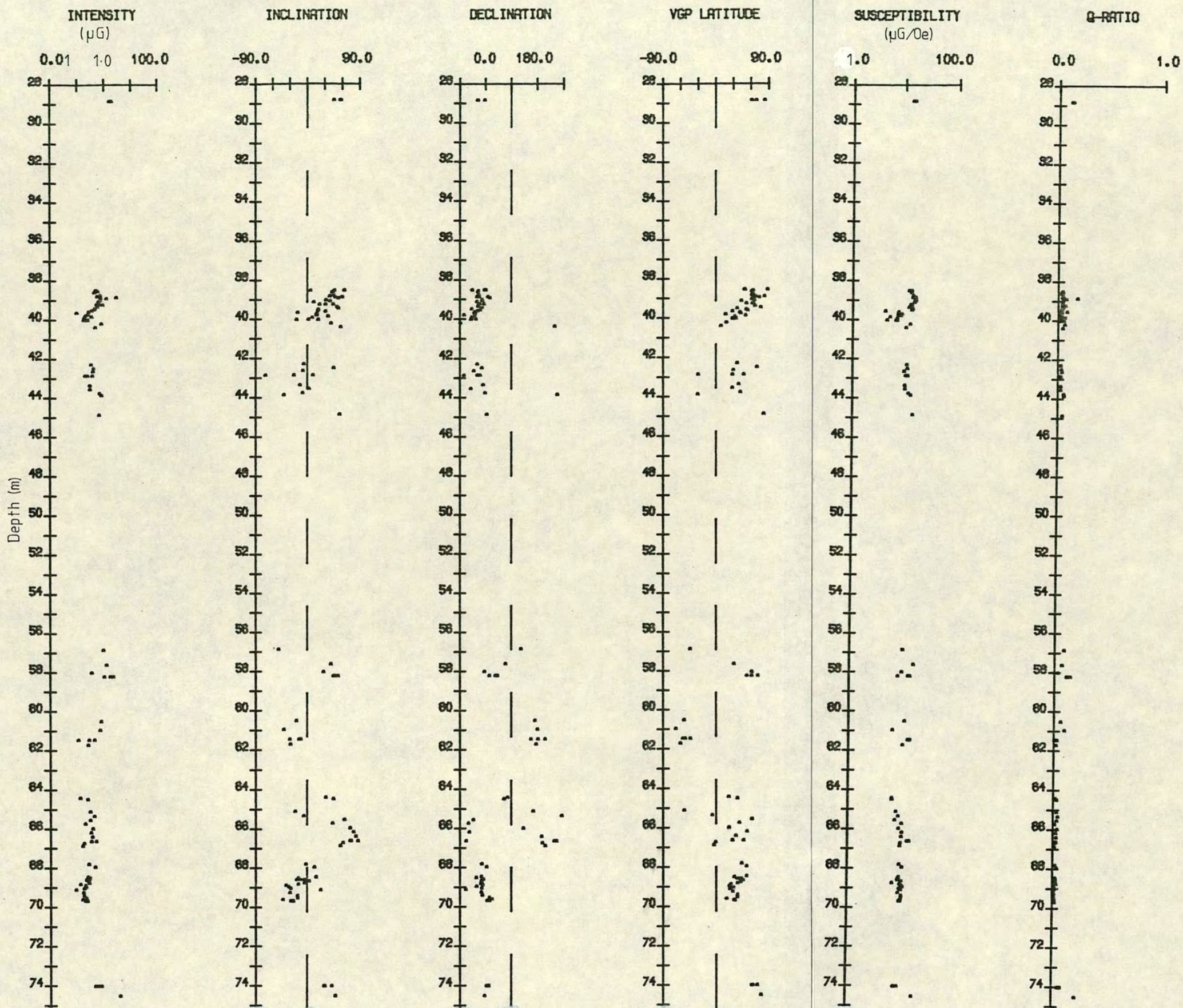


units have an average intensity of between 0.1 and 1.0 μ G. Susceptibility averages 16.74(\pm 15.97) μ G/Oe, with high values in the soil and the Rivalentella Unit (20-60 μ G/Oe), the remainder of the continental series and the marine series being more consistent. Q-ratios are much higher in the marine deposits than in the continental deposits (0.48(\pm 0.34) compared with 0.08(\pm 0.09)), the Rivalentella Unit being slightly higher than the other continental sediments (0.20 to 0.25).

Directions are normal in the upper two units of the continental series, although two samples at 12.40 and 12.70m have easterly declinations. The lower two units of the continental series are much more complex, these are shown in detail in Figure 62. Declination in the Casa Romensini Unit is mainly northerly, apart from two isolated samples. Six samples at the bottom of the unit show declination of between 0 and 120°. Inclination is normal at the top of this unit, but between 33 and 44m shows signs of reversing. There is a large amount of scatter in this interval, VGP latitudes are mainly between 0° and 30°N. Of the six samples at the base of this unit, the uppermost has negative inclination, giving a VGP latitude of 45°S, but the others are normal. In the Casa Bacchi Unit, the uppermost samples between 60.50m and 61.71m are reversed albeit with low inclinations (-10° to 40°), nevertheless giving VGP latitudes of around 60°S. Below these samples there is an interval with much variation in declination, and largely normal inclination down to 66.86m, then an interval of northerly declination and inclination between 0° and 30°S, both giving VGP latitudes of around 30°N. Finally at 74m four normal samples occur with VGPs of 60° to 70°N.

The marine series has reversed polarity down to about 460m, with a larger degree of variation at the top of the series, mainly in declination. Between 460m and the bottom of the section there are two

Figure 62. Detailed NRM Results for the Interval 28-75m



wide normal zones: 460m to 507m and 514m to 591m, separated by a short reversed interval. Both normal zones are split by samples that give equatorial VGPs.

Examples of pilot demagnetization are shown in Figure 63. Samples from the top two units, and also from the upper part of the third unit of the continental series, all show of stability (CC5: Rivalentella Unit, 12.80m; CC12': Melmare Unit, 17.72m; CC17': Casa Romensisi Unit, 38.75m). Median destructive fields for these samples are low, ranging from 80 to 150 Oe. The majority of the remaining continental samples are weakly magnetized, and as a result show much variation with demagnetization. Median destructive fields are often less than 100 Oe, so intensity falls below the noise of the magnetometer at higher fields. Samples between 39.10 and 39.78m change from normal to reversed inclinations with demagnetization (e.g. CC25: 39.48m). Below this samples are only stable at low fields, and often show much variation about the NRM direction, which may be close to the initial stable direction, (CC47 and CC50: Casa Romensisi Unit at 57.60 and 60.50m; CC61: Casa Bacchi Unit: 66.16m). Below 68m the three samples that were demagnetized stepwise proved to be unstable.

The majority of samples from the marine series were very stable, with median destructive fields of over 300 Oe (MC18': 127.50m, MC80: 425.2m). Samples from the soil of Rivalentella also showed little change with demagnetization, median destructive fields were between 200 and 280 Oe, although unlike the marine samples, these were still stable at 600 Oe; (e.g. SC4: 62cm).

Samples were demagnetized at 150 Oe, apart from the samples in the Casa Romensini and Casa Bacchi Units of the continental series (CC16 onwards), which were demagnetized at 100 Oe. Results are shown in Figure 64, with the detail of the lower units of the continental section

Figure 63. Examples of Pilot Demagnetization
from Crostolo

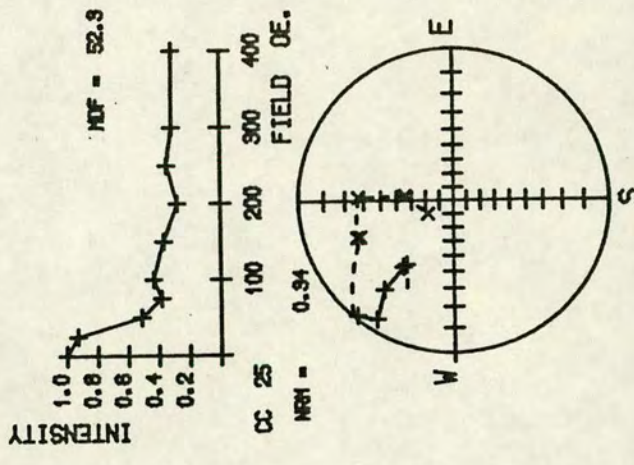
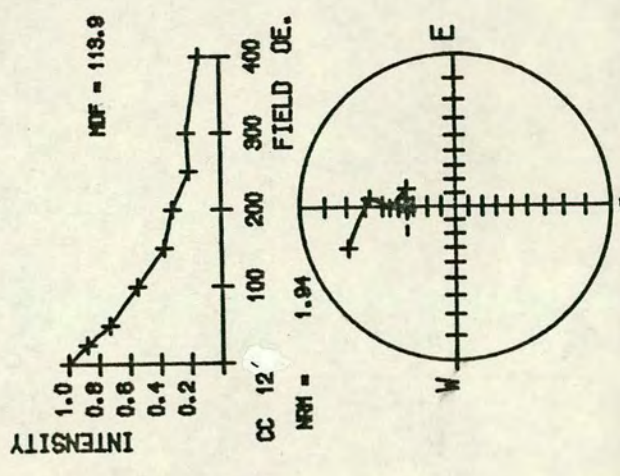
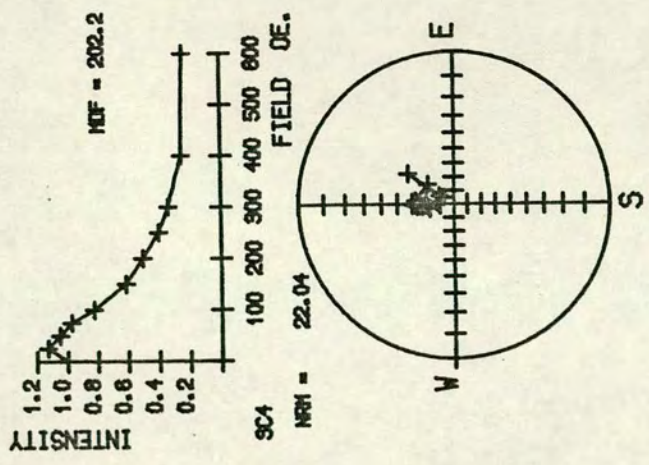
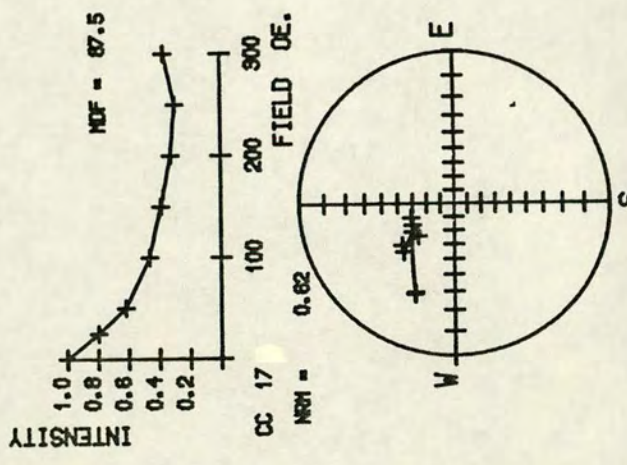
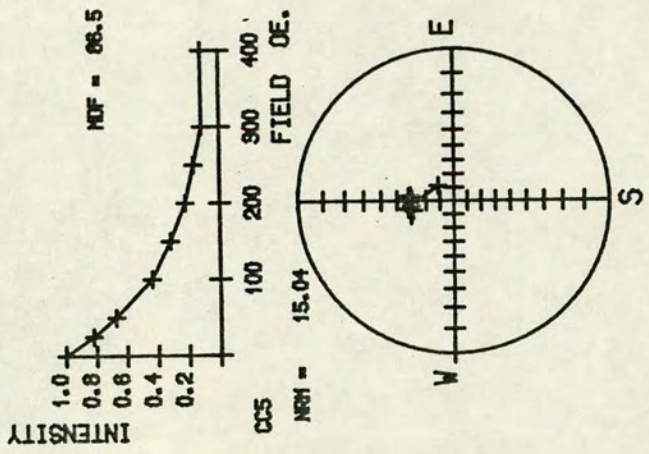
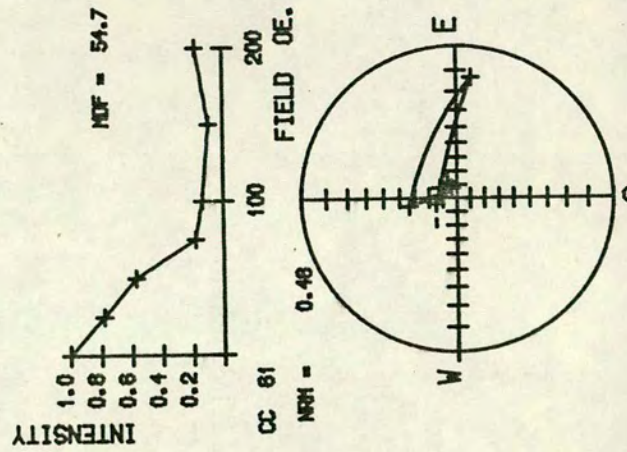
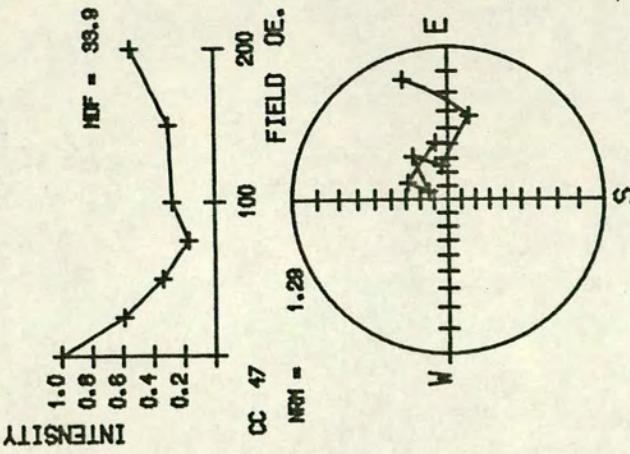
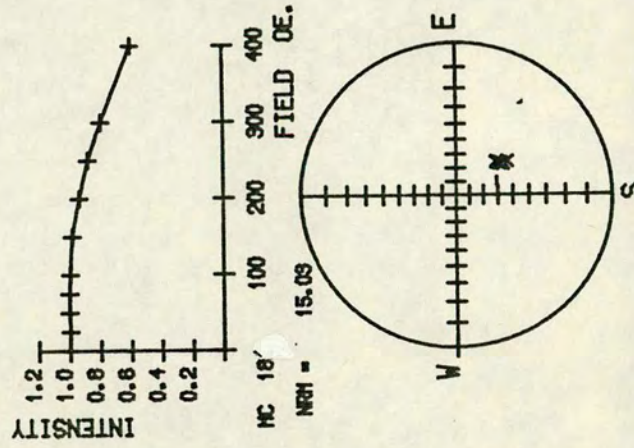
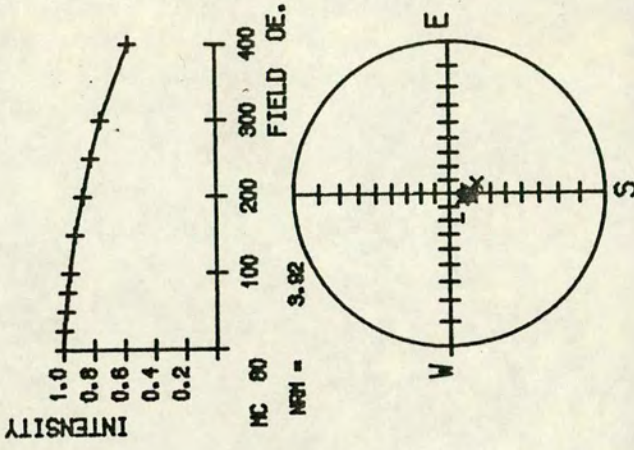
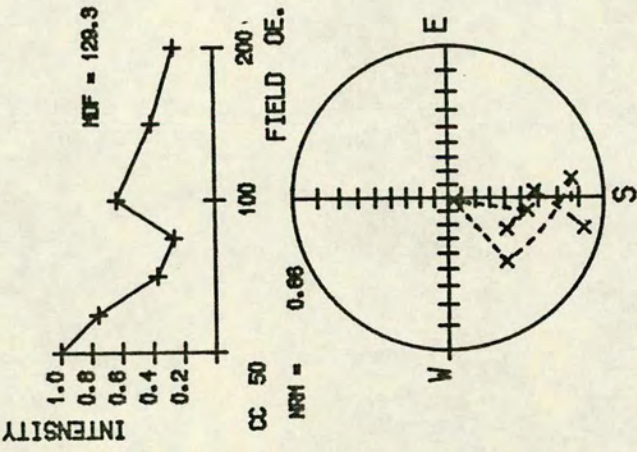


Figure 63, continued



in Figure 65. Overall intensity drops by about 45% to $2.76 \pm 6.05 \mu\text{G}$. The marine series shows the smallest decrease, although isolated samples lose more than half of their intensity. The continental series as a whole shows a large decrease in intensity. The upper two units of the continental deposits remain normal, but one sample at 19.05m has low inclination, and another at 12.70m has declination of 125° . The apparent reversal in the Casa Romensini Unit is more strongly emphasized, as negative inclination increases in some samples, and southerly declination is also seen. VGPs reach a maximum of 35°S . At the bottom of this unit there are two samples which were demagnetized stepwise and show moderately stable normal directions, although with easterly declination. Another sample just above retains a reversed direction. The reversed interval at the top of the Casa Bacchi Unit remains after demagnetization; however the samples below this show an increased amount of variation. Only four samples with relatively high intensity at 74m are stable and normal. When the samples with unstable demagnetization paths and remanent intensities of less than $0.1 \mu\text{G}$ are removed from the interval between 62 and 70m this interval still shows much variety. In this interval only sample CC61 (66.16m) was moderately stable giving a normal direction.

Samples in the marine series do not show much change after demagnetization, however some of the anomalous samples (but not all) at the top of this part of the section become fully reversed. The large normal intervals remain, each split by samples with intermediate VGPs.

TRANSITIONS

Many transitions are seen at Crostolo, however none are recorded with any great accuracy. Sampling was not dense enough in the lower part of the marine section, although two intermediate poles in the

Figure 64. Blanket Demagnetization of all samples

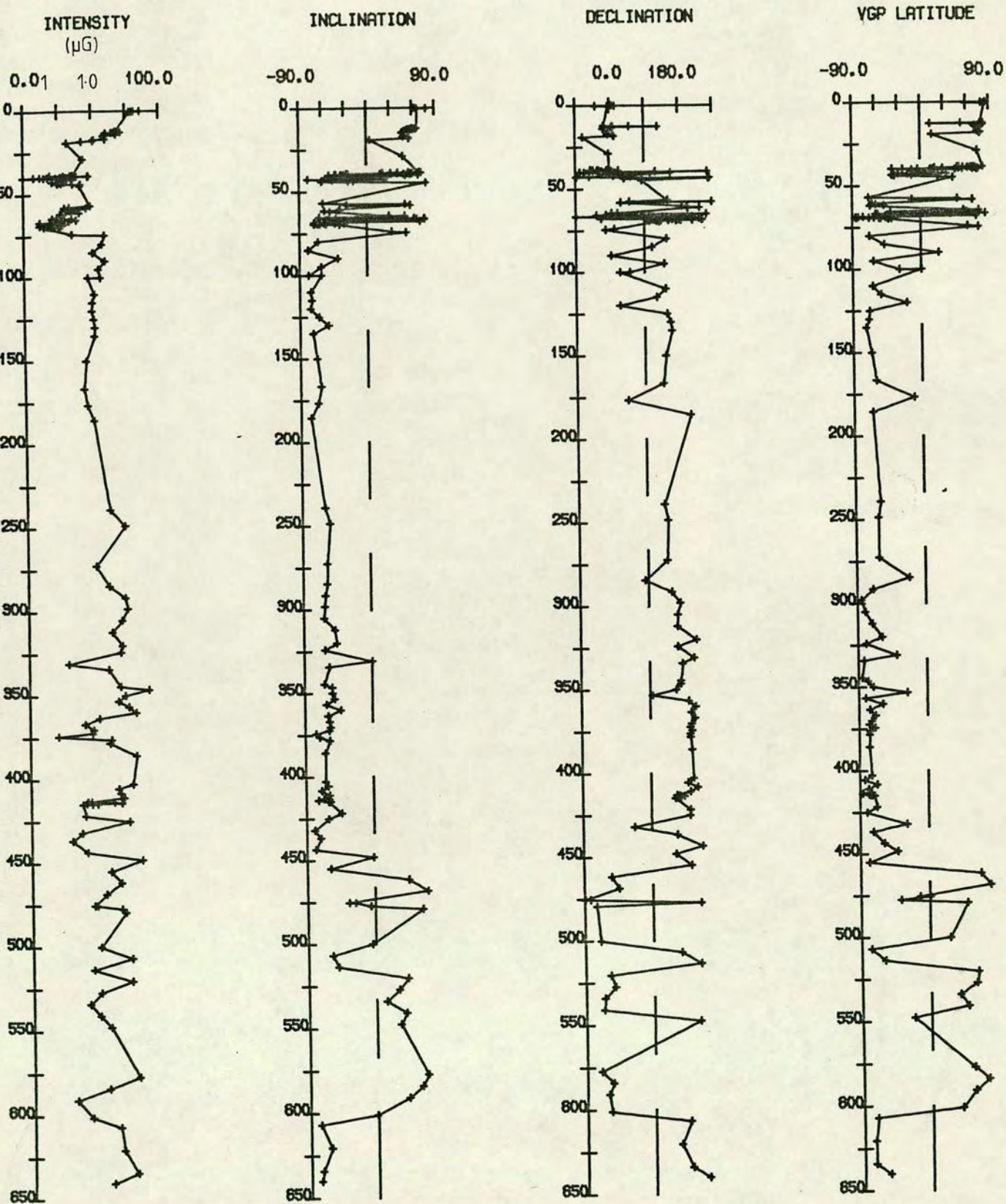
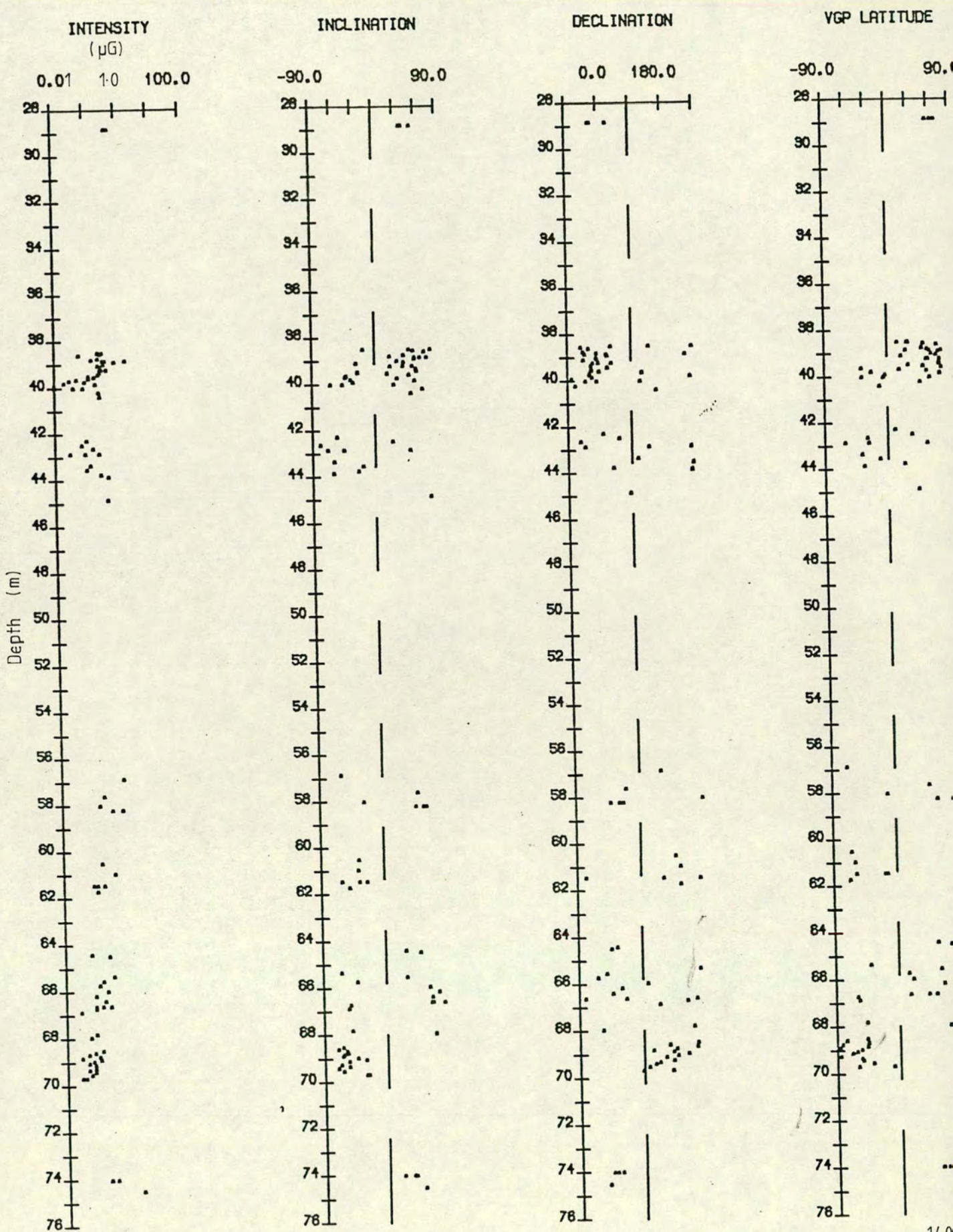


Figure 65 Detailed Results for 28-76m after Demagnetization



oldest transition seen give a path through the eastern Pacific. This reversed to normal transition may be the Upper Mammoth boundary (Figure 66). At the base of the continental series low intensities cause scattered results giving a confused picture.

It would appear that at 40m to 44m there is part of a transition recorded in sediments with intensities of over $0.1\mu\text{G}$. These are clays and silty clays with no sign of any breaks. Inclination becomes reversed below 41m, however declination is scattered between 90° and 270° . This is the youngest indication of reversed directions seen at Crostolo, however much of the sediment above was not sampled. All of the poles in this interval are shown in Figure 67, many occur in the eastern Pacific, between 90° and 180° west of the site. Smoothed directions for this transition are shown in Figure 68. The VGPs reach a maximum southerly latitude of 45° at 43m. Both above and below this depth the latitude of the pole becomes more northerly, however for the most part the paths are confined to the far-side, although poles drift across Europe to North America above the 'transition'.



Figure 66. Upper Mammoth (?) Transition

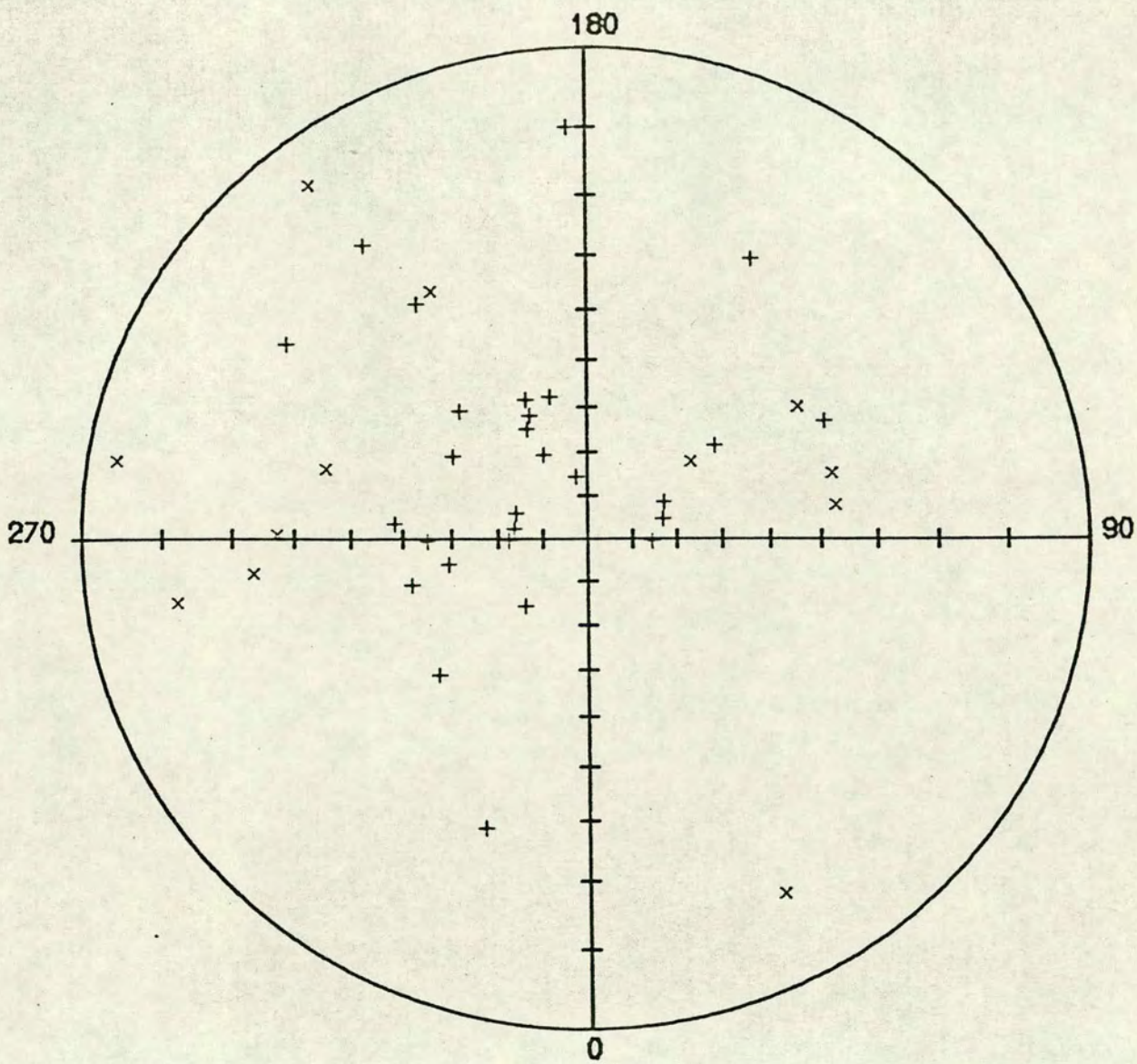


Figure 67. All Intermediate Poles at 39-44m

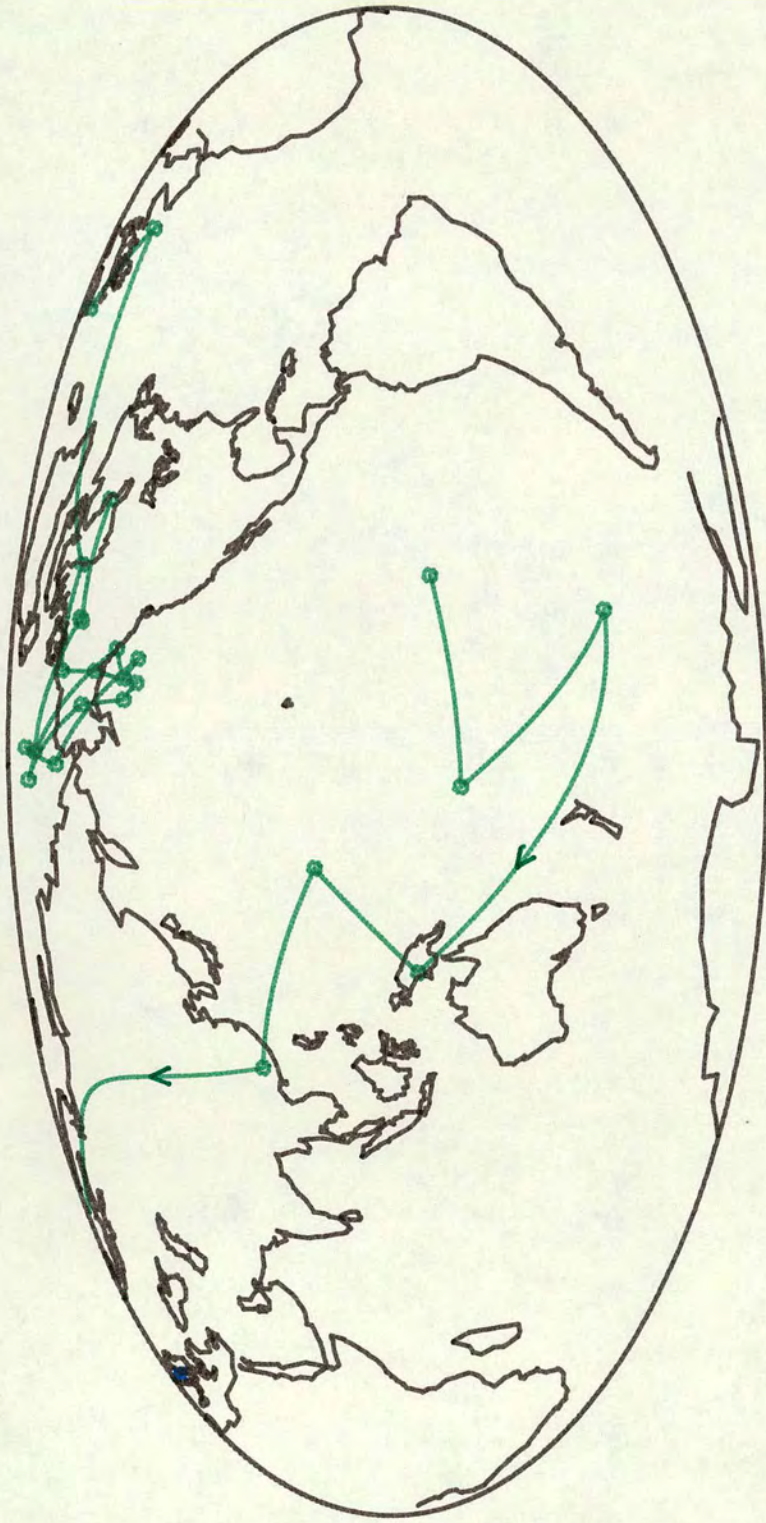


Figure 68. VGP Path for Transition at 39-44m

PART III TIEPIDO

GEOLOGY

The Tiepido river is a left bank tributary of the Panaro river which itself is a tributary of the Po, both rivers flowing northeast from the Appennines. The sediments exposed in the Tiepido valley were deposited in the same sedimentary basin as those of Stirone, Crostolo, and Panaro. Recently accelerated erosion over the past ten years has removed the overlying alluvial deposits and exposed older sediments along a 3.5km section between Torre Maina (c. PQ 492293) and Pozza bridge (PQ 510321), approximately 15km south of Modena (Map 36 I S.E., Formigine): Figure 69. The section can be divided into a marine series and a continental series, similar to those seen at Crostolo (30km to the west) and at Stirone (80km to the northwest). The following geological description is based on the work of Annovi et al (1979), see Figure 70.

The Marine Series.

Almost 700m of lower Pleistocene marine clays are seen in the Tiepido area, although the lowermost 80m are not exposed in the river section. The base of the series is represented by 20-30m of transgressive sands and gravels with shell breccia, deposited unconformably on a pre-Pliocene basement. These are followed by approximately 670m of calcareous grey-blue siltose clays. The beds are often massive and devoid of structure due to the remarkable lithological homogeneity and to the intense effects of bioturbation, traces of which remain in the form of silt-filled burrows. Occasionally silt laminae are seen, usually with gradual contacts above and below, however in some instances the lower contact is sharp with ripple structures. These layers contain an abundant mollusc fauna, often represented by broken

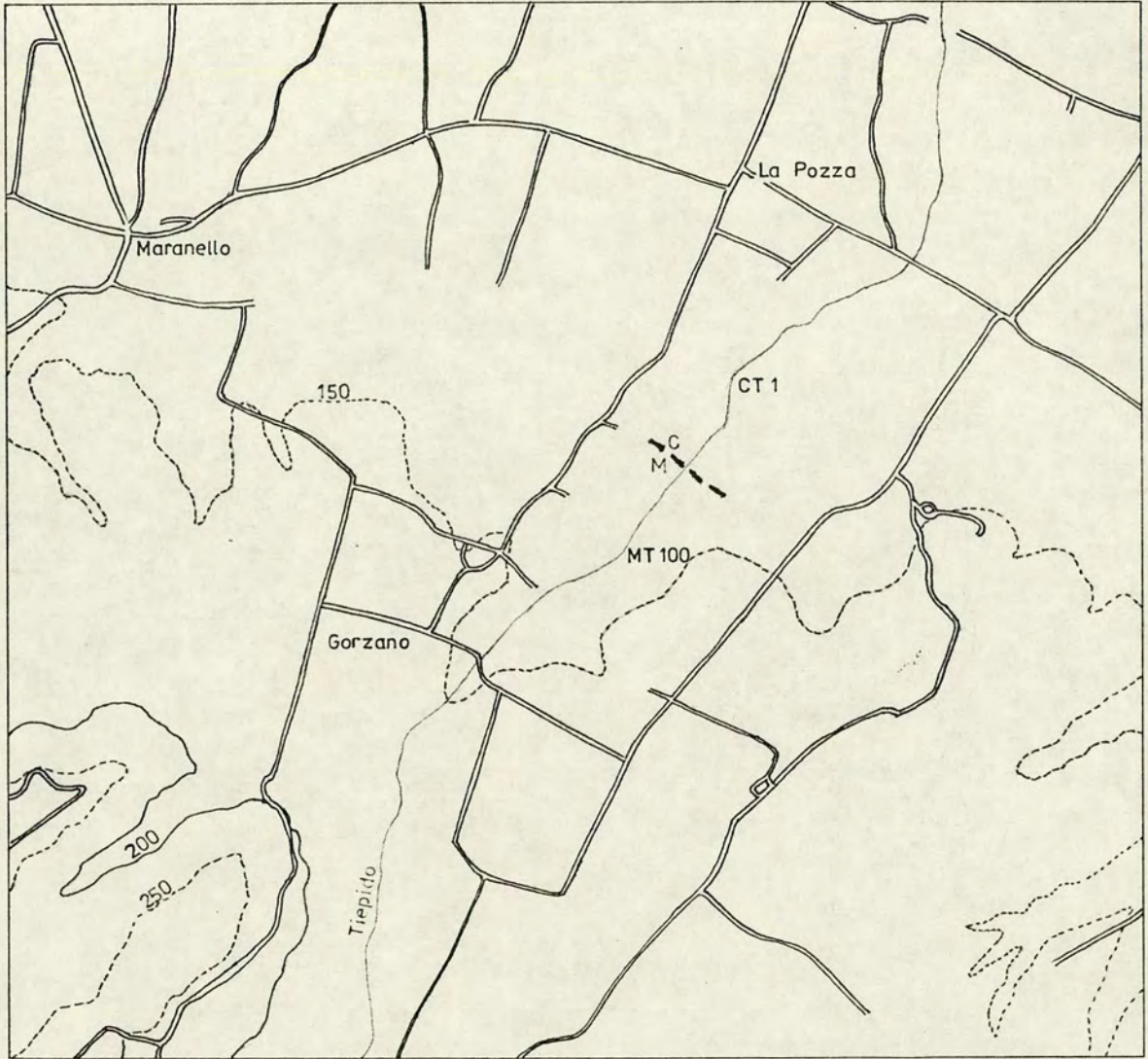
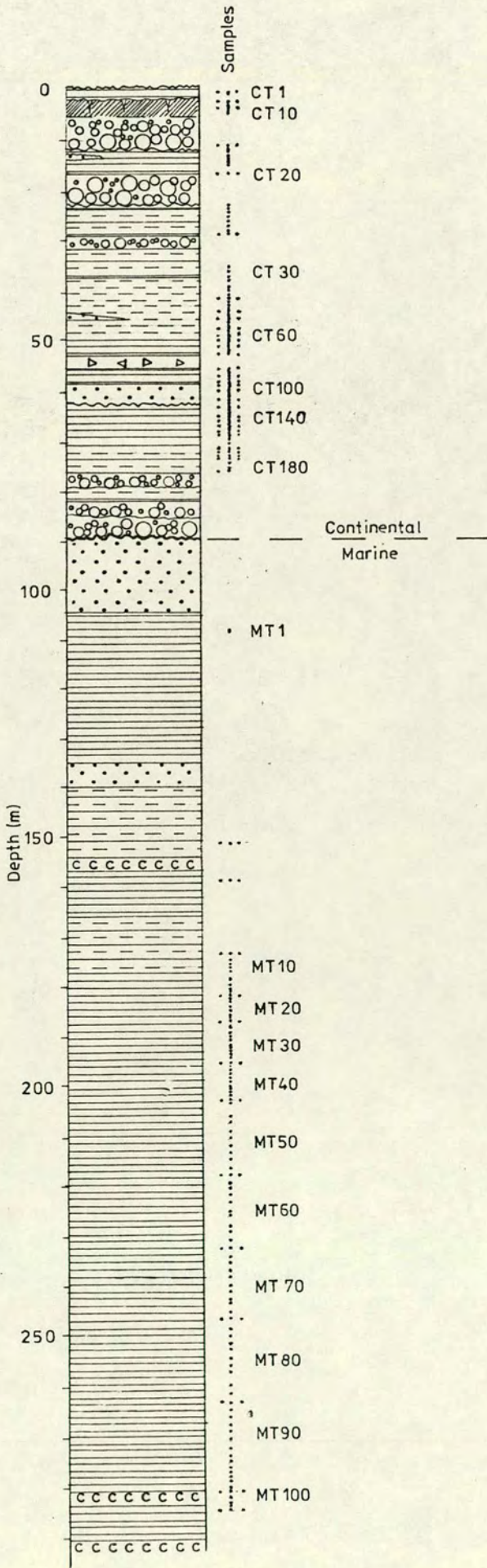


Figure 69. Map of the Tiepido Valley 500m

Figure 70. Sedimentary Column for Tiepido with Sampling Levels



shells. The environment of deposition was a protected platform, the sea closed to the south by the Appennines, and to the north by a chain of barely emerged islands. The high rate of accumulation (almost 700m in approximately 1 million years) shows that sedimentation was almost perfectly compensated by subsidence.

The marine clays contain abundant well preserved foraminifera which can be used to determine the age of the deposits, and the environment of deposition. All of the foraminifera found in the marine series indicate a Lower Pleistocene age. No forms pertaining to the Plio-Pleistocene boundary were seen, although Arctica islandica does not appear until a depth of 625m. Hyalinea balthica first appears 445m below the top of the section, allowing the section to be divided into Zone C, Calabrian or Santernian (or the G. pachyderma zone) below this marker; and Zone D, the Emilian (H. balthica zone) above.

The majority (92%) of the foraminifera are benthonic, or bottom living, comparison of the ratios of forms such as Cassidulina on one hand, and Ammonia and Elphidium on the other allow the relative depth to be determined. Comparison with environments existing in the Mediterranean at present indicate that at all times the marine clay was deposited in a neritic infra-littoral environment, at depths not greater than 70m. There was a gradual decrease in depth with time although at two points (310m and 220m) an increase in depth is seen. The foraminifera also indicate that a climatic deterioration had begun before the first deposits in this series, the start of this deterioration usually coinciding with the Plio-Pleistocene boundary.

Within the marine clays 50m below the top of the series there is a 10m thick yellow sand containing calcareous lenses, fossil lenses and tree trunks several metres long. The sands display ripple structures and represented by a yellow beach sand, 12m thick with a

sharp base which is almost devoid of macrofossils and consists mainly of quartz sand.

The Continental Series.

The 90m of continental deposits follow the marine series after a short hiatus, marked by an erosional surface, however without unconformity. The time represented by the hiatus is shorter than that at Stirone (Cremaschi pers comm.), the transition from neritic environment to beach environment was apparently rapid. The basal continental deposits are gravels with a sandy matrix showing cross lamination. Pebbles within this gravel bed which are of both sandstone and limestone show no current structure, indicating that the deposit was that of a beach. The remaining, mainly fluviatile sediments are varied, consisting of brown and yellow clays with gravel and sand lenses, which form beds in the upper part of the series. The clays are sandy with calcareous concretions, and contain continental mollusc fossils including pulmonate gastropods (in which the mantle cavity is developed as a lung). The clays are occasionally black through organic remains, and rarely there is evidence of a low energy environment such as a pond or lagoon. The gravel lenses have irregular outlines, the bases are erosive contacts, as they are mainly channel fills. The pebbles are imbricated towards the south and southwest, indicating currents from that direction. The source of material was the Appennine formations - the composition is similar to that seen in the river today. The continental series was interrupted many times by periods of non-deposition and erosion. During one of these periods of emergence a palaeosol formed, this is seen 3m from the top of the section. The soil is well developed, although the uppermost layers are missing through erosion. The base of the soil is sharp, possibly representing a faulted contact. The alteration is excessive, giving a red colour,

and suggesting that the climate was warmer than that of today, but with much seasonal variation. A further palaeosol developed on alluvial gravels at the top of the series, which can be correlated with other soils that are overlain by Rissian loess. At Tiepido, therefore, there are two distinct pedogenetic phases preceding the Riss glaciation.

Structure and Relationship with the surrounding area.

The sediments of both series dip towards the northeast, initially at 50° , decreasing in the marine beds to 10° , increasing to 30° at the marine - continental boundary, before becoming horizontal toward the Po plain. The deposits are cut by normal and reversed faults of Appennine trend.

The marine sediments of the Tiepido area become thicker towards the centre of the basin in the north, reaching 1810m in a borehole at Albaretto 20km away. In the Tiepido region the Pleistocene is transgressive on Pre-Pliocene formations. Towards the east, between Villabianca and Panaro, 200m of Upper Pliocene sediments are preserved as a syncline, while to the west the Pleistocene is usually transgressive on Pre-Pliocene sediments, and occasionally on Lower Pliocene sediments.

Outside the area between the Panaro and Secchia rivers the situation changes abruptly, suggesting that the two rivers follow lines of major faults. The Pliocene is well developed both to the east of Panaro and to the west of Secchia indicating that the Tiepido block was relatively uplifted during this time. The thickness of 700m of Lower Pleistocene marine deposits compares with 150m of Calabrian deposits at Crostolo, and 82m at Stirone, both of which lie to the west. Sixty kilometres to the southeast over 1100m of Pleistocene marine sediments are seen at Santerno. The sedimentation rate there-

fore increases from west to east, as does the uniformity of sedimentation. The environment of deposition was generally deeper in Tiepido than at Stirone, so it was not affected by cyclic deposition, except at one point 50m below the top of the marine series, where there was a short period of emergence. The onset of continental sedimentation generally progressed from west to east, and at both Stirone and Tiepido it was preceded by a brief period of emergence. The regression was not accompanied by a major tectonic event at Tiepido as the continental deposits follow with no unconformity. At Stirone there is unconformity, and the interval of non-deposition probably lasted for a longer period of time.

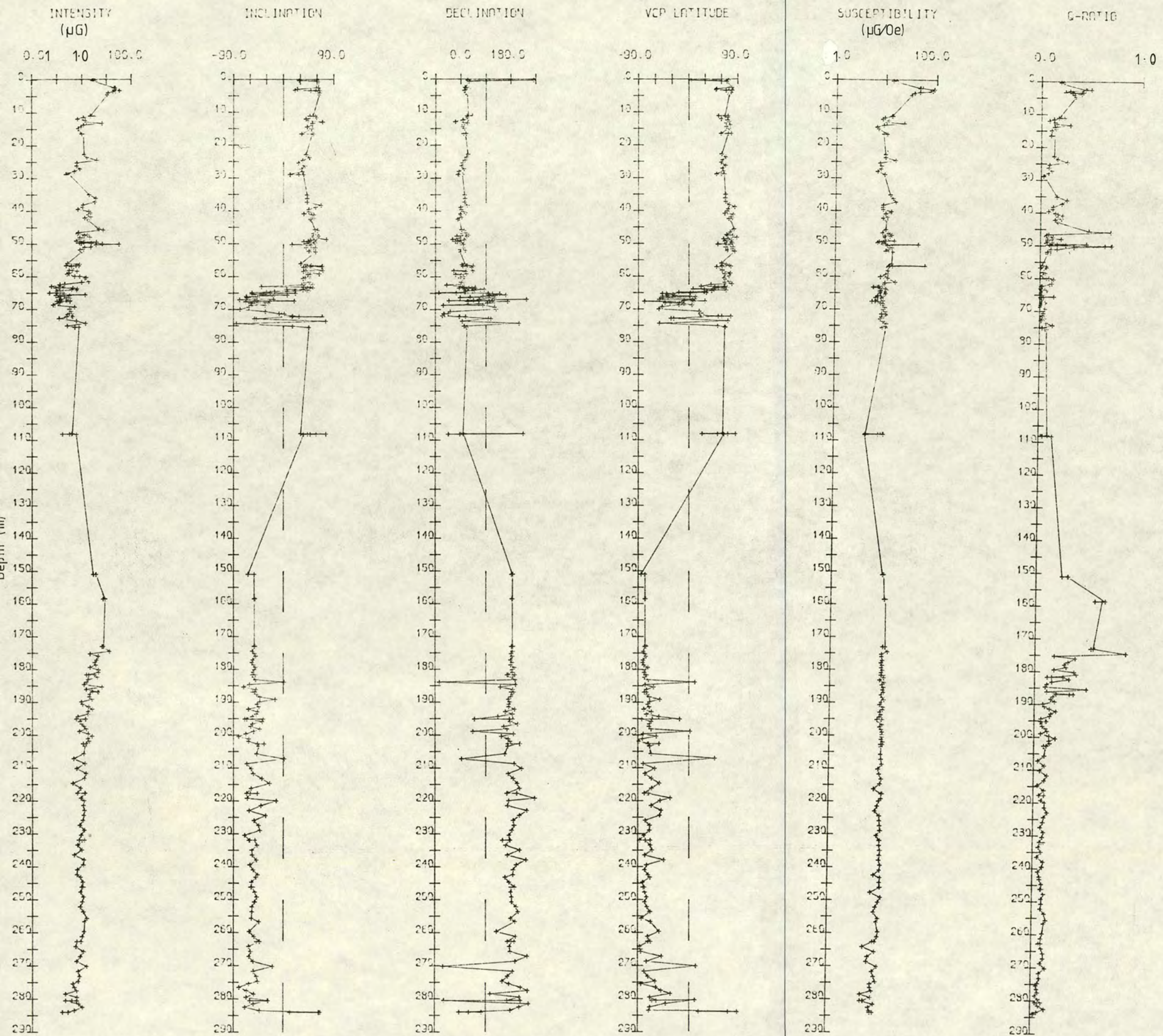
SAMPLING

The whole of the continental series, save for 25m of conglomerate at the top and the uppermost 190m of the marine series were sampled at intervals of 1m where possible. Closer sampling was carried out in the lower part of the continental series, where the Matuyama-Brunhes transition was thought to be. Conglomerates occur in the upper part of the marine series, as well as in the continental series, causing gaps in the sampling. In addition flooding of the river while sampling was in progress prevented a continuous section being obtained.

RESULTS

NRM directions for the whole series are shown in Figure 71, together with intensity, susceptibility and Q-ratio. Intensity averages $1.96(\pm 4.08)\mu\text{G}$ throughout the section, with high values occurring at the top of the continental series in the palaeosol (2.5-5.0m from the top of the sampled section: intensity $20\mu\text{G}$), and also at the top of the marine series between 150m and 180m ($c5\mu\text{G}$). Lower values occur in the bottom 25m of the continental series (0.1 to

Figure 71. NRM Results for Tiepido



0.5 μG) and also towards the bottom of the marine deposits sampled (0.5 μG). Susceptibility is more or less constant in both the marine and continental deposits, averaging $11.82(\pm 9.9) \mu\text{G}/\text{Oe}$, the high standard deviation being due to the high values occurring in the palaeosol (averaging 60 $\mu\text{G}/\text{Oe}$). Thus Q-ratio shows a decrease from top to bottom in both the continental and marine sections.

Most of the samples in the marine series are reversed with inclinations around -55° and declinations around 180° giving high VGP latitudes. The inclination is lower than that expected at this site (-63°) but this may result from inaccurate measurement of dip. Normal samples are seen at the top of the marine series in the interval where sampling was interrupted. Other isolated normal samples occur in the section, but only the lowermost three samples from a shell bed show consistent directions.

The continental samples are normal above 60m, although occasionally inclinations are as low as 30° . The section between 52m and the base of the continental series is shown in detail in Figure 72. An interval of negative inclination occurs between 65m and 70m, although declinations are mainly easterly, averaging 90° giving VGP latitudes of 30°S . The transition above the reversed interval takes place over 2m with some large variations in inclination, the transition at the bottom of the section occurring between 70m and 75m shows variation of up to 180° in both inclination and declination, and hence rapid alternation of northerly and southerly VGP latitudes.

Examples of pilot demagnetization are shown in Figure 73. Due to the low intensities at the bottom of the continental series, comparisons of direction after each demagnetization step are susceptible to instrumental noise. Samples from elsewhere in the Tiepido section are stable, as illustrated by CT1' (35cm) and CT71' (49.91m) in the

Figure 72. Detail of the NRM Results between 52m and 6m

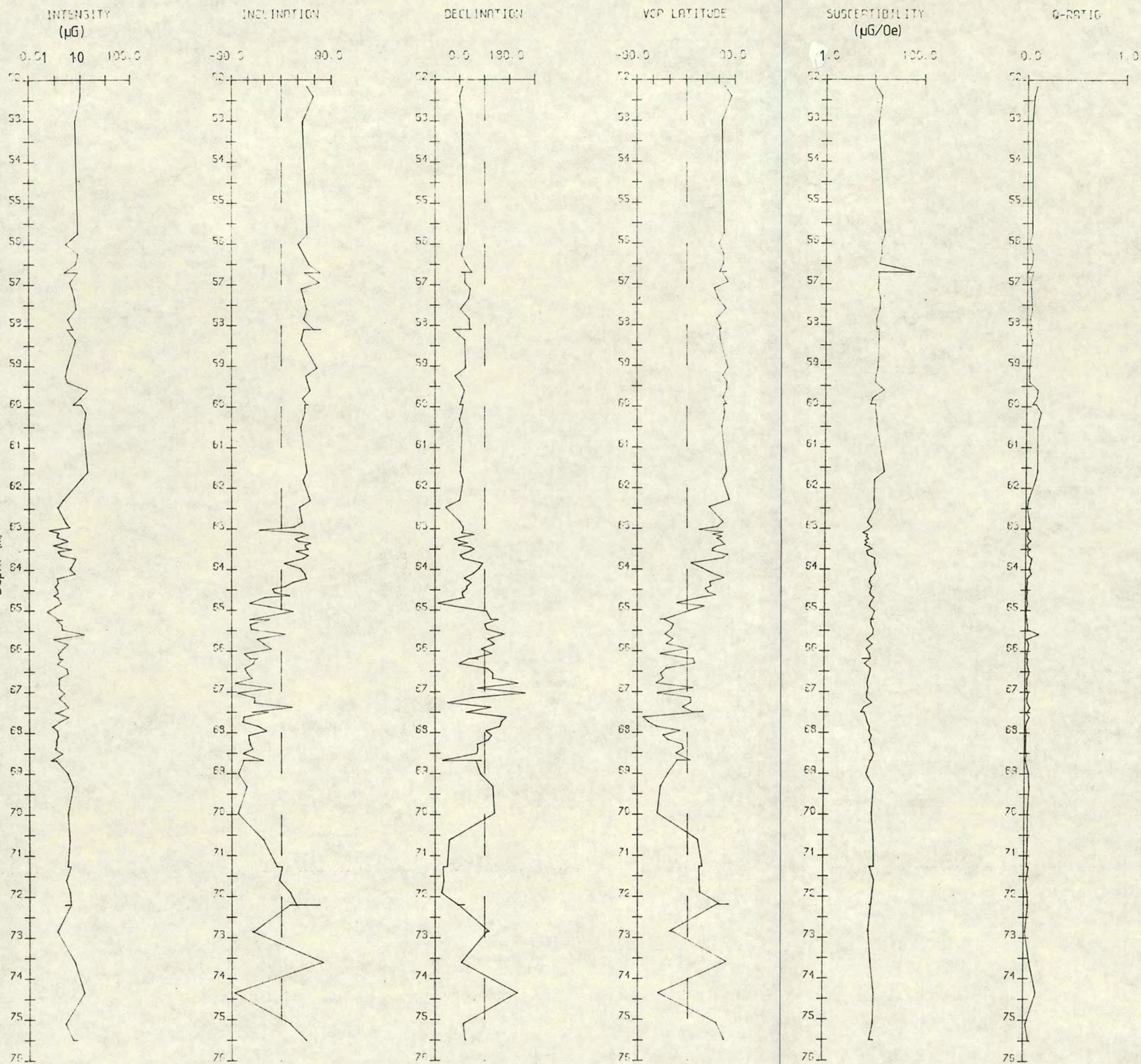


Figure 73. Examples of Demagnetization
from Tiepido

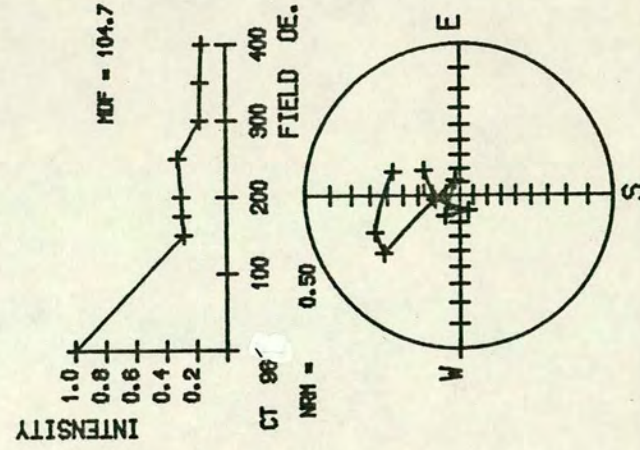
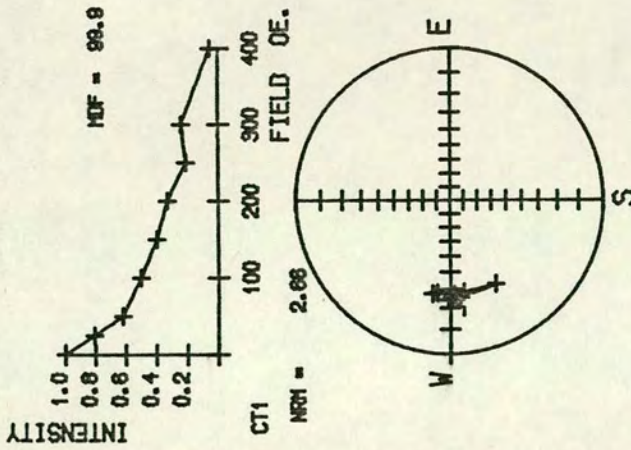
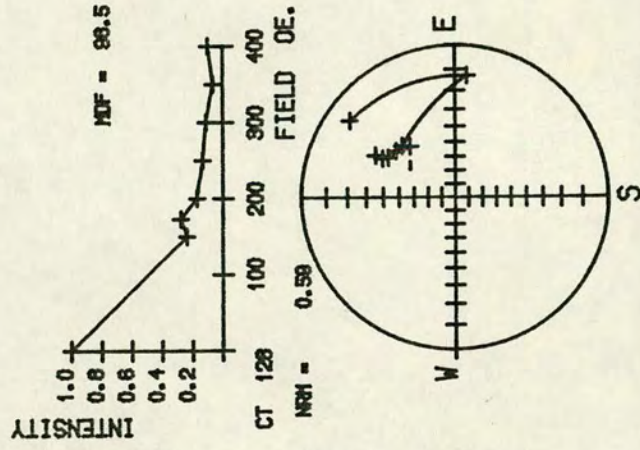
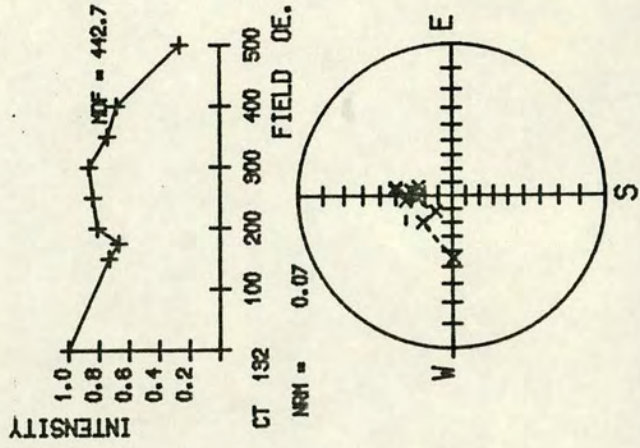
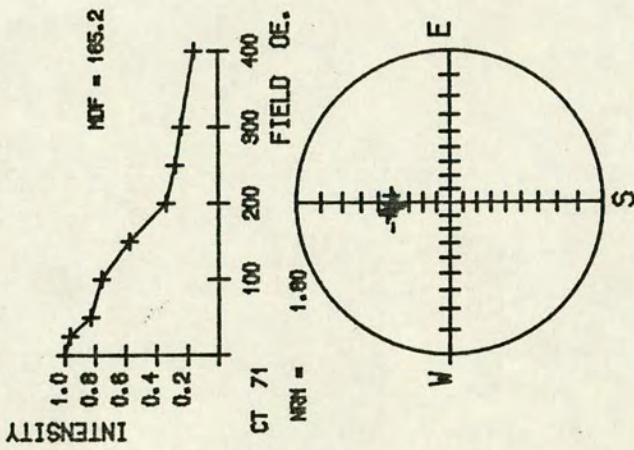
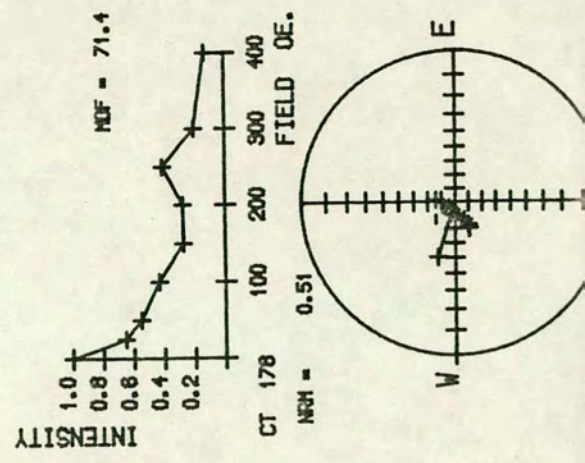
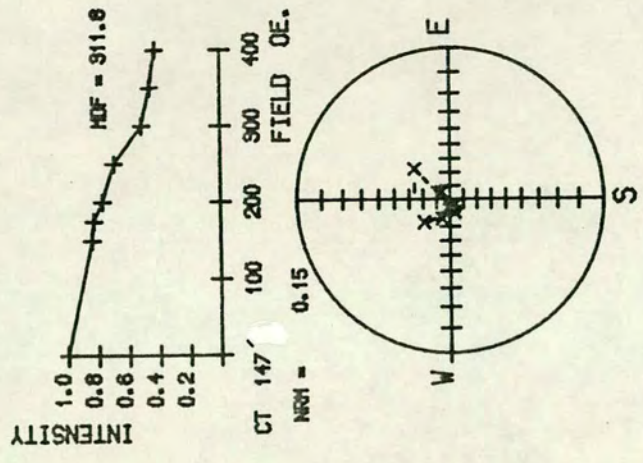
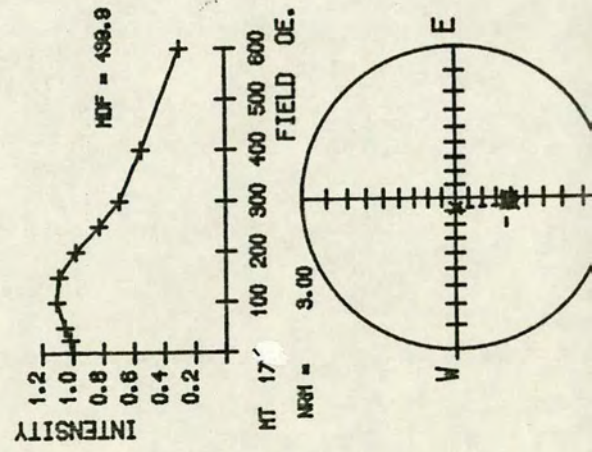
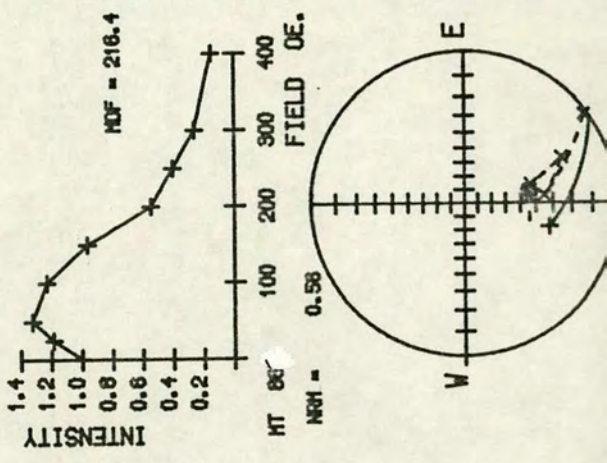
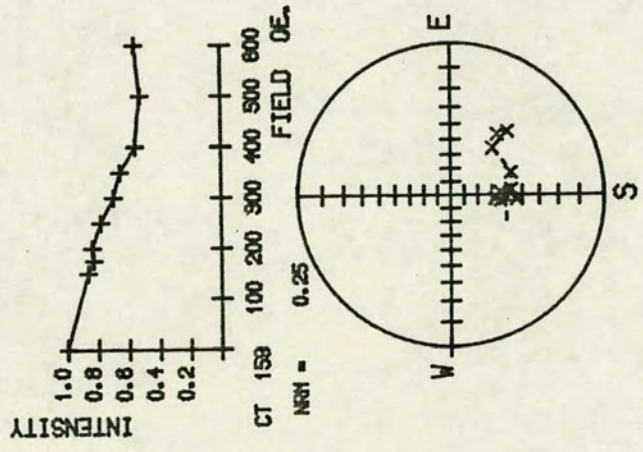


Figure 73 continued



continental series, and MT17' (181.65m) and MT86' (262.70m) in the marine series. These samples have median destructive fields ranging from 90 to 450 Oe, with the marine series being harder, as well as having a normal viscous overprint.

The samples from between 50 and 75m, the most interesting interval palaeomagnetically, show a large amount of random variation, especially at higher fields. Samples such as CT128 (64.10m) and CT178 (73.60m) however record stable normal directions, and samples CT147' (66.19m) and CT159 (67.62m) record stable reversed directions. Samples from within the transitional zone and just above it (CT96': 58.10m and CT132: 64.48m) often show variation of about 40° about a mean direction, probably due to their low intensity. On the other hand some samples can be rejected as unstable. Median destructive fields for these samples vary from less than 100 Oe to over 600 Oe, both this and the variation in stability are reflections of the variation in lithology in this section.

After blanket demagnetization at 150 Oe intensity decreases by 40% to an average of $1.13 \pm 2.05 \mu\text{G}$, however the decrease is much larger in the continental sediments than in the marine clays, the removal of a soft normal component from the reversed marine clays tending to increase intensity. There is little change in direction in the marine series, with directions remaining reversed, and where anomalous samples occurred the normal overprint was usually removed. The normal interval at 98m remains after demagnetization, becoming more consistent, however one of the three normal samples at the bottom of the section becomes reversed, the cone of 95% confidence for these samples after demagnetization has a half angle of over 90° suggesting that this mean direction is not a true reflection of the geomagnetic field.

In the continental series there is a general decrease in inclination, however this is not very large in the upper 50m. The results for the interval between 52m and 75m are shown in Figure 74. Inclination between 52 and 62m has decreased to between 0 and 30° with some southerly declinations between 56 and 58m. This gives average VGP latitudes of 30 to 60°N, with excursions to the southern hemisphere. This large, rapid fluctuation in VGP position suggests that the record is distorted by noise, rather than representing a geomagnetic excursion, the intensity of these samples after demagnetization averages 0.1 μ G.

The directions between 62 and 64m become more reversed with negative inclinations and declinations mainly around 90° but showing a large amount of variation. VGP latitudes for this part of the section are grouped near the equator. Below this declinations become uniformly southerly giving VGP latitudes of 70 to 90°S, confirming that a complete reversal of the field is recorded in these samples. Demagnetization has not been able to clean up the lower transition zone between 70 and 75m, which still involves much fluctuation of the pole.

Alpha 95 values at Tiepido are 20-40° at NRM, rising to 40° to 80° in the reversed interval. With demagnetization these values rise to between 40° and >90° in the reversed interval, as intensity is lowered towards the noise level.

TRANSITIONS

The main transition from reversed to normal polarity between 60m and 66m shows a large amount of variation, however most of the intermediate poles are concentrated in the Pacific as shown by Figure 75, giving a far-sided path. The transition was recorded in clays suggesting more or less constant, uninterrupted deposition.

Figure 74 Detailed Results for 52-76m after Demagnetization

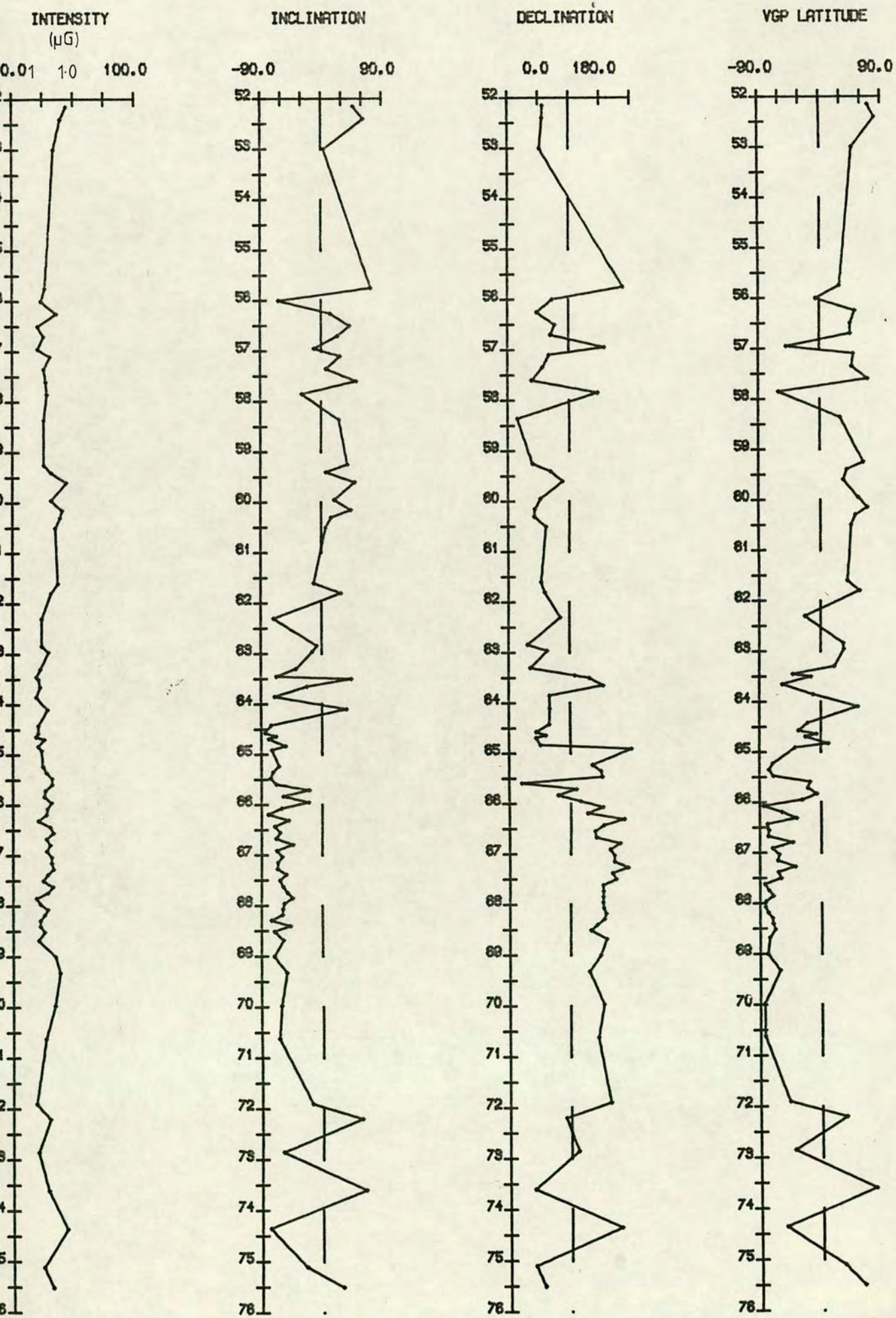


Figure 76 shows a Mollweide Projection for the transition with a running mean of three samples. Samples with unstable demagnetization paths and with intensities of less than $0.05 \mu\text{G}$ have been removed. There appears to be a short excursion to Australia then a large anticlockwise loop encompassing Australia and New Zealand. The actual transition is smoothed to a path confined more or less to the longitudes of 160 to 190°E , although the pole does not become completely normal below the coarser sediments in which the excursion occurs.

The lower transition at 76 to 71m consists of very few samples, widely separated which give scattered results. It is not possible to select a definite transitional path for this interval, however most of the intermediate poles lie in the Pacific region (the far-side). The possible excursion at 57m consists of backwards and forwards motion, mainly across Asia and Europe. The paths are mostly near-sided and cannot be correlated with the excursion at Stirone. The very erratic distribution of poles suggests that the excursion is not real.

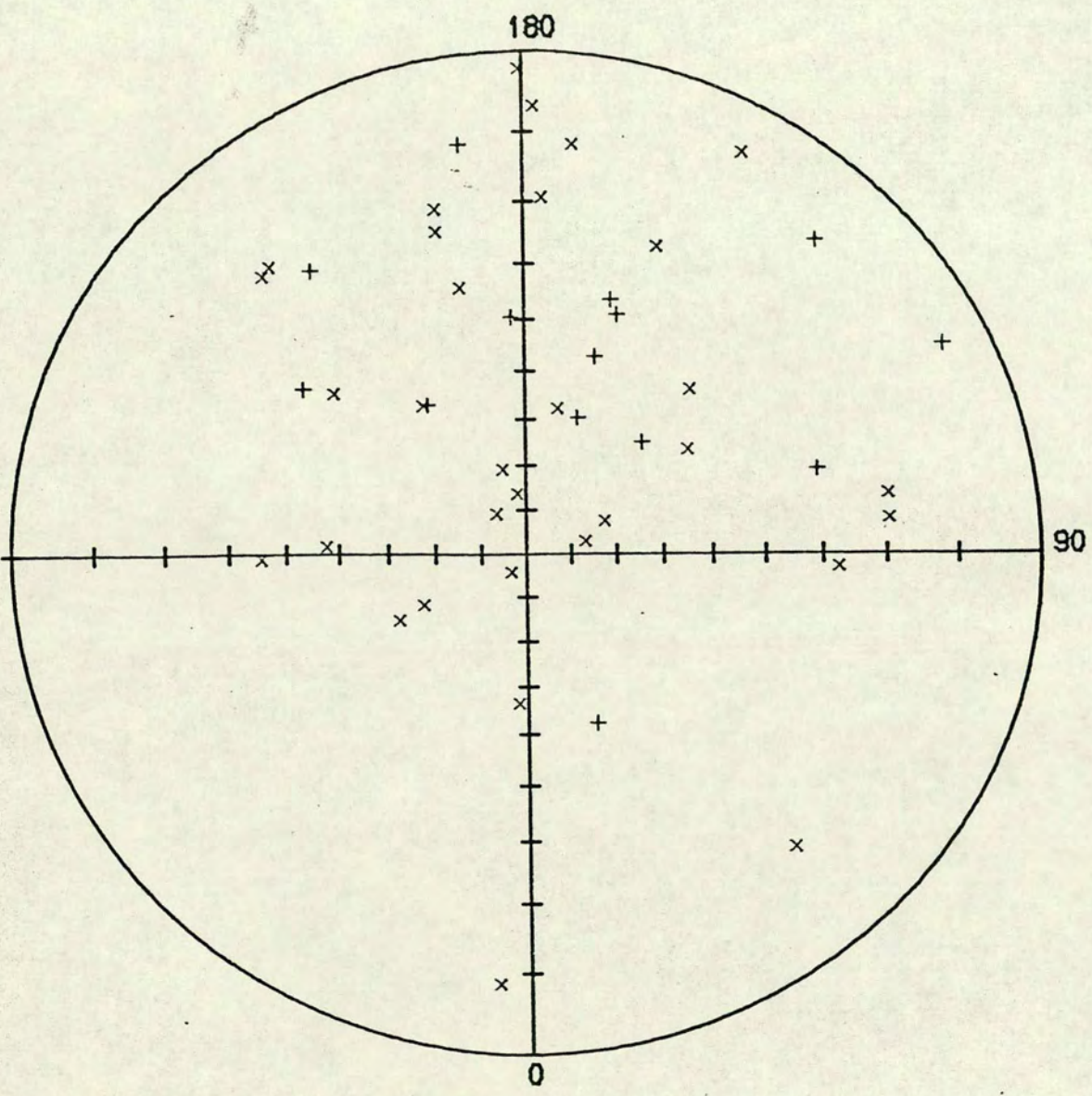


Figure 75. Stereographic Projection of Intermediate Poles

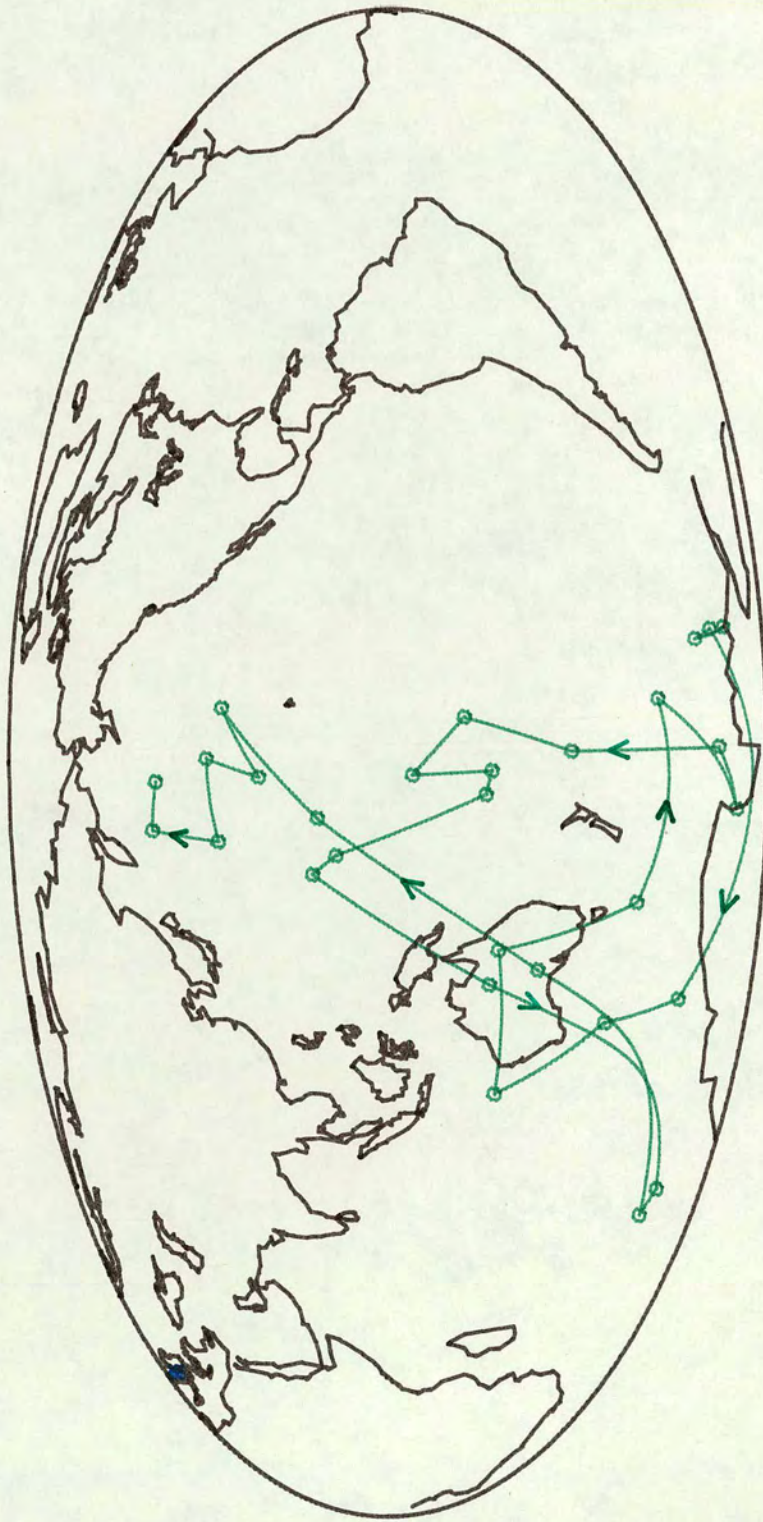


Figure 76. VGP Path for 60 to 65m

PART IV PANARO

The Panaro is one of the larger rivers draining the northern slopes of the Appennines. It is the most easterly of the rivers studied in this area; lying 5km east of Tiepido, 20km east of Crostolo, and 55km east of Stirone. Marine sediments are overlain by continental deposits; the marine sediments are neritic grey clays, and are similar to Tiepido, both sections representing deeper water than Crostolo or Stirone. The top of the marine series is represented by an erosion surface which is overlain by a beach conglomerate. Ten metres of grey alluvial plain clays follow, then a fluvial episode marked by erosion and deposition of sand in channels.

Unfortunately the period of sampling coincided with the start of the rainy season, the river rose by about 3m during the first morning of sampling, so it was only possible to obtain a few samples from either side of the marine-continental boundary (see Figure 77).

RESULTS

NRM results are shown in Figure 78. Intensity averaged $1.89(\pm 2.37)\mu\text{G}$ with higher intensities occurring in the marine deposits (about $5\mu\text{G}$). Susceptibility is more or less constant in both series averaging $11.04(\pm 5.65)\mu\text{G}/\text{Oe}$, giving higher Q-ratios in the marine clays. The marine deposits are clearly reversed, while the continental deposits are mainly normal, but show two independent samples with VGPs in the southern hemisphere, the lower one reaching only 15°S .

Demagnetization proves that all deposits have a stable remanence (CP6: 8.70m and CP11: 18.60m are shown in Figure 79). Median destructive fields for these samples are high: at least 400 Oe.

Demagnetization was carried out at 150 Oe, giving rise to a decrease of about 18% in intensity to $1.55(\pm 2.16)\mu\text{G}$ (Figure 80). The

Figure 77. Sedimentary Column for Panaro with Sampling Levels

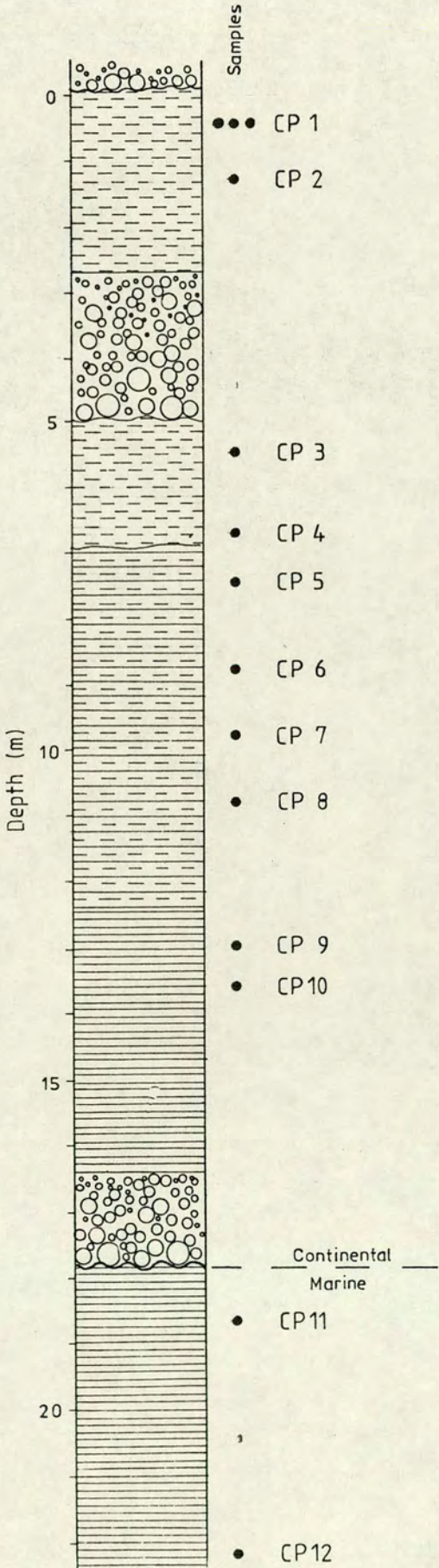
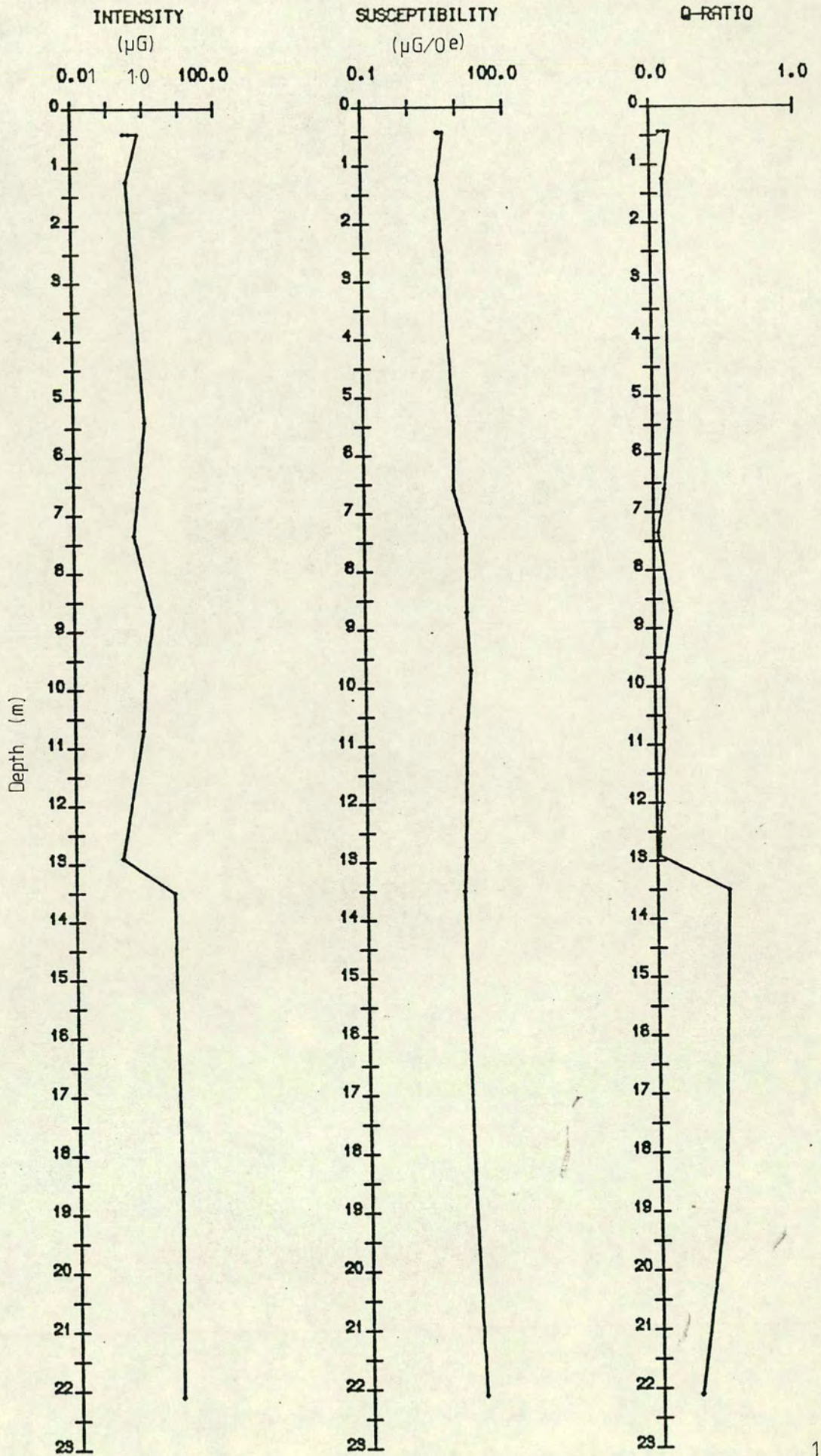


Figure 78 NRM Results for Ponaro



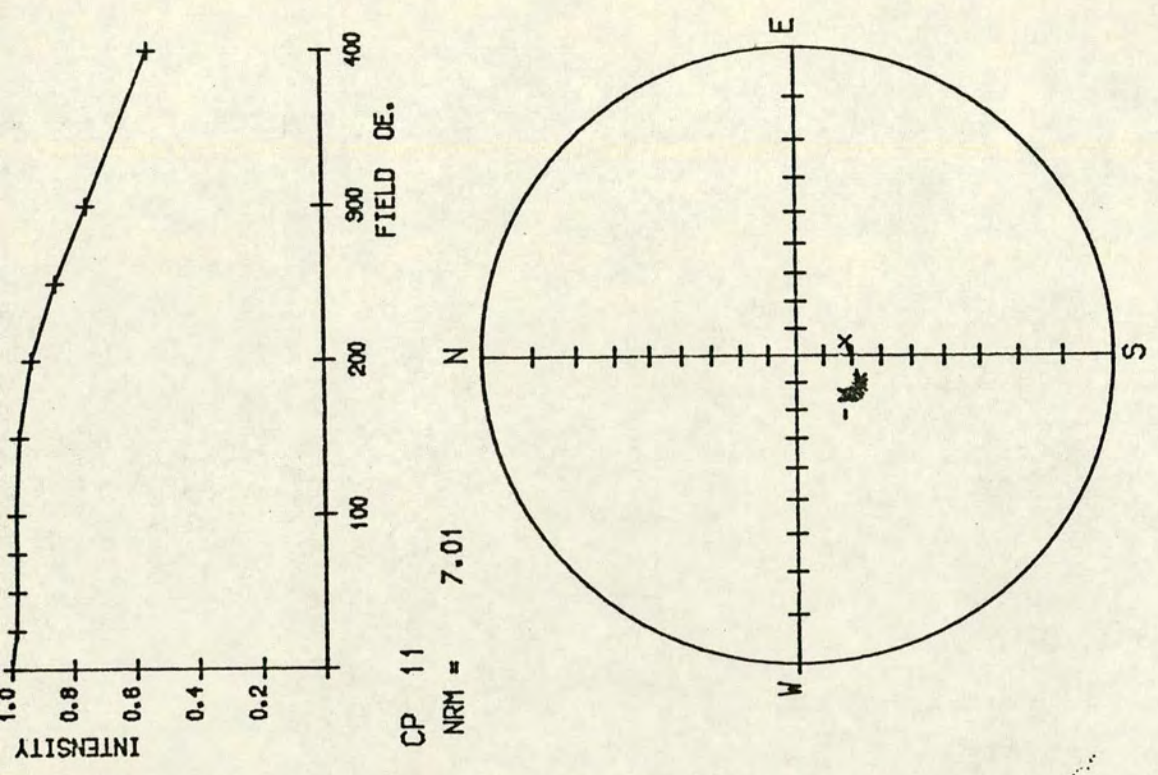
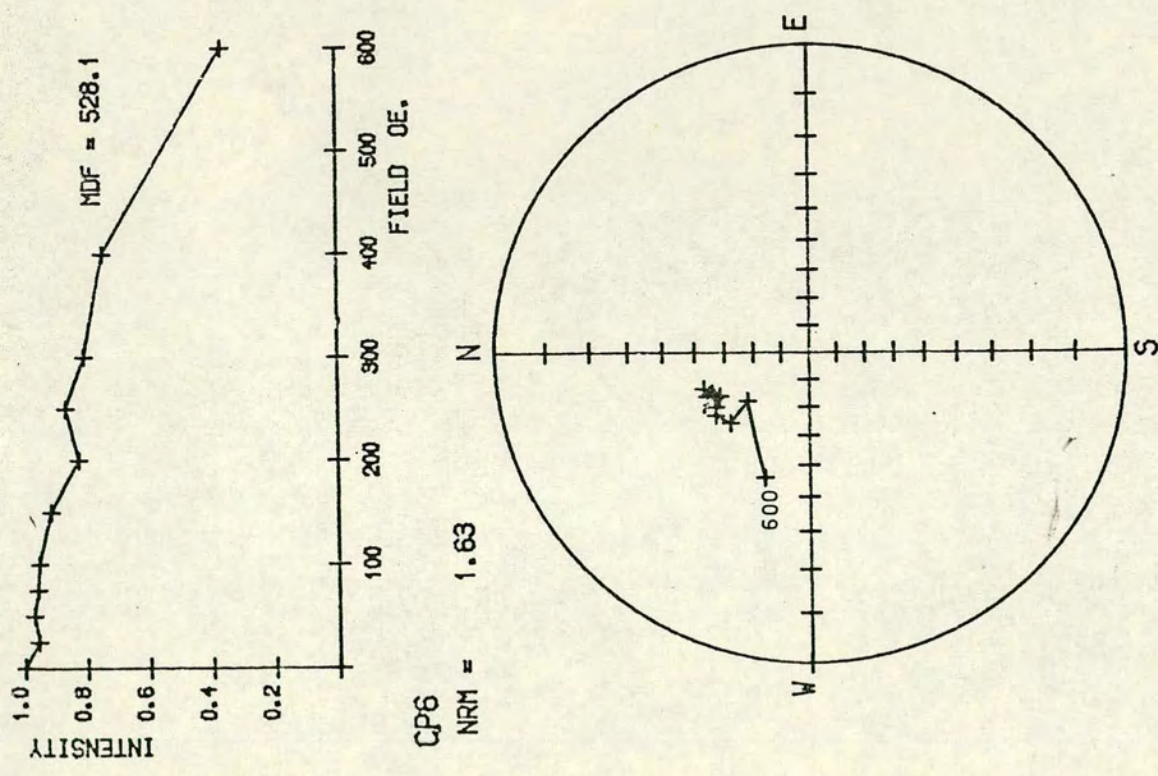
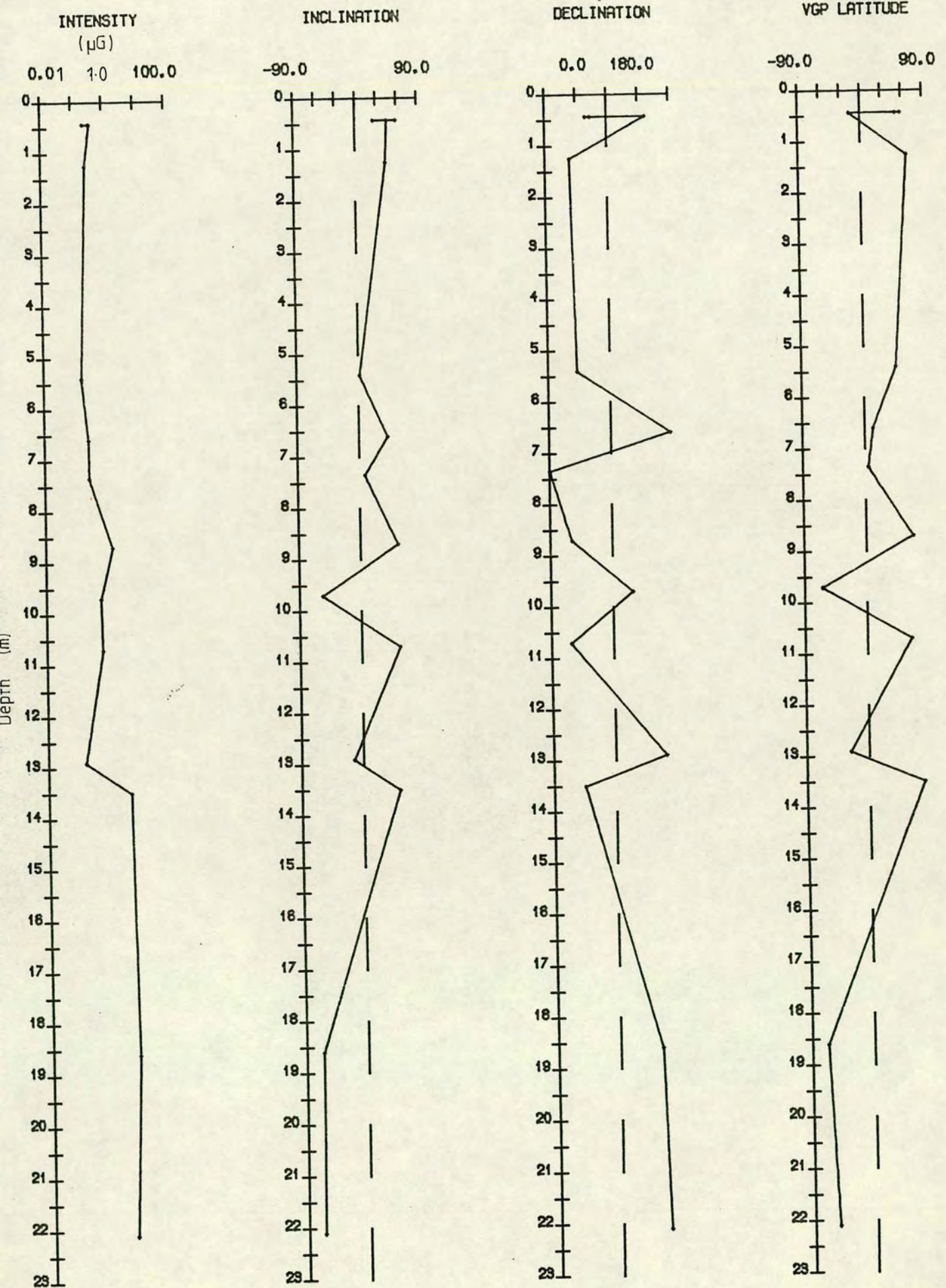


Figure 79. Examples of Pilot Demagnetization from Panaro

continental sediments showed a slightly larger decrease than the marine beds. Only one sample at 6.60m shows any major change in direction, developing a westerly declination resulting in a low latitude pole position. The marine series is reversed, but the continental deposits, especially those below the upper erosion surface, show much variation, with two independent reversed samples, and a period of intermediate polarity between 6.60m and 7.35. The transition between reversed and normal polarity at Panaro involves much scatter, like that at the bottom of the continental series of Tiepido (which was normal to reversed). Unlike the transition at Tiepido, most of the intermediate poles at Panaro are centred around South and Central America.

Figure 80 Results for Panaro after Demagnetization at 150 Oe.



PART V FIDENZA

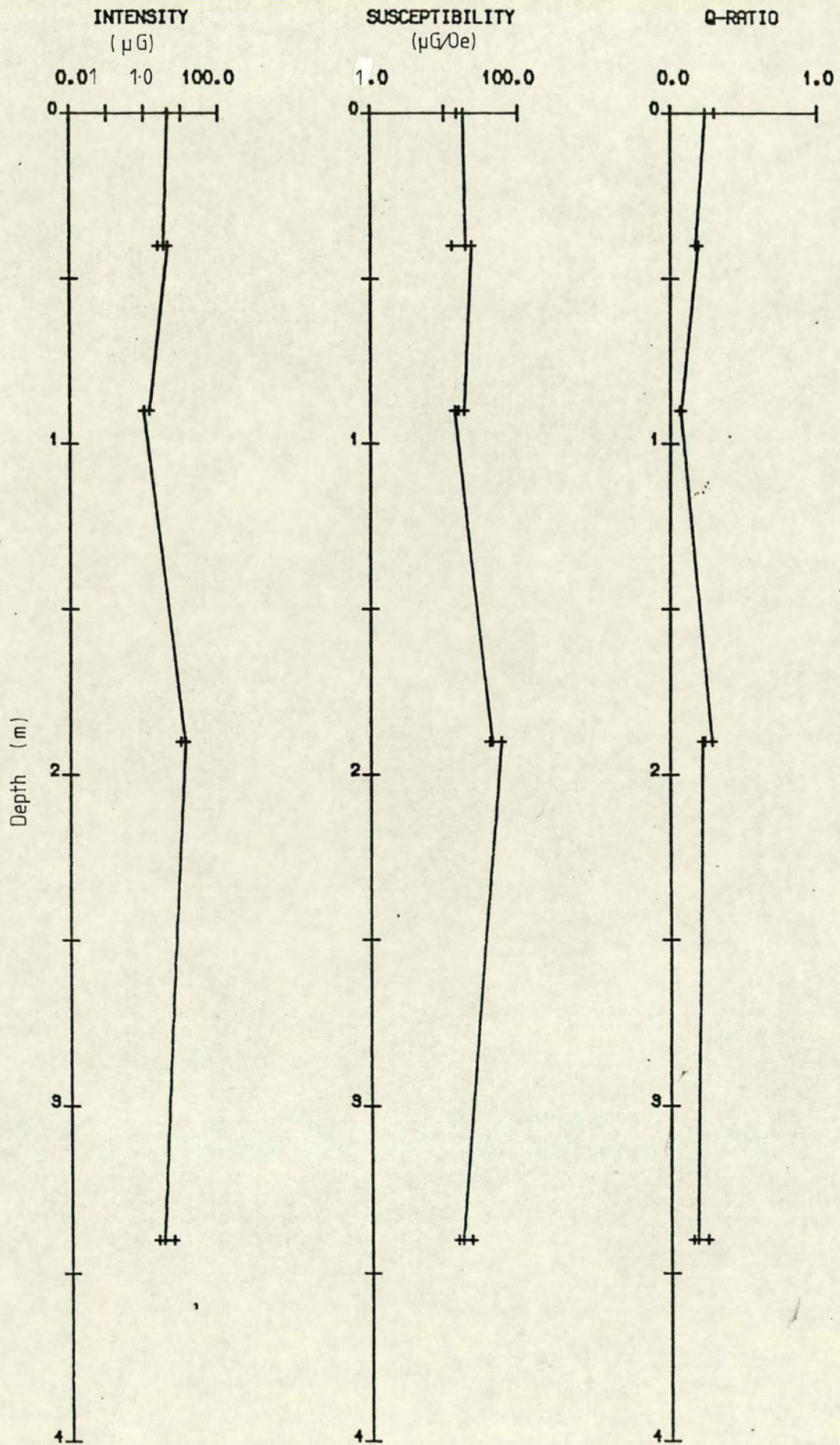
A new road cutting near Fidenza Servito Militare, on the road between Noceto and Fidenza has exposed a 4m section comprising roughly 75cm of Wurmian loess, 1m of Riss-Wurm soil, and over 2m of red Mindel-Riss soil, the latter correlating with that at Rivalentella. At least three samples were taken from each of these units.

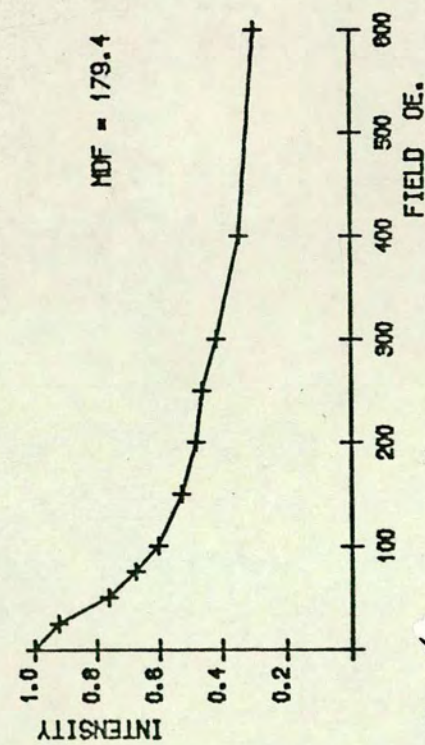
NRM intensity averages $4.79(\pm 3.67)\mu\text{G}$ with higher values at the top of the Wurmian loess and at the top of the Mindel-Riss soil (Figure 81). Susceptibility averages $23.45(\pm 13.16)\mu\text{G}/\text{Oe}$, and is also higher at the top of the Mindel-Riss soil. Q-ratios are similar to those at Rivalentella (about 0.2), though intensity and susceptibility are much lower.

The samples are relatively stable with demagnetization, PL1' from the Wurmian loess has a median destructive field of 180 Oe, and PL4' from the Mindel-Riss soil has a median destructive field of only 60 Oe (Figure 82). Both samples are softer than examples from Crostolo which had median destructive fields of 200 to 300 Oe (see SC4, Figure 63).

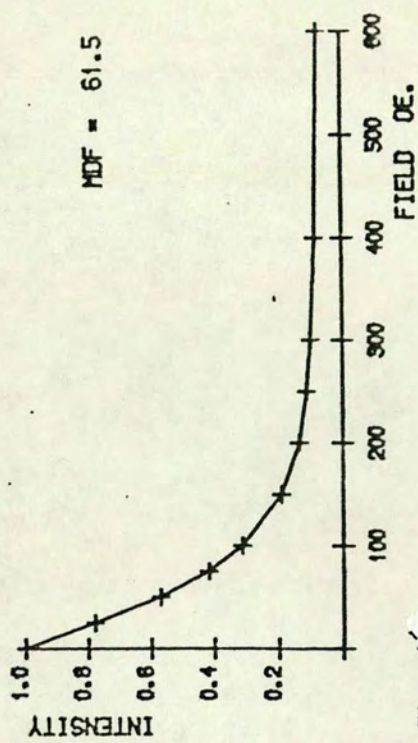
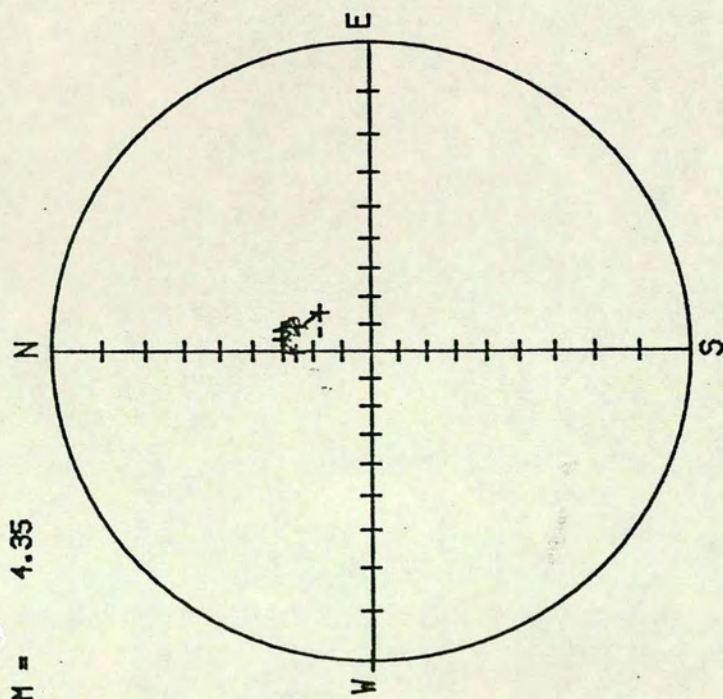
After blanket demagnetization intensity has decreased by 70% to $1.38(\pm 0.95)\mu\text{G}$, the amount of decrease is constant within the section, showing that the magnetic carriers of all samples have low coercivity. All of the samples are normal, with inclinations of around 50° and declinations near 0° , only the samples at 190cm have a different (though not significantly different) direction, with a more westerly declination (Figure 83). The grouping of samples at the same level is better at the top of the section, with alpha 95 of 10° to 20° in the upper units, and 40° to 70° in the Mindel-Riss soil. Demagnetization gives a closer grouping near the top of the section, but alpha 95 increases in the Mindel-Riss soil.

Figure 81 NRM results for Fidenza





PL 1
NRM = 4.35



PL 4
NRM = 12.50

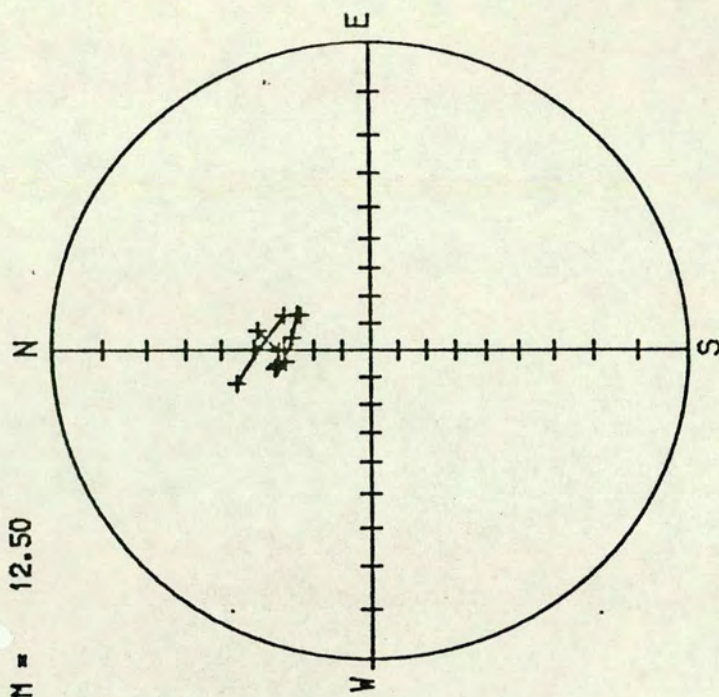
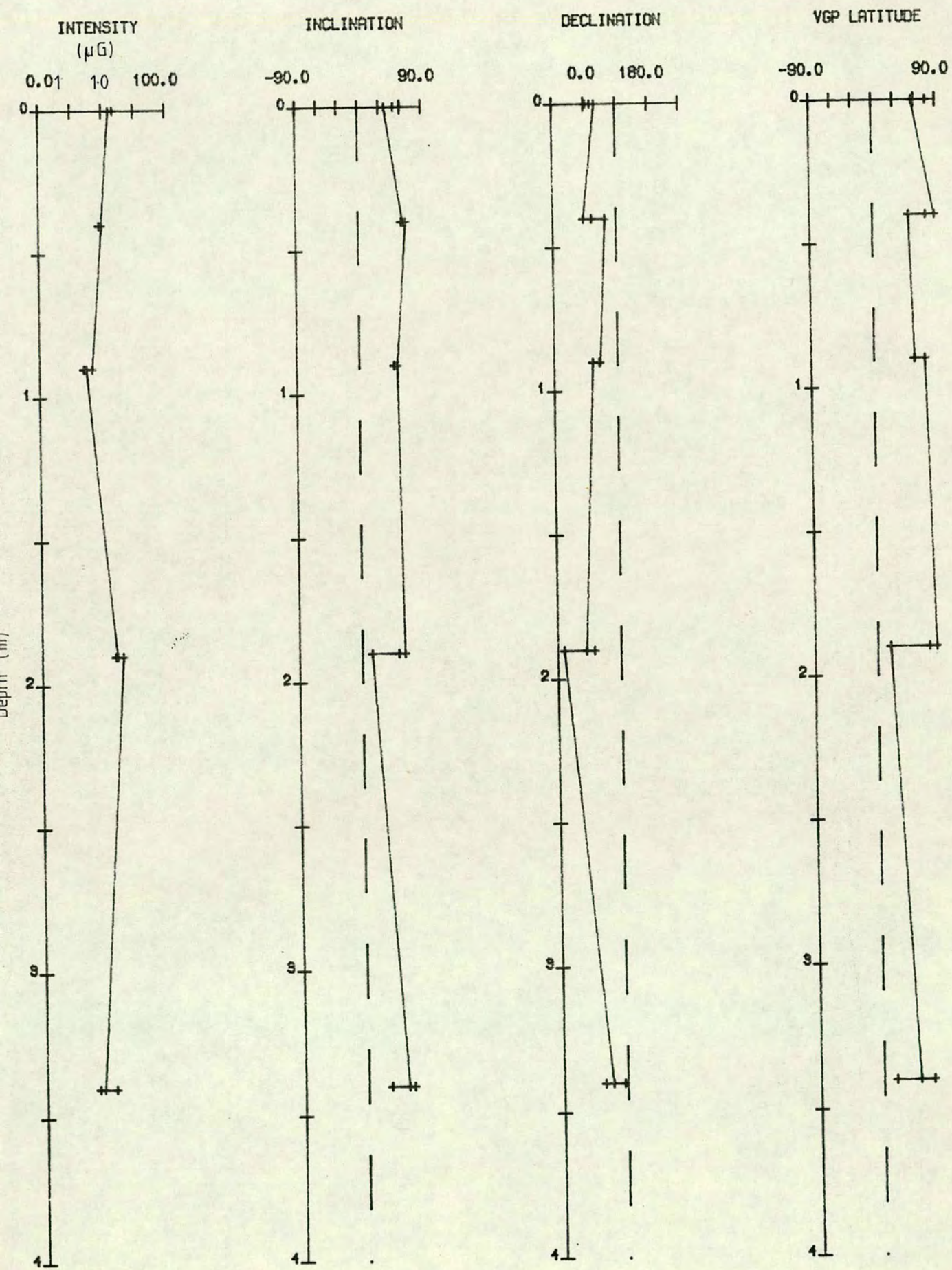


Figure 82. Examples of Pilot Demagnetization from Fidenza

Figure 83 Results for Fidenza after demagnetization at 150 Oe



PART VI CORRELATIONS

Figure 84 shows a summary of the results for the uppermost deposits at the four river sections studied together with geological features which may be used for correlation.

STIRONE

At Stirone the continental series is mainly normal, apart from perhaps two or three excursions; the marine series is reversed with two normal events at 140 to 145m and 175 to 186m. The simplest interpretation would be to put the Matuyama-Brunhes transition just below the top of the marine series (104m) and correlate the two events with the Jaramillo and Olduvai. Kukla et al (1979) report that the first appearance of Arctica islandica at Santerno (90km southeast of Stirone) coincides with a normal event interpreted as the Reunion Event. Another normal event occurs above the first appearance of Hyalinea balthica, and is correlated with the Olduvai Event. The correlation between Arctica islandica and the Reunion Event is also made at two profiles from Tuscany: Ceppato and Collesalveti (Arias et al 1982). Therefore the two normal events at Stirone should be the Olduvai and Reunion Events.

If this correlation is correct, it raises the question of the position of the Jaramillo Event. It may be represented by the excursion at about 120m, or it may have been removed by erosion. The period of non-deposition between the continental and marine deposits is thought by Italian geologists to represent a fairly long period so it is possible that the whole of the Upper Matuyama is missing that is period of at least 180,000 years is absent. The continental series may be entirely Brunhes, and the top of the marine series is the Jaramillo Event.

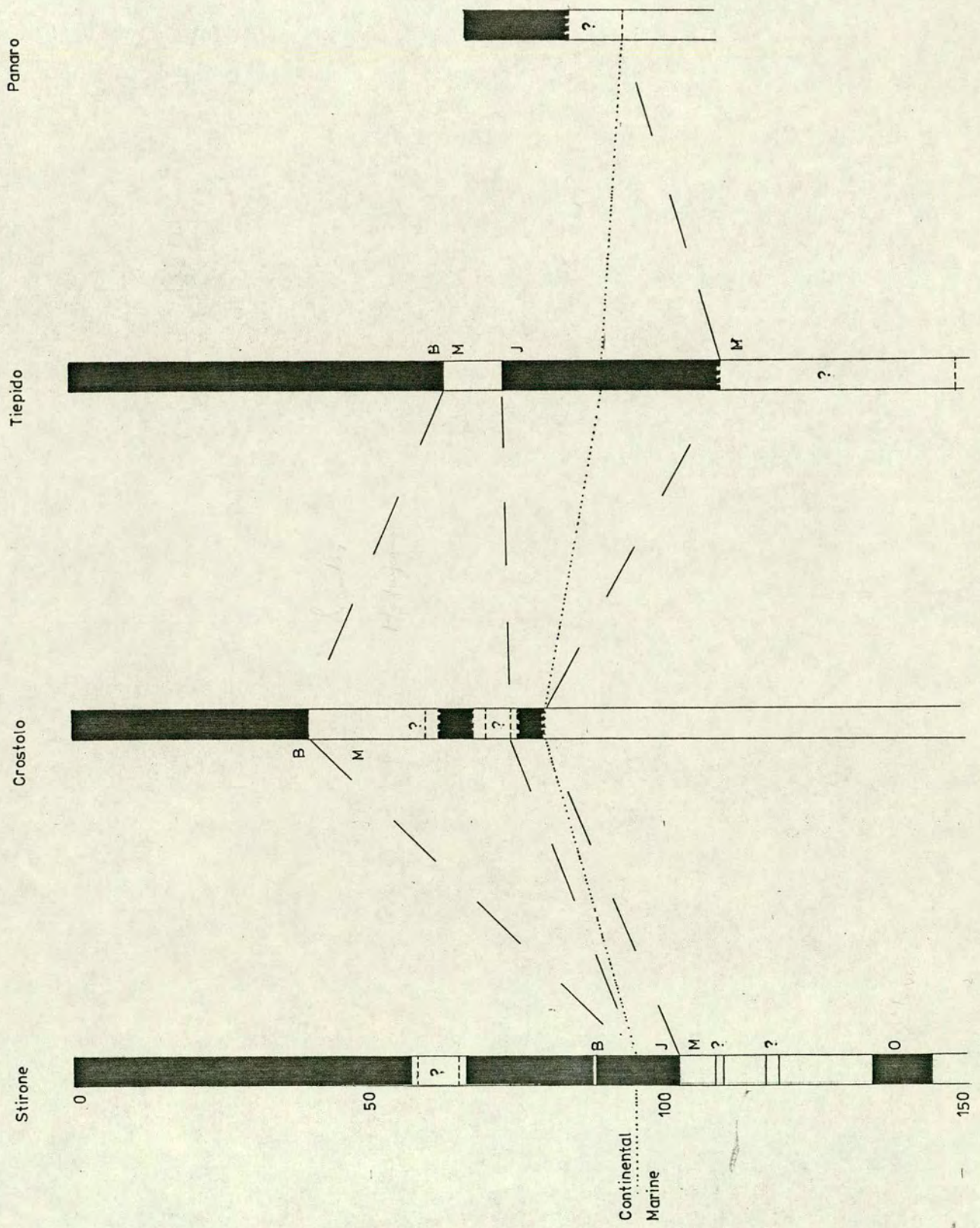


Figure 84. Results from Po Valley sections with possible Geological Correlation

Bucha et al (1975) put the Matuyama-Brunhes transition at about 57m, which is at the top of the anomalous interval recorded in this study. Their results (Figure 2, p14) show that much of the interval between 57m and the marine-continental boundary is characterized by normal inclination and northerly declination. The upper anomalous zone may be affected by slumping, especially in view of the occurrence of slumped beds just a little upstream. The Dicerorhinus hemitoechus found at about 90m is younger than 800,000 years, so as these samples are normally magnetized they must represent the Brunhes.

If we accept this identification of the major epochs and events it is possible to speculate on the identity of the excursions reported. The results from the continental series are too scattered to enable identification of long period secular variation, however there are two intervals, at 57m and 88m which may be interpreted as excursions, and the possibility of a third at 66m. All were resampled in 1981: the first gave consistent directions with horizontal inclinations and southerly declinations, the second interval gave similar directions then a transition to normal polarity. The lower interval showed a clear reversal within a section suggesting that this is at least in situ. Given an age of greater than 37,000 years for the top of the continental series, (Aléssio et al, 1980), and an age of less than 730,000 years for the base of the continental series (95m), the excursions can be dated at 450,000 520,000 and 680,000 years B.P. even though continental deposition is rarely constant these ages are probably close enough estimates. Calculations of the duration will be too large because the overall sedimentation rate will include periods when no deposition took place, and the actual sedimentation rate at any particular time will have been faster. Even for overestimated durations the intervals are short:

50cm at 57m giving 3,650 years, about 1m at 66m giving 7,300 years, and only 30cm at 88m giving 2,200 years. During the third excursion the pole changed from northern latitudes to southern latitudes in less than 1,000 years.

Most of the apparent excursions in the marine series have been dismissed as due to anomalous results arising from either low intensity or poor fidelity of sands. The sands may initially record anomalous directions due to deposition in a high energy environment, or in some cases these anomalous directions may result from percolation of water which collects in the sands, being prevented from further downward movement by impervious clays. When sampled the bottom layer of a sand bed was often so waterlogged that it would start to flow out of the vertical face. Given this high water content, it is possible that grains are free to rotate in the present normal field.

The interval just above the Plio-Pleistocene boundary is represented by a complex magnetic period, consisting of at least two events, one at 171m and one between 174 and 186m, the second event split in at least one place by reversed directions. These are identified as the Reunion Events, suggesting that there were two or more events in this interval.

CROSTOLO

At Crostolo the top of the continental series is normal to about 40m, then shows much variation until the top of the marine series. The marine series is mainly reversed to a depth of about 460m, below which two large normal events occur separated by a short reversed interval. The oldest samples taken are Piacenzian and probably younger than the Gilbert Epoch (Labrecque et al 1977). The base of the Pleistocene is placed at 125m, however inclinations between 80m and

450m are entirely reversed, and only variations in declination give low VGP latitudes. This interval of 370m includes no normal intervals, although short events may have been missed due to gaps in sampling. The normal interval below 460m is probably the Gauss, with the Kaena and Mammoth Events at 507-514m and 606 to 640m. Gauss excursions may occur above and below the Kaena Event, however there are only limited samples at these points so positive identification must await further work.

The top of the marine series has some samples with low VGP latitudes, however the first definitely normal samples above the Gauss Epoch occur at 74m, at the base of the Casa Bacchi Unit. This is a similar stratigraphic position to the Hippopotamus (cf. amphibus) fauna that is dated at greater than 900,000 years (Cremaschi pers. comm.). This puts the oldest continental sediments within the Jaramillo Event as a date of 1,670,000 years is too old. The Casa Bacchi and Casa Romensini Units have low magnetic fidelity and the exact position of the Upper Matuyama reversed interval is uncertain. The reversed samples at 68-70m were shown to have little stability after demagnetization, even though the results of all samples at 100 Oe are closely grouped. This suggests that the Upper Matuyama may occur at the top of the Casa Bacchi Unit (60.62m) or in the Casa Romensini Unit below the apparent reversal at 40 to 44m. While it is conceivable that the results record a Brunhes excursion at 44m and a middle Matuyama excursion at 74m, the more likely explanation is that the poor fidelity of these deposits has confused the palaeomagnetic record.

The large reversed interval in the marine sediments probably covers 1,510,000 years from the base of the Jaramillo to the top of the Gauss. This gives a sedimentation rate of 25cm/1000 years which

compares with 75cm/1000 years at Tiepido (Annovi et al 1979) and Santerno (Kukla et al, 1979) during the Lower Pleistocene. The position of the Plio-Pleistocene boundary as defined by Barbieri and Petrucci may be affected by environmental factors; the fossil species may not have entered the region until some time after the end of the Pliocene.

TIEPIDO

At Tiepido 60m of normal continental sediment overlie a short reversed interval 10m thick. Beneath this a few normal samples are seen, in the lowermost continental sediments and in the uppermost marine deposits; the remainder of the marine sediments are reversed. As the lowest level sampled lies above the first appearance of H. balthica the long reversed period can be correlated with the middle Matuyama above the Olduvai Event.

There was little recovery between 150m and 80m, nevertheless a few normal samples were recovered that allow the marine regression to be placed within the Jaramillo Event, as at Stirone. The Upper Matuyama occurs therefore, between 70 and 65m, which is shorter than would be expected, but this period was apparently represented by no deposition at Stirone.

The transition at 65m is far-sided, which is dissimilar to that at 102m at Stirone, but similar to the part of the reversal seen at 44m in Crostolo. Transitional paths should be similar at sites only 200km apart as the sources for the magnetic field are within the core. This supports the suggestion that the lowermost Brunhes and uppermost Matuyama are missing from Stirone. If the highest transition at Crostolo is real, and represents the Matuyama-Brunhes then more continental deposition occurred there during the Upper Matuyama than

at any other site.

The lowermost deposits of the Brunhes Epoch have low normal inclination at Tiepido, which becomes reversed occasionally between 56 and 58m. This excursion consists of rapid alternation in VGP latitude, and although similar in stratigraphic position to the third excursion at Stirone, it is not represented by similar VGP positions. The deposits in which this transition was recorded are sandwiched between conglomerates, so the directions may again reflect poor magnetic fidelity.

PANARO

The marine deposits of Panaro are reversed, while the overlying continental deposits are mainly normal, but with at least two reversed samples. By comparison with the other sections, the marine deposits probably correspond to the middle Matuyama. The continental deposits may correlate with either the Jaramillo or the Brunhes. The 14m of continental deposits compare in thickness with the Upper Matuyama and Jaramillo at Tiepido, so it is possible that both the Brunhes and Jaramillo are recorded with the Upper Matuyama at 7-13m. It is interesting to note that the Upper Matuyama transition at Tiepido also seems to involve rapid alternation of northerly and southerly VGP latitude while at Crostolo mixed polarity is seen in this interval. The intermediate VGPs at Panaro are near-sided, suggesting that the transition is more likely to be the Matuyama-Jaramillo than the Matuyama-Brunhes.

CONCLUSIONS

The marine regression along the Po valley occurred approximately 900,000 years ago, that is during the Jaramillo Event. The regression occurred slightly later at Tiepido than at Crostolo, while at Stirone

the regression occurred later than at Crostolo and was followed by a period of non-deposition. In all deposits the sediments just above the marine regression are discontinuous. Figure 85 shows sedimentation rates during the Brunhes and Matuyama Epochs. This shows much faster deposition of the marine deposits at Crostolo and Tiepido than at Stirone, followed by a period of little or no deposition coinciding with the marine regression. From estimated sedimentation rates, the transitions lasted much longer than the accepted length of 5-10,000 years, which probably indicates inaccurate calculation of deposition rates due to the intermittent deposition involved, especially in the continental deposits.

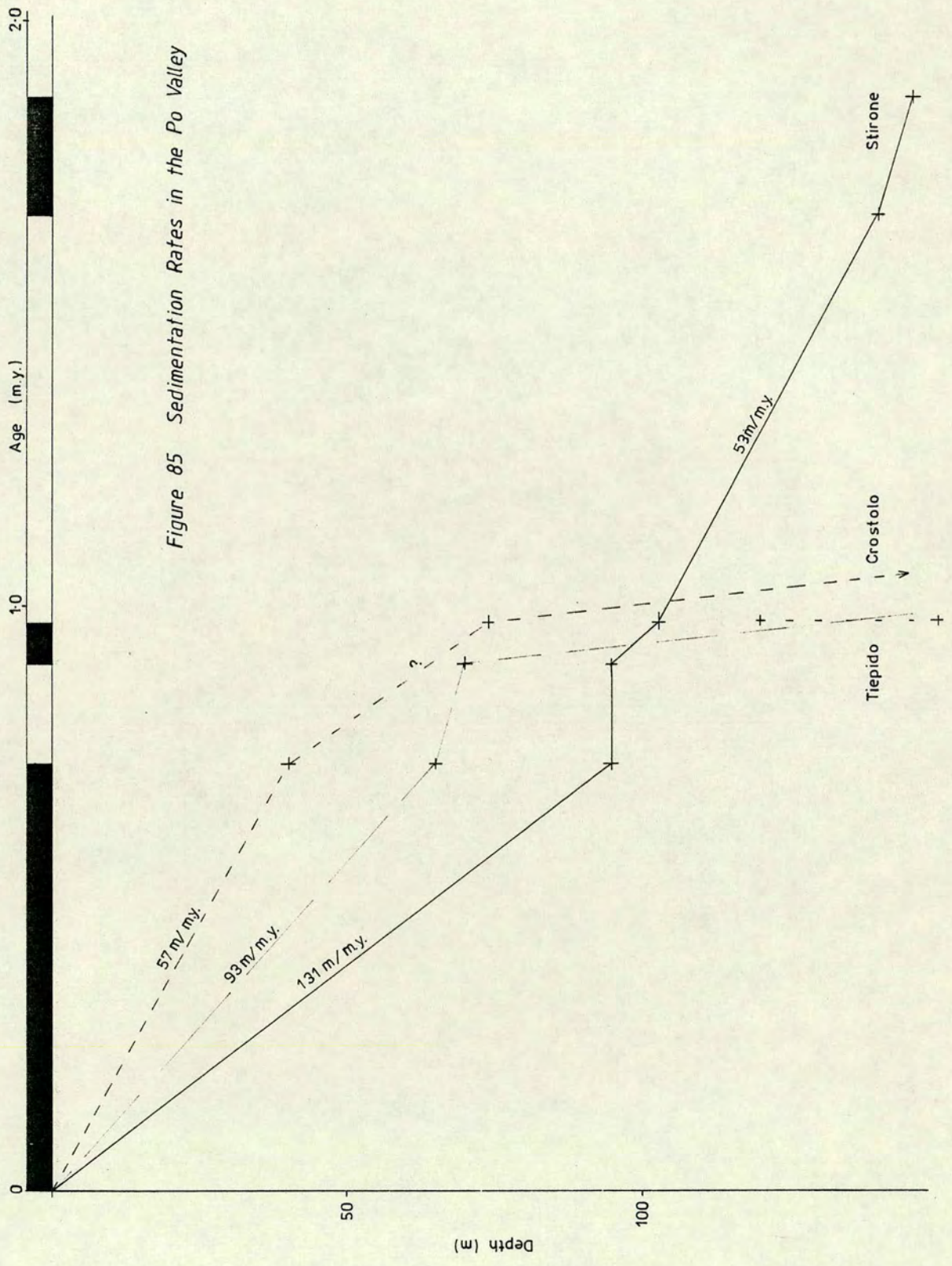


Figure 85 Sedimentation Rates in the Po Valley

CHAPTER 5

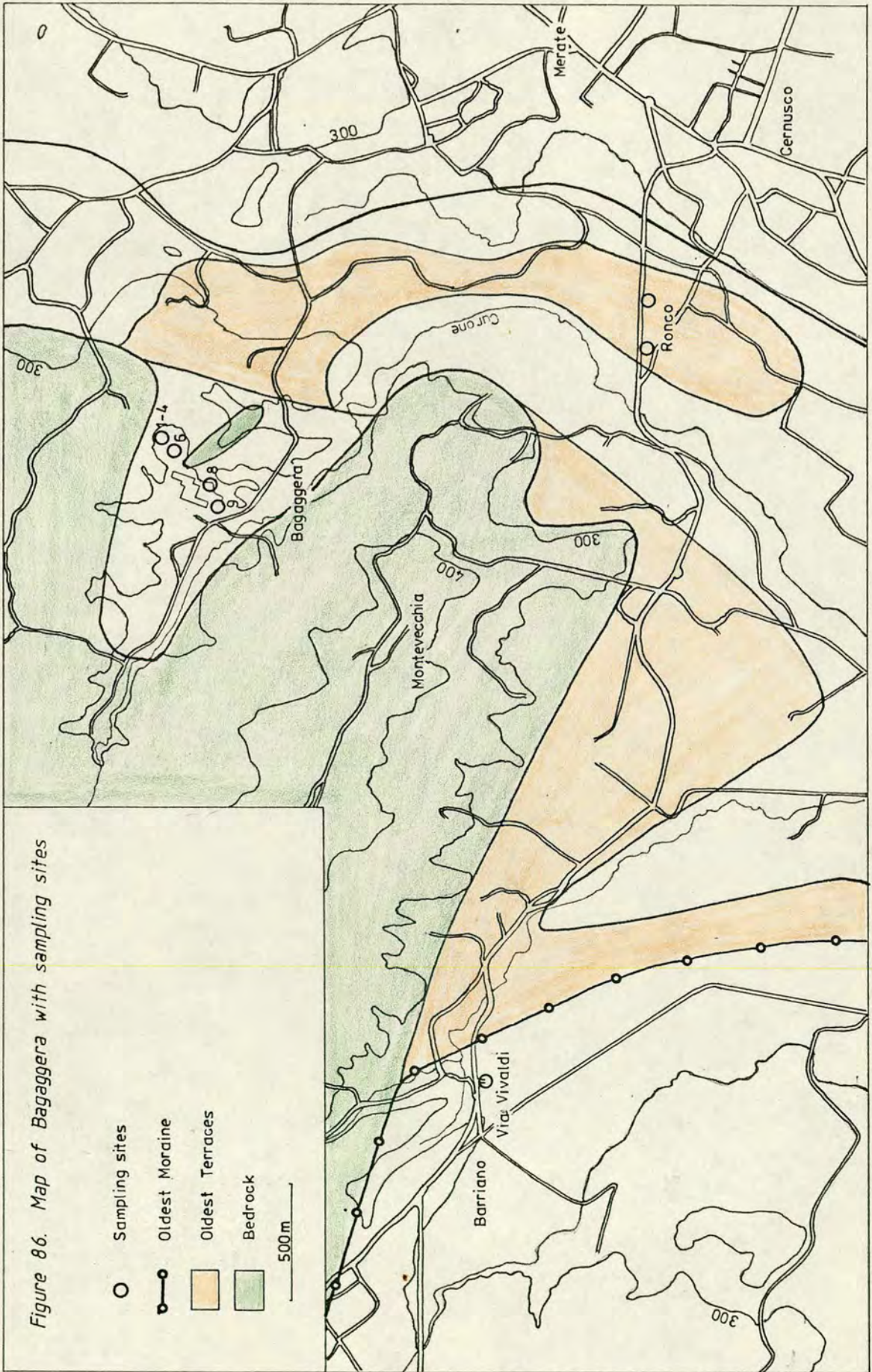
LOMBARDY SECTIONS

PART I BAGAGGERA

GEOLOGY

Bagaggera quarry is located 30km northeast of Milan, and 2.5km west of the town of Merate (Map 32 II S.E. NR 300625, Figure 86). The sediments exposed in the quarry were deposited in two small basins dammed by a terrace formed of conglomerate, and separated by a bedrock threshold. The basins which occupy the Curone valley on the side of Montevicchia Hill were surrounded by glaciers throughout the Quaternary, but were never actually covered. The complex sequence of deposits which results has been described at nine sections by G. Crombelli and M. Cremaschi (Figures 87 and 88, see Cremaschi et al, in prep.).

In the southern sub-basin at least 4m of laminated silty clay occur at the base of sections 8 and 9. The clays which comprise Unit 9 of Cremaschi et al contain local sand lenses and also mollusc shells. The base of this unit is not seen. The clays are overlain by a coarse to medium grained sand up to 70cm thick (Unit 7), which is separated from Unit 9 by an erosional surface. Clasts of chert and quartz are seen in this layer, and isolated pieces of lignite plants (Abies alba). Unit 7 is followed by fluvial silts and sands up to 9m thick. The lower beds of this unit (Unit 6) are thinly laminated fine silts containing thin sand beds. Towards the top of Unit 6 the sediments become generally coarser, but can be divided into four cycles which themselves become finer upwards. The cycles start with ripple sands developed on an erosion surface and end with a dark massive clay with high organic content.



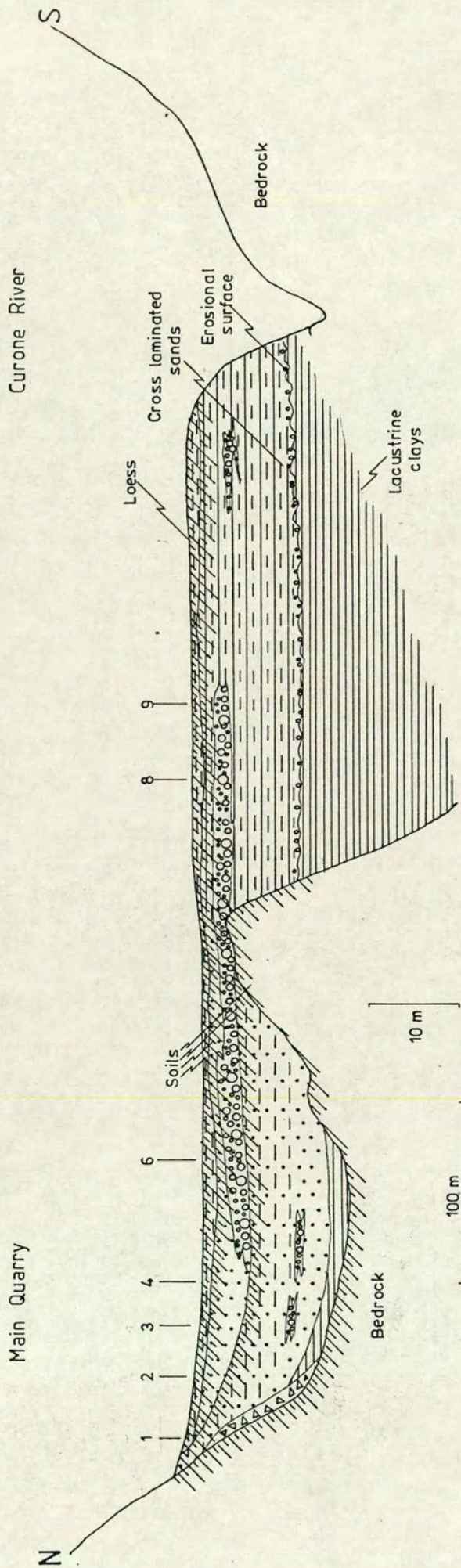


Figure 87. Cross Section of the Bagagera Basin

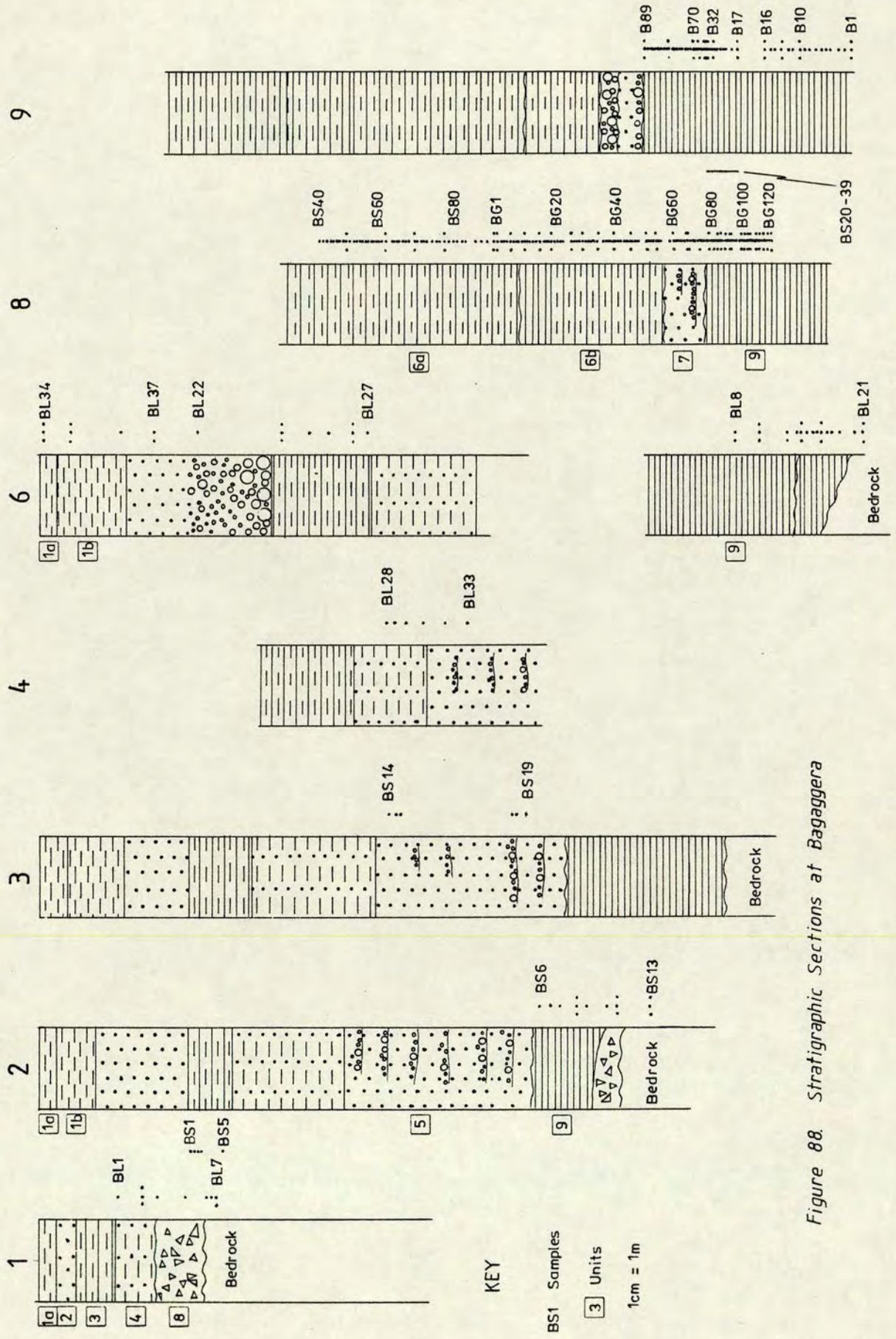


Figure 88. Stratigraphic Sections at Bagaggera

In the northern sub-basin up to 2m of lacustrine clays belonging to Unit 9 are seen immediately overlying the steeply dipping Cretaceous flysch in the centre of the quarry. The clays pinch out laterally and at one point (section 2) contain a slope deposit (Unit 8) consisting of angular clasts. Nearer the edge of the basin (section 1) this slope deposit is not overlain by Unit 9 clays. The flysch is heavily weathered wherever it is exposed, but the slope deposit is only intensely altered at Section 1 indicating that this weathering took place after Unit 9 had been laid down, and therefore represents a later period of alteration than that developed on the flysch. Above Units 8 and 9 there are five units in the northern sub-basin, each separated by an erosion surface, each with a soil developed on top. Unit 5 directly overlying the lacustrine clays consists of up to 4m of fluvial sand and gravel with a clay matrix. The size of the clasts increases towards the threshold to the south. Unit 4 is a gravelly loam, likewise becoming coarser to the south, ranging from 1 to 3m in thickness. Unit 3 is a loam deposit up to 2.5m thick with angular clay clasts, probably from Unit 9, at the base, and aeolian deposits at the top. Units 3, 4, and 5 are restricted to the northern sub-basin, but Unit 2 covers both parts of the quarry. It consists of at least 3m of fluvial sand and gravel capped by aeolian silt which contains Middle Palaeolithic artefacts. Unit 1 which also covers the entire area of Bagaggera is comprised of two loess sheets each 1 to 2m thick. The uppermost sheet contains Upper Palaeolithic artefacts, and is thus correlated with the Würm glacial period.

In the surrounding area soils are seen in sections at Via Vivaldi (NR 27286130) and Ronco (NR 305606). Via Vivaldi is immediately behind the moraine, the soils are developed on till.

At Ronco the soils are developed on gravel which is possibly the same terrace as the one which dammed Bagaggera.

SAMPLING AND MEASUREMENT

Samples were taken at intervals of 1-5cm from the lacustrine and fluviolacustrine clays and silts of Sections 8 and 9. Bucha and Sibrava (1977) reported the occurrence of a polarity reversal in Unit 9 at a profile similar to Section 9. The reversal occurs very close to a vertical change from grey silty clay to oxidized brown silty clay. At Section 8 the oxidation is not seen in Unit 9, perhaps because downward percolation of water was prevented by a thick black clay at the top of Unit 6b. Palaeomagnetic investigation of both sections was undertaken to determine whether the reversal is real, or if it was caused by superimposition of a chemical remanence at a later date. In 1982 the quarry was revisited to allow resampling of the transition, and to extend Section 8 to cover 4m of Unit 6 which was exposed through excavation in the autumn of 1981.

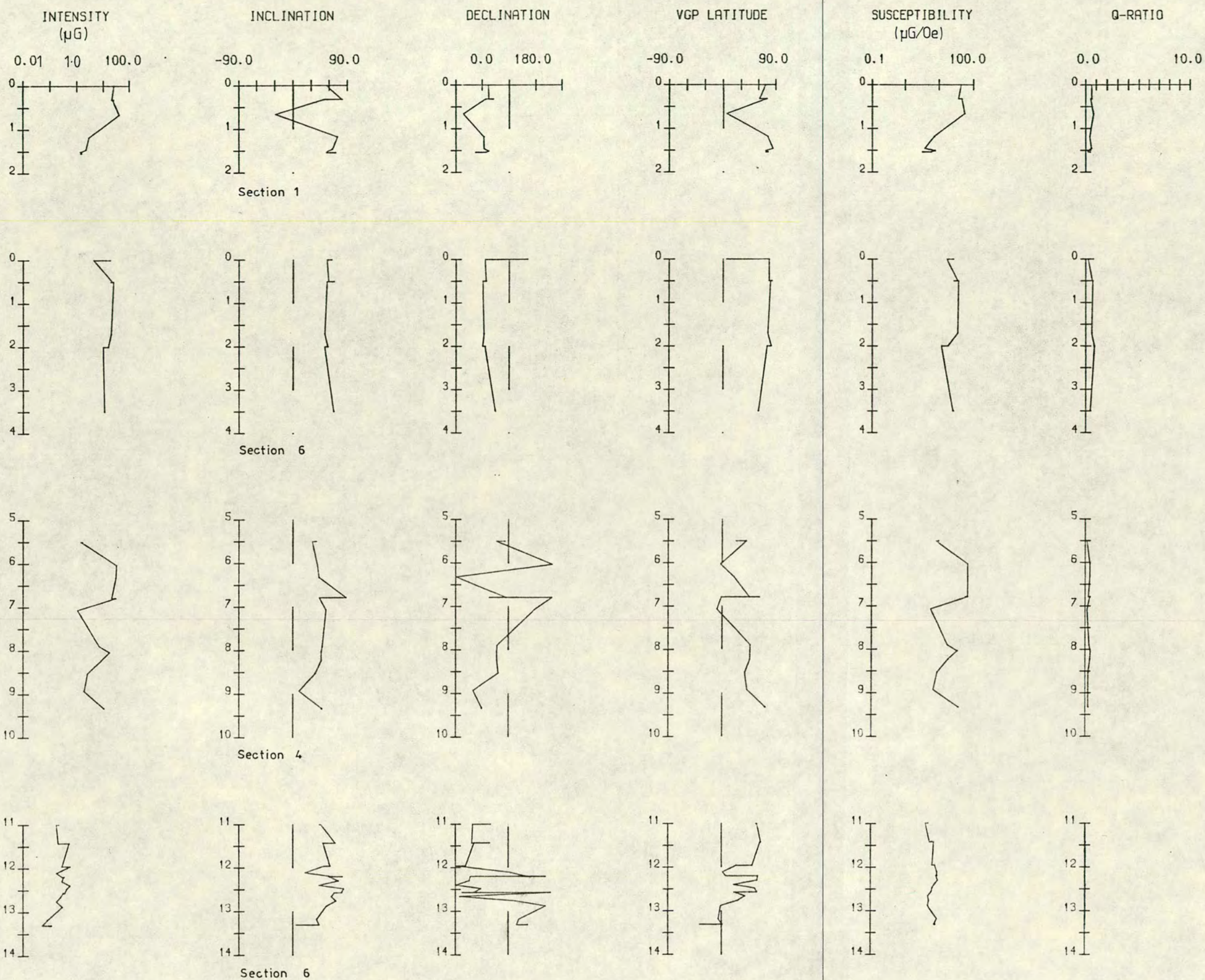
Samples were also taken from the matrix of weathered profiles developed on Units 1 to 5 and on the flysch bedrock in the northern sub-basin, as shown in Figure 88. The lacustrine clays at the base of section 6 were also sampled. A number of samples were taken from the soils of Ronco and Via Vivaldi to investigate whether any correlation could be made with soils in the quarry.

RESULTS

Northern Sub-basin

The natural remanent magnetization (NRM) of samples from the palaeosols, varies in intensity from 10 to 100 μG , although intensity in the flysch of Section 1 is slightly lower (between 1 and 2 μG).

Figure 89 NRM Results for Sections in the Northern Sub-Basin



Susceptibility lies between 10 and 100 $\mu\text{G}/\text{Oe}$, giving Q-ratios of almost 1. The clays of unit 9 in section 6 have lower intensities (0.1 to 1.0 μG) with susceptibilities of slightly less than 10 $\mu\text{G}/\text{Oe}$ giving lower Q-ratios (Figure 89).

Examples of pilot demagnetization are shown in Figure 90. Most samples from the weathered profiles are stable, changing little in direction with demagnetization, however hardness varies considerably: median destructive field varies from about 115 Oe (BL2) to over 600 Oe (BL7'). Samples from the bottom part of section 6 show larger changes in direction with demagnetization, BL16 appears to have a moderately stable normal magnetization, however BL12' becomes intermediate in direction at 200 Oe, accompanied by a rise in intensity. In both cases the initial remanence is low (0.5 μG) so the directions may be masked by instrument noise.

The results after blanket demagnetization at 150 Oe are shown in Figure 91. The samples of Section 1 showed little change in intensity reflecting a hard magnetization as seen in sample BL7'. This behaviour is characteristic of haematite which is resistant to alternating field demagnetization. Most of the samples from Section 1 are normal, however one sample from Unit 8 has a low negative inclination. This may be due to alteration during a reversed epoch, or it may represent the primary remanence of a fallen block. The remanent directions in the flysch below are more consistent with stable normal polarity before correction for dip, suggesting that the alteration that gave rise to the magnetization in these rocks occurred after folding.

Samples from Units 1, 2, and 3 in Section 6, and Unit 4 in Section 4 have normal inclination, probably representing alteration during a normal epoch, although one sample (BL27) at the base of Unit

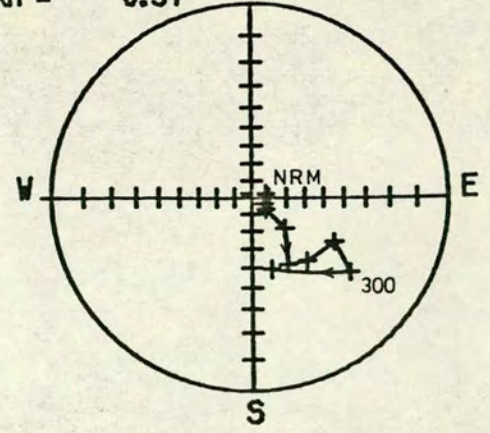
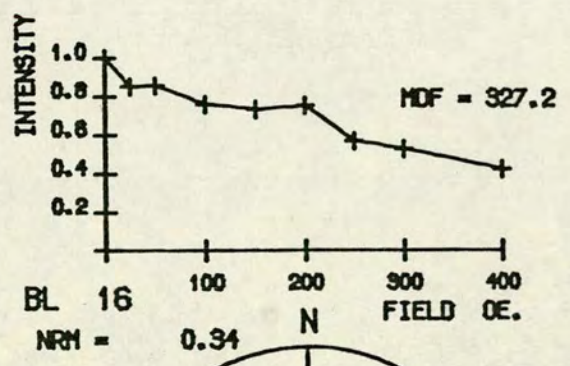
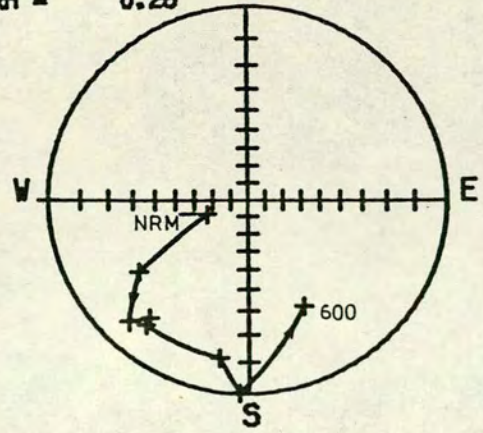
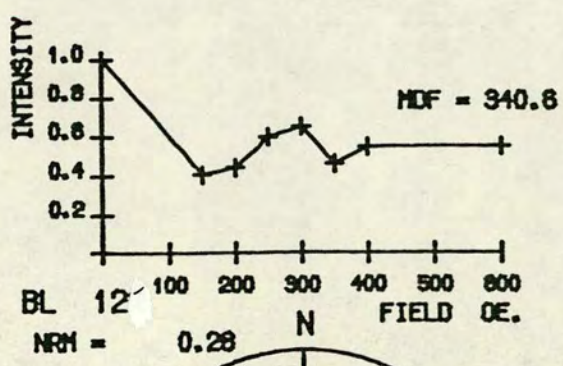
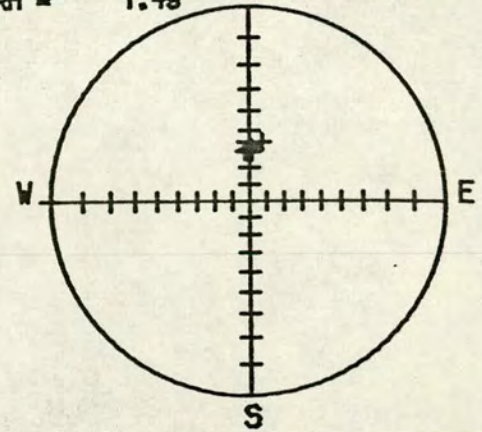
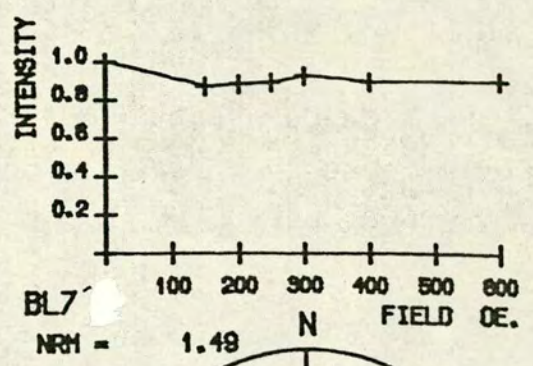
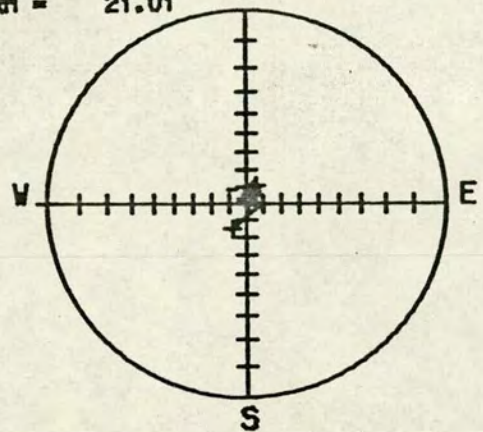
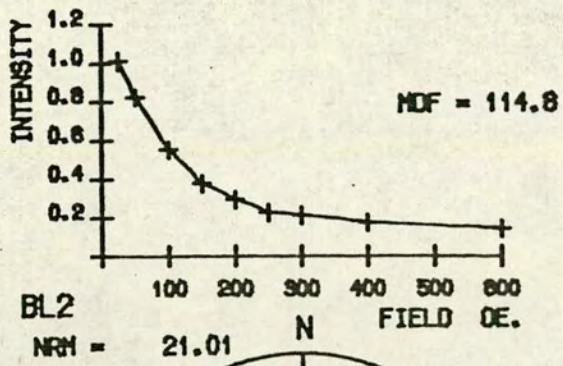
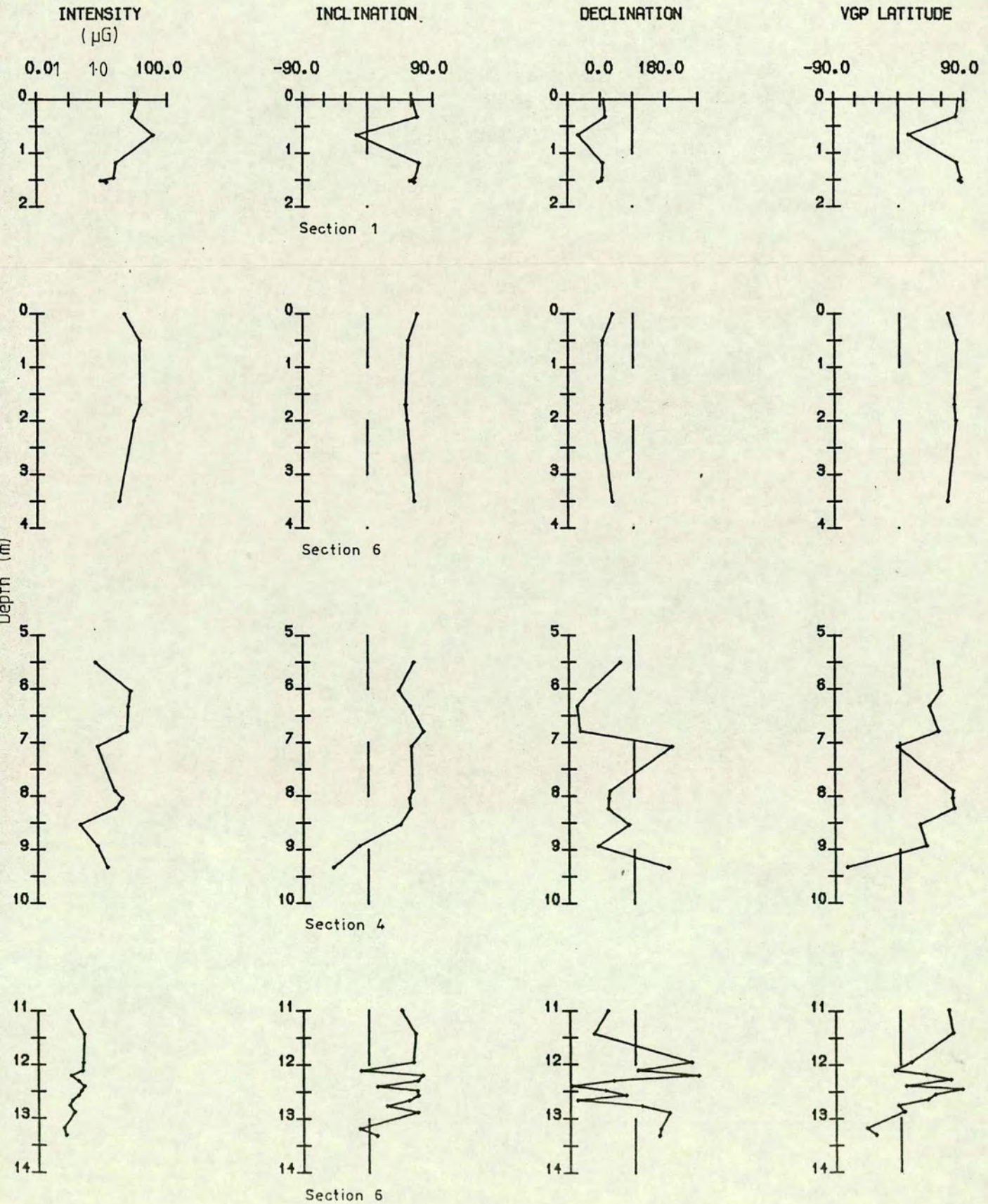


Figure 90. Examples of Pilot Demagnetization from the Northern sub-basin

Figure 91 Results for Northern Sub-Basin after Demagnetization



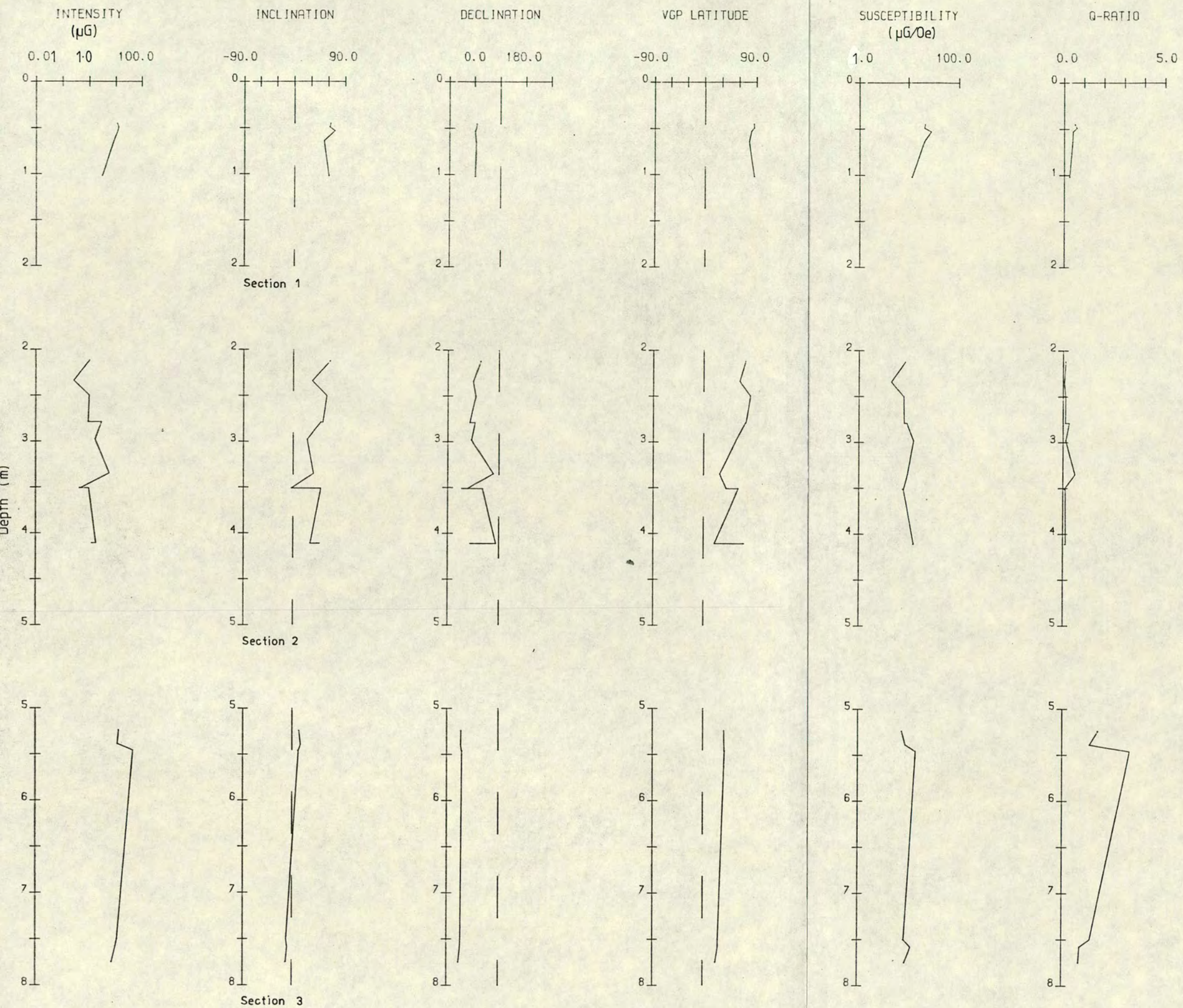
3 has a southerly declination, giving an intermediate virtual geomagnetic pole (VGP) latitude. Unit 5 is represented by two samples, both with reversed inclination, one with southerly declination, suggesting that the palaeosol on Unit 5 formed during a reversed epoch.

Samples from the lacustrine clay in Section 6 have mainly normal inclination, however there is much scatter in declination, probably due to low intensity. Two samples from the flysch (13-14m) are reversed. These differ in strength (NRM = 0.1 μ G) and in direction from the flysch in Section 1, so they may represent a different, less intense period of alteration, or they may reflect the original detrital remanence of the flysch.

The resampled sections in the northern sub-basin were studied to check the magnetizations of Units 5 and 8. Three sections were sampled, one entirely in Unit 5 (Section 3), and the other two sampling Unit 8, one where it had been oxidized (Section 1) and one where it had been protected from oxidation by overlying clay (Section 2). NRM results for these three sections are shown in Figure 92. Intensities in the two weathered sections are high, averaging $17.8(\pm 14.3)\mu$ G in Unit 5 and $9.3(\pm 3.5)\mu$ G in the breccia. In section 2 intensity averaged $1.6(\pm 1.4)\mu$ G the breccia having a slightly stronger remanence than the lacustrine clay. Section 1 is entirely normal at NRM with high positive inclination averaging $61.8(\pm 6.1)^\circ$. Section 2 shows a large amount of variation, however directions are mainly positive. In Section 3 inclination is very low, and declination slightly to the west of north giving VGP latitudes of between 25 and 40°N.

With demagnetization (Figure 93) sample BS3 from the breccia of Section A shows signs of reversing, although the median destructive

Figure 92 NRM Results for Resampled Sections



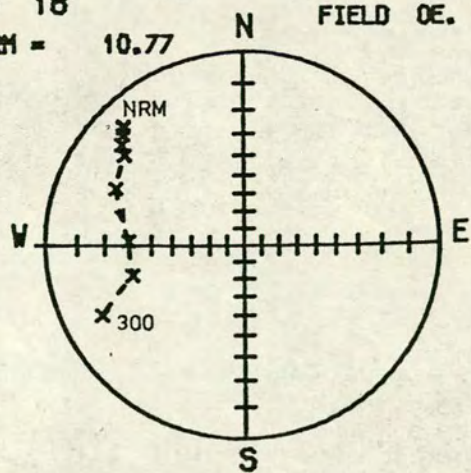
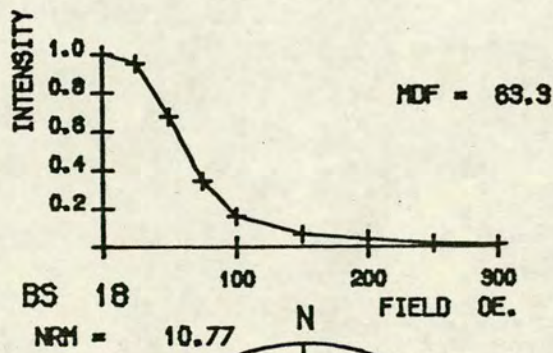
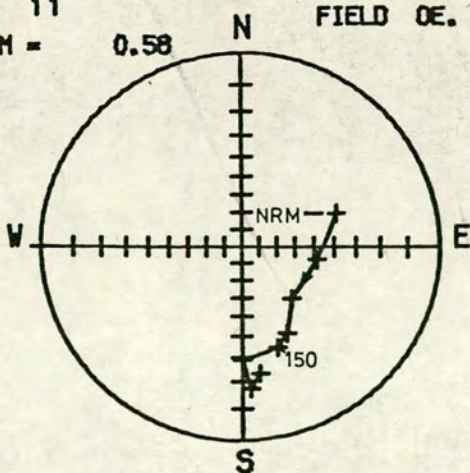
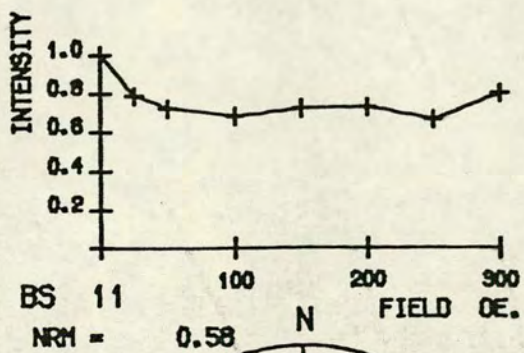
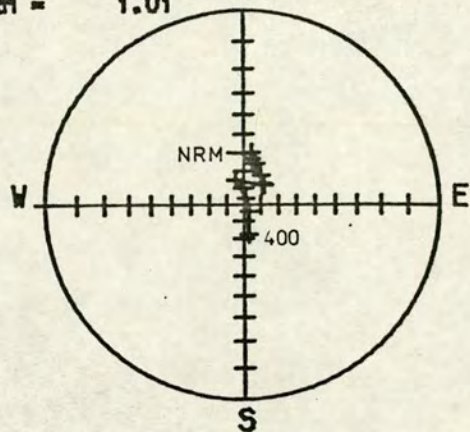
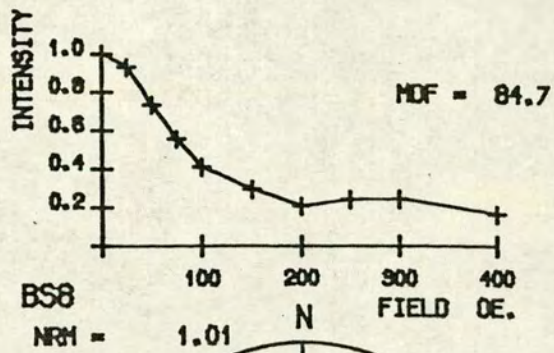
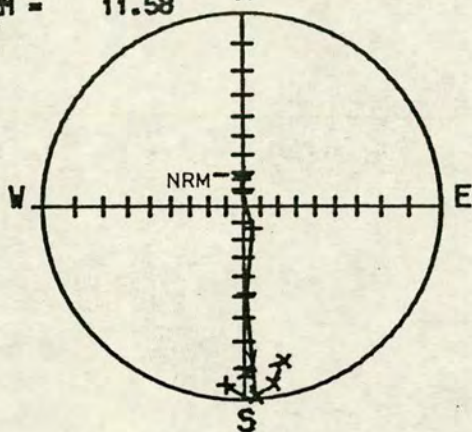
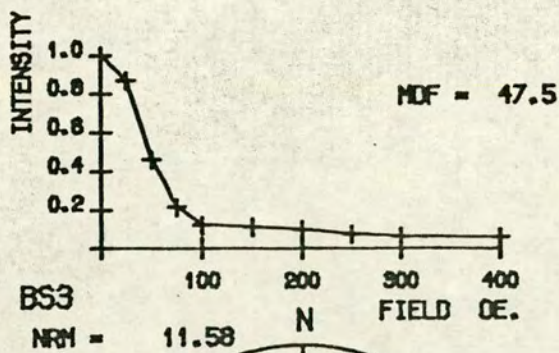


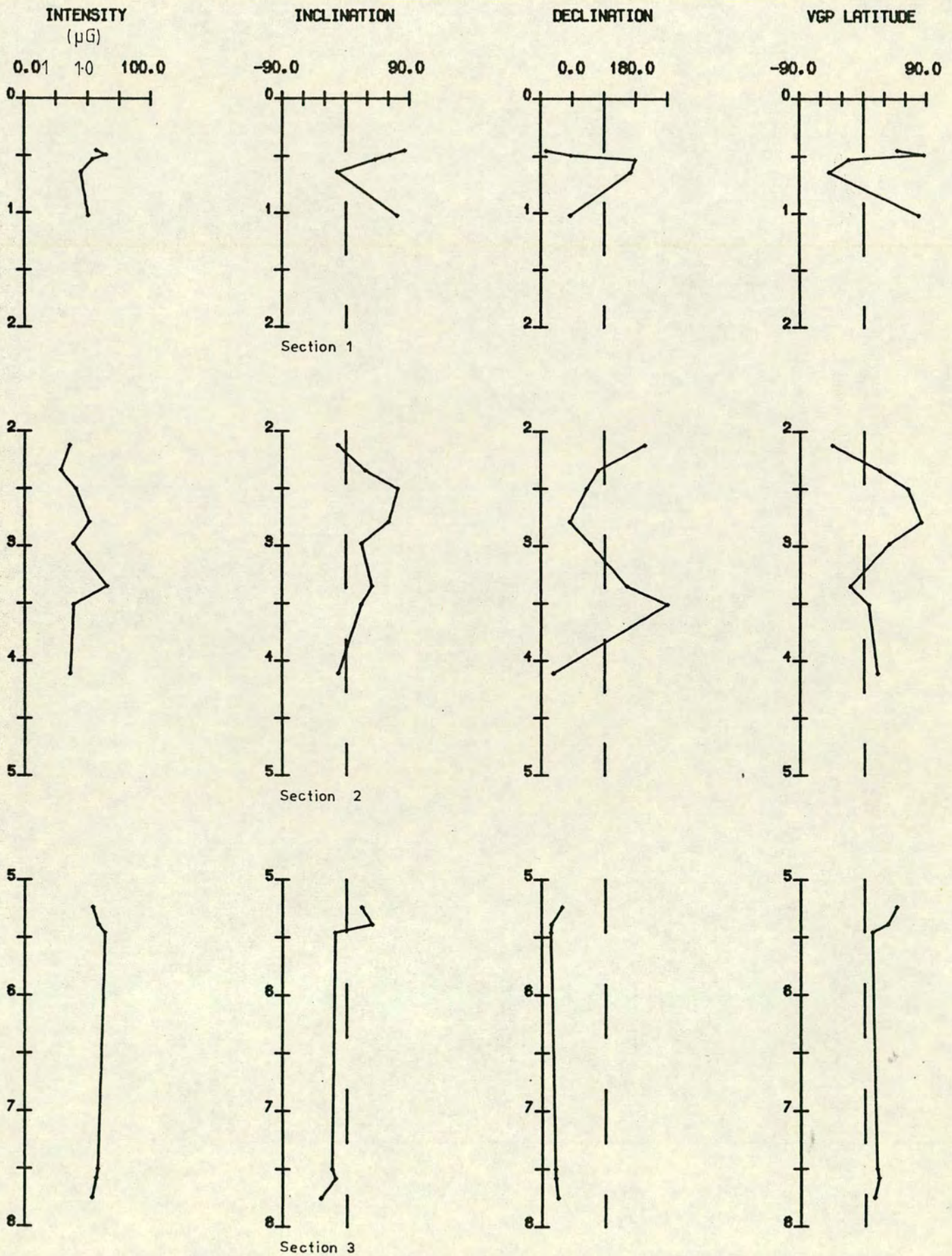
Figure 93. Examples of Pilot Demagnetization from Resampled Sections

field is very low (47.5 Oe) and the negative direction is carried by only a small percentage of the remanence. Sample BS8 from the lacustrine clay is stable although it has a low median destructive field (85 Oe). Sample BS11 from the unweathered breccia shallows in inclination, while changing declination, but decreases by only 30% between 0 and 250 Oe. Unit 5 samples also have low median destructive fields, BS18 loses half of its magnetization at 63 Oe, and shows signs of becoming more negative, with a slight increase in negative inclination.

Demagnetization results at 100 Oe are shown in Figure 94. The weathered sections (1 and 3) had lost 81% and 89% of their initial remanence to give intensities averaging $1.7(\pm 1.1)\mu\text{G}$ and $2.0(\pm 0.7)\mu\text{G}$ respectively. Intensity in Section 2 had fallen by 58% to $0.7(\pm 1.0)\mu\text{G}$. The samples from Unit 5 showed only a slight change in direction, with inclination becoming slightly more negative giving VGP latitudes of 10 to 30°N . In Section 1 two samples from the breccia became reversed, however two other samples remained normal as did one from the flysch. The samples in Section 2 gave a variety of results with both positive and negative directions in the lacustrine clays, southerly declinations, but shallow positive inclinations in the breccia and an intermediate direction in the bed-rock. Three samples taken at the same level in the breccia give widely differing directions ($\alpha_{95} > 90^\circ$). This suggests that the results are random, due to the mode of deposition of this unit. Only when the breccia is oxidized does it give more consistent results. Further blanket demagnetization at 150 Oe did not cause any further change in direction.

Results for the whole of the Northern sub-basin are summarized in Figure 95. Units 1, 2, 3, and 4, together with the flysch give

Figure 94. Results for Reampled Sections after Demagnetization



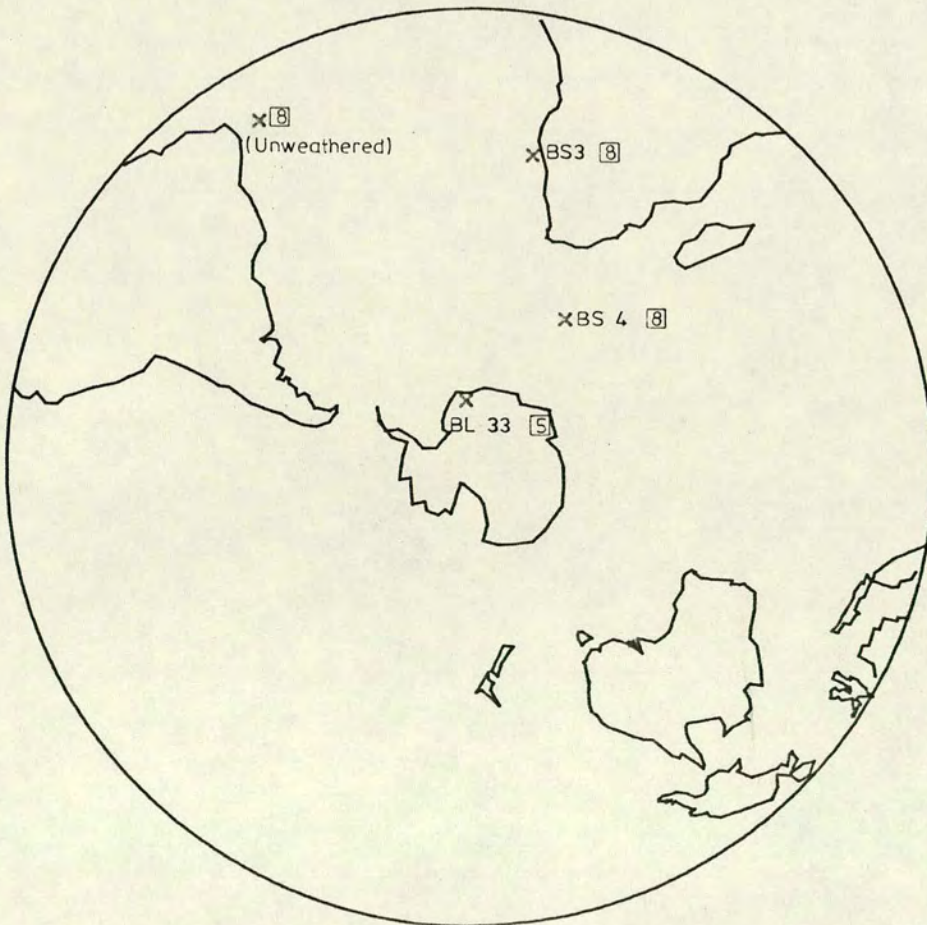
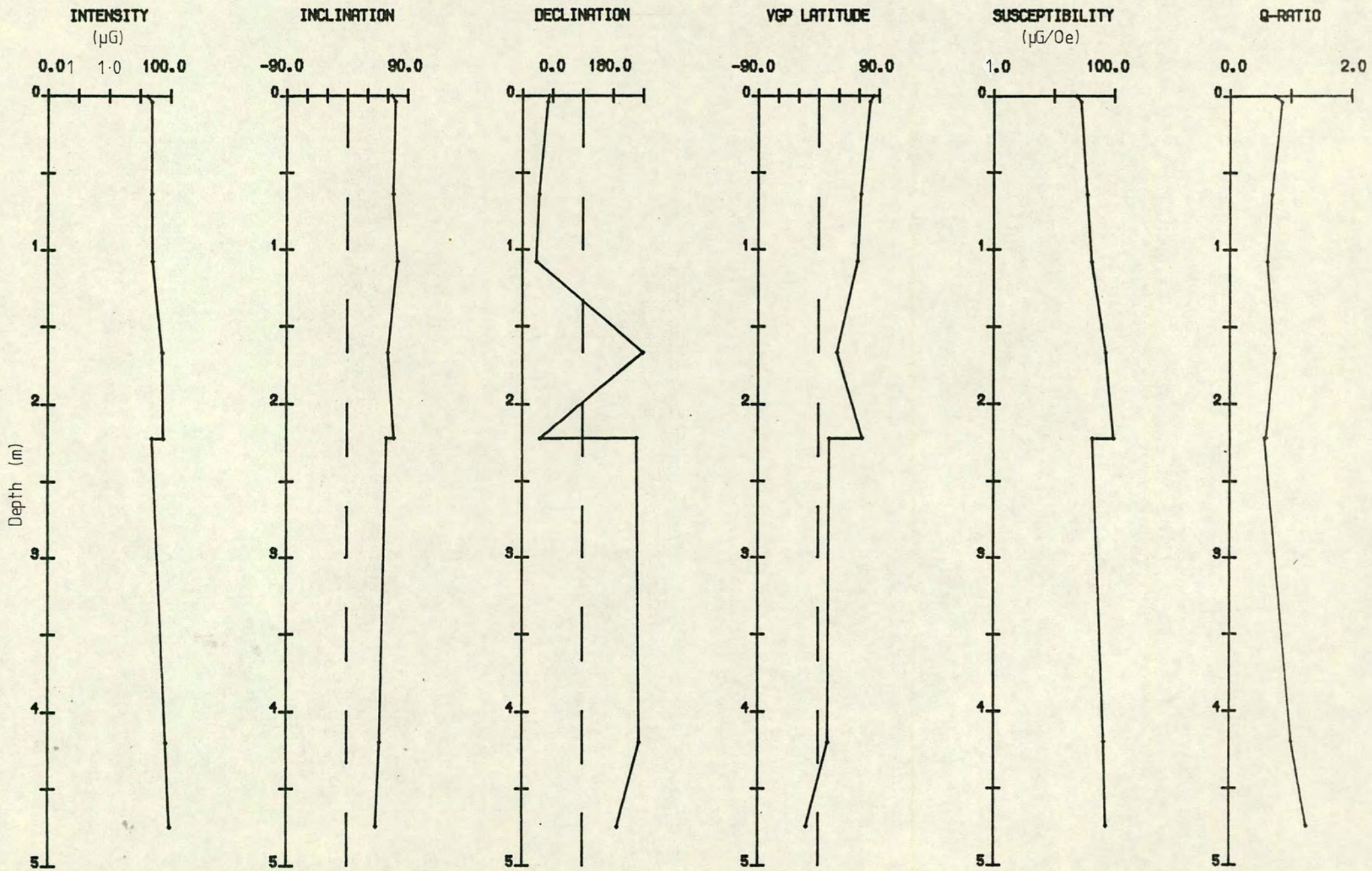


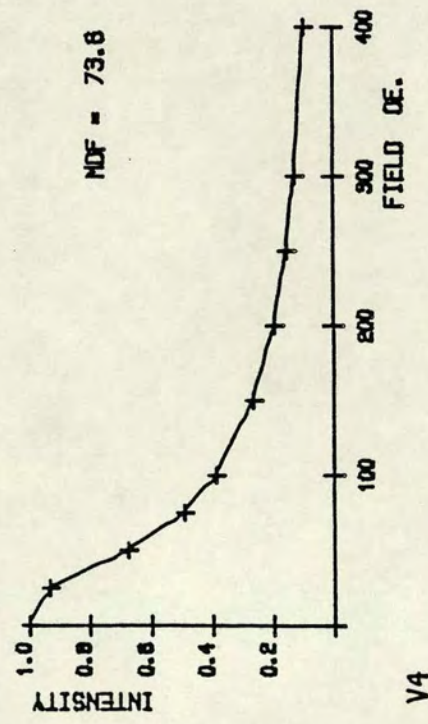
Figure 95. Average Pole Positions for all Soil Units

reasonably accurate positive results, with circles of 95% confidence about the directions of less than 20°. Units 5, 6, and 8 give directions which are intermediate. For the unweathered breccia directions are very scattered, in the weathered breccia directions become progressively more negative with depth. No adjacent samples were taken, however results from different levels are often quite different. The results of Section 3 show that Unit 5 is consistently intermediate. Samples toward the top of Unit 5 are more normal in both sections suggesting an overprint of a normal direction on a reversed direction, with the normal overprint being stronger towards Unit 4. This implies at least two periods of weathering, which may also affect Unit 8, although the results are not as conclusive. It is interesting to note that all of the soils at Bagaggera have very low coercivities except that developed on the flysch which loses very little of its remanence with demagnetization (as typified by sample BL7').

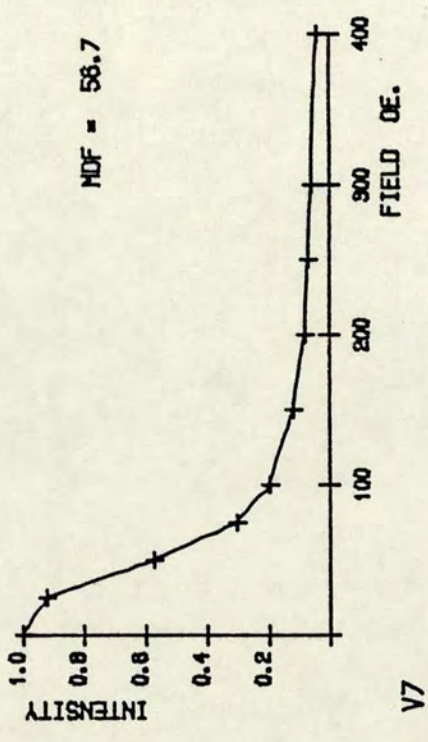
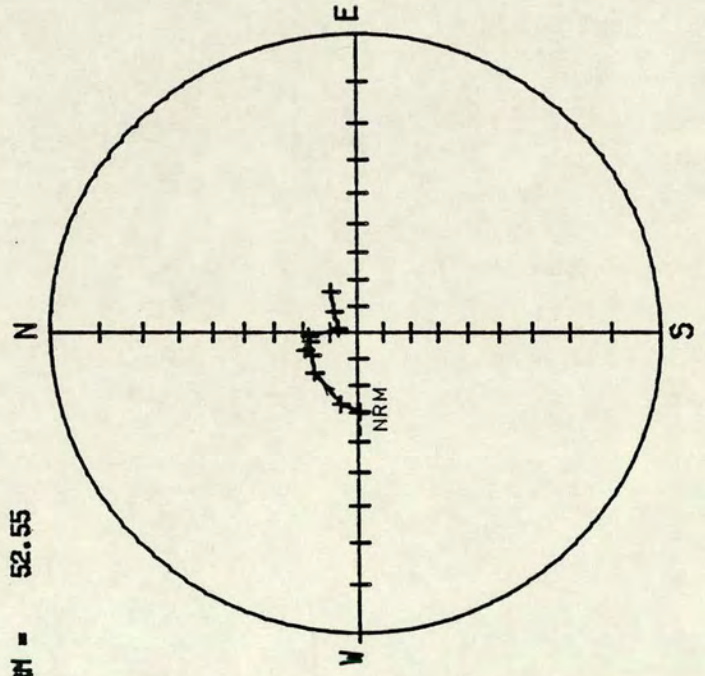
Vivaldi

The NRM results from Vivaldi are shown in Figure 96. Intensity is high averaging $42.6(\pm 24.3)\mu\text{G}$, inclinations are positive but declinations become southerly towards the base giving intermediate VGPs. Susceptibility averages $52.9(\pm 23.1)\mu\text{G}/\text{Oe}$ giving high Q-ratios ($0.79(\pm 0.22)$). Demagnetization (Figure 97) shows that samples are mainly stable, however those with southerly declinations change to northerly declinations (e.g. V4) Median destructive fields are low (57 to 183 Oe). At 150 Oe intensity had dropped by 73% to $11.4(\pm 2.8)\mu\text{G}$ (Figure 98). Except for the lowermost sample (V7) all the directions had become normal giving VGP latitudes of 75 to 90°. V7 retained its southerly declination to give a VGP at a latitude of 12°, in northern Africa. The samples show behaviour similar to the





V4
NRM = 52.55



V7
NRM = 91.87

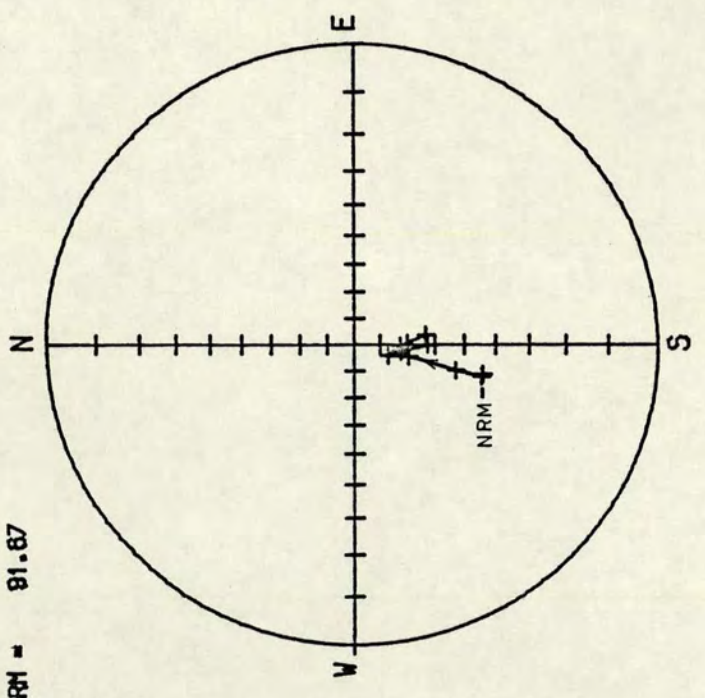
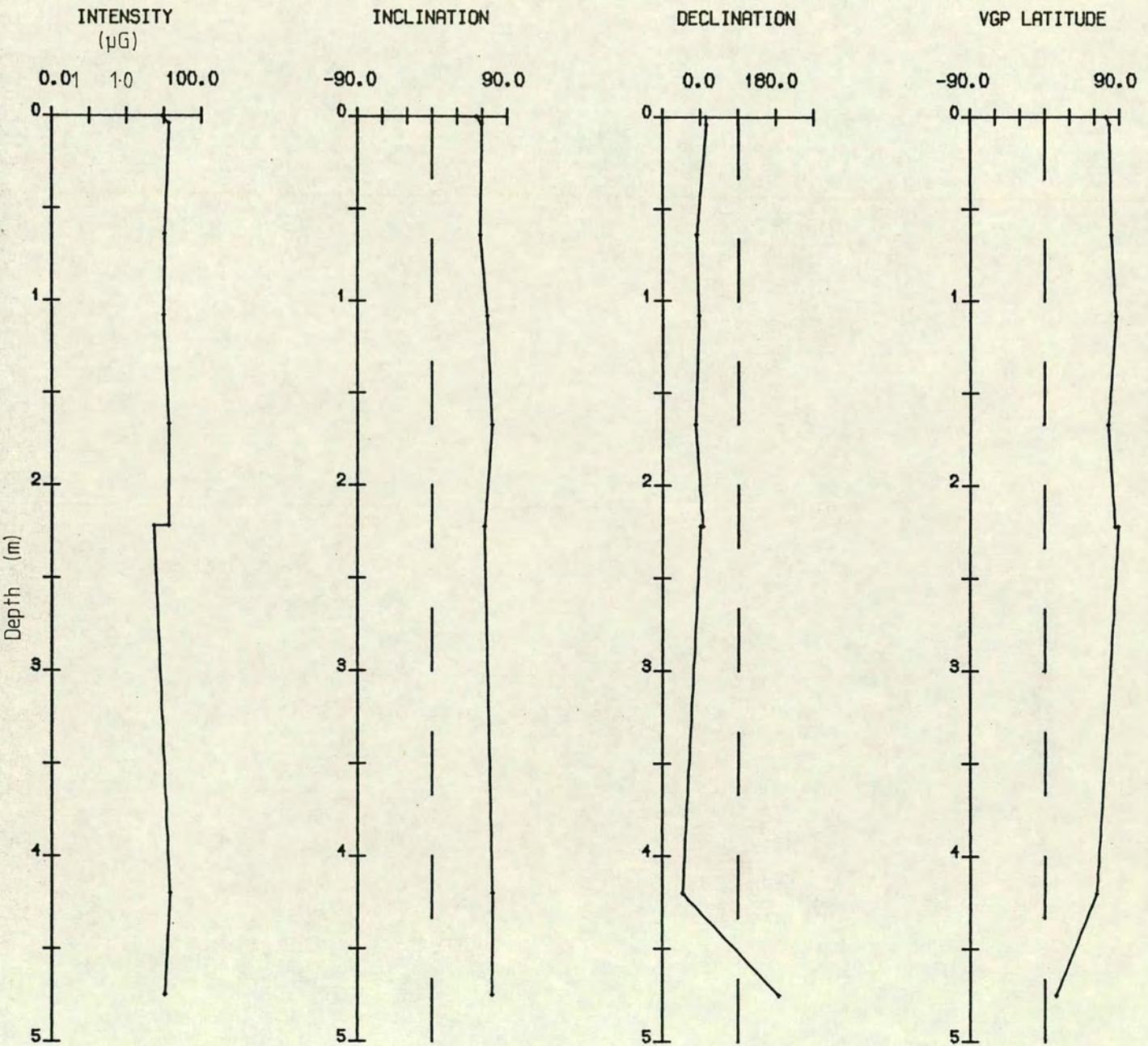


Figure 97. Examples of Pilot Demagnetization from Via Vivaldi

Figure 98. Results for Via Vivaldi after Demagnetization



upper four units at Bagaggera so it is unlikely that they correlate with Unit 5.

Ronco

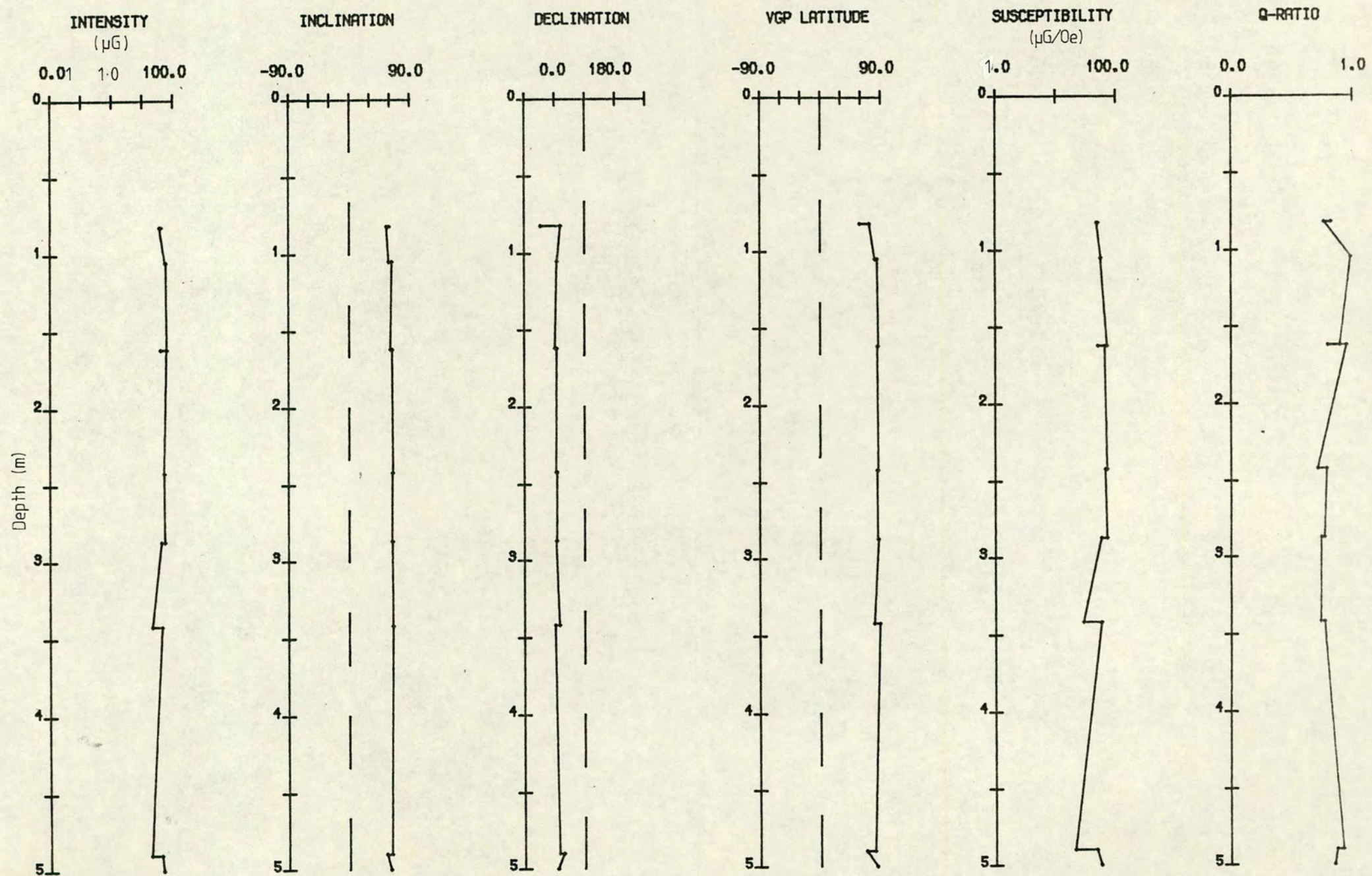
NRM results from Ronco show that intensity is more or less constant, averaging $45.8(\pm 12.6)\mu\text{G}$ (Figure 99). Susceptibility is high and more or less constant within the section ($54.6(\pm 13.8)\mu\text{G/Oe}$) giving Q-ratios averaging $0.84(\pm 0.10)$. Demagnetization (Figure 100) indicates that all samples are stable, although median destructive fields are low, as they are for most soils (ranging between 89 and 164 Oe). Results after blanket demagnetization (Figure 101) show very little change in direction, although intensity had dropped by 62% to $17.2(\pm 6.1)\mu\text{G}$. Inclination averages $62.2(\pm 5.8)^\circ$, however declination is slightly biased to the east giving VGP latitudes of 80 to 85° . Again these results show that soils are capable of carrying a very accurate remanence. The higher intensity compared with samples from Units 1 to 4 at Bagaggera suggest a slightly different process is involved in the formation of the remanence.

Southern Sub-basin

1. Section 8.

NRM intensity in the clays of Units 6 and 9 averaged $5.2(\pm 7.2)\mu\text{G}$, including the samples taken in 1981 and 1982. Unit 6a has higher intensity toward the bottom especially in the black clays. The lowermost 150cm of Unit 6b has lower intensity compared with the top of this Unit, and Unit 9, this low is also seen in susceptibility indicating that there was a reduction in magnetic mineral content during this interval. Susceptibility averages $7.7(\pm 3.6)\mu\text{G/Oe}$ throughout the section giving Q-ratios of about 0.6 (Figure 102).

Pilot demagnetization demonstrated that most of the samples



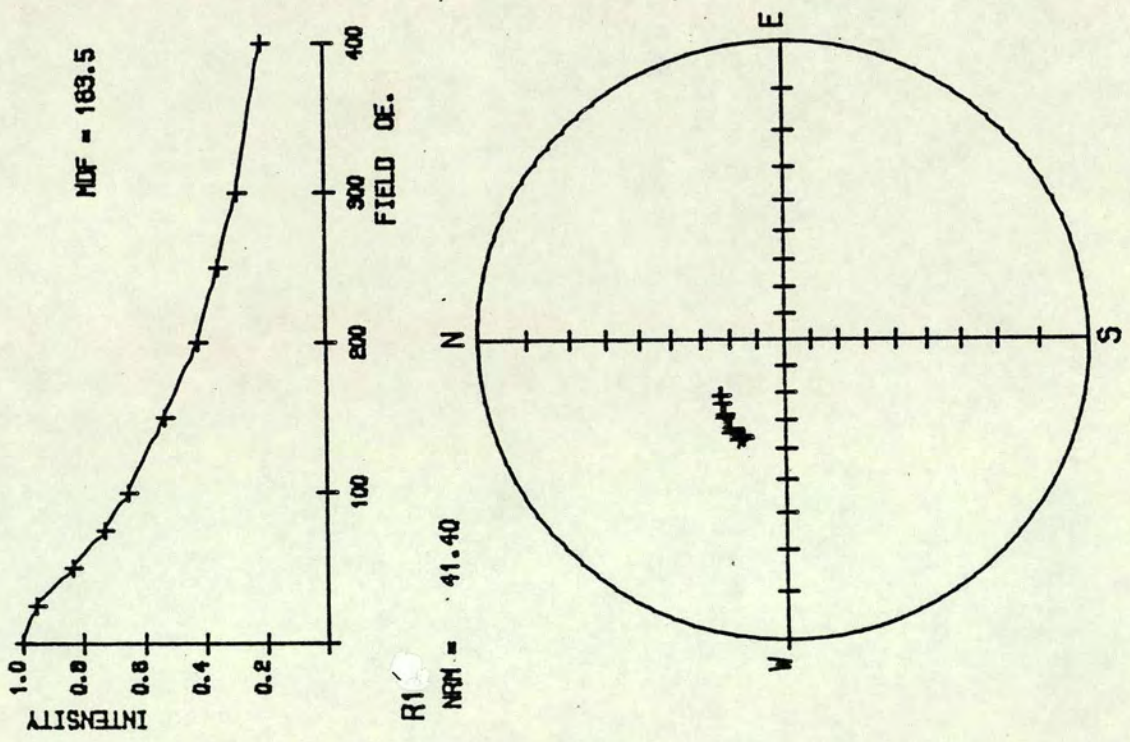
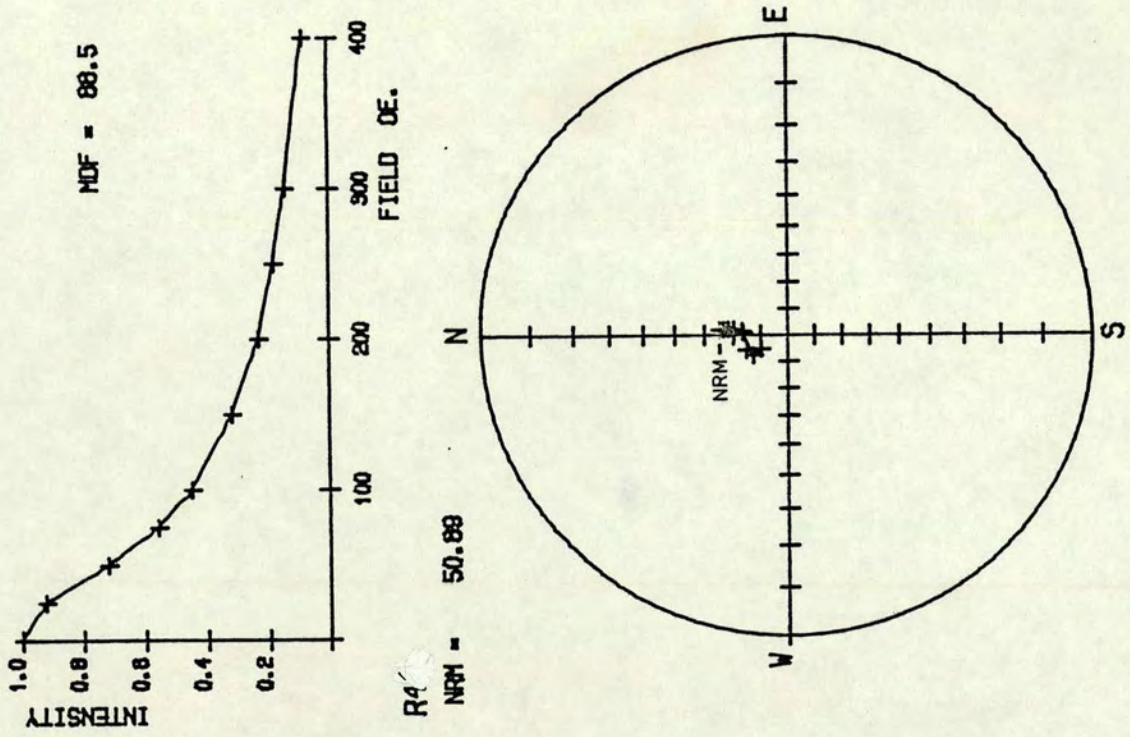


Figure 106. Examples of Pilot Demagnetization from Ronco

Figure 101 Results for Ronco after Demagnetization (150 Oe)

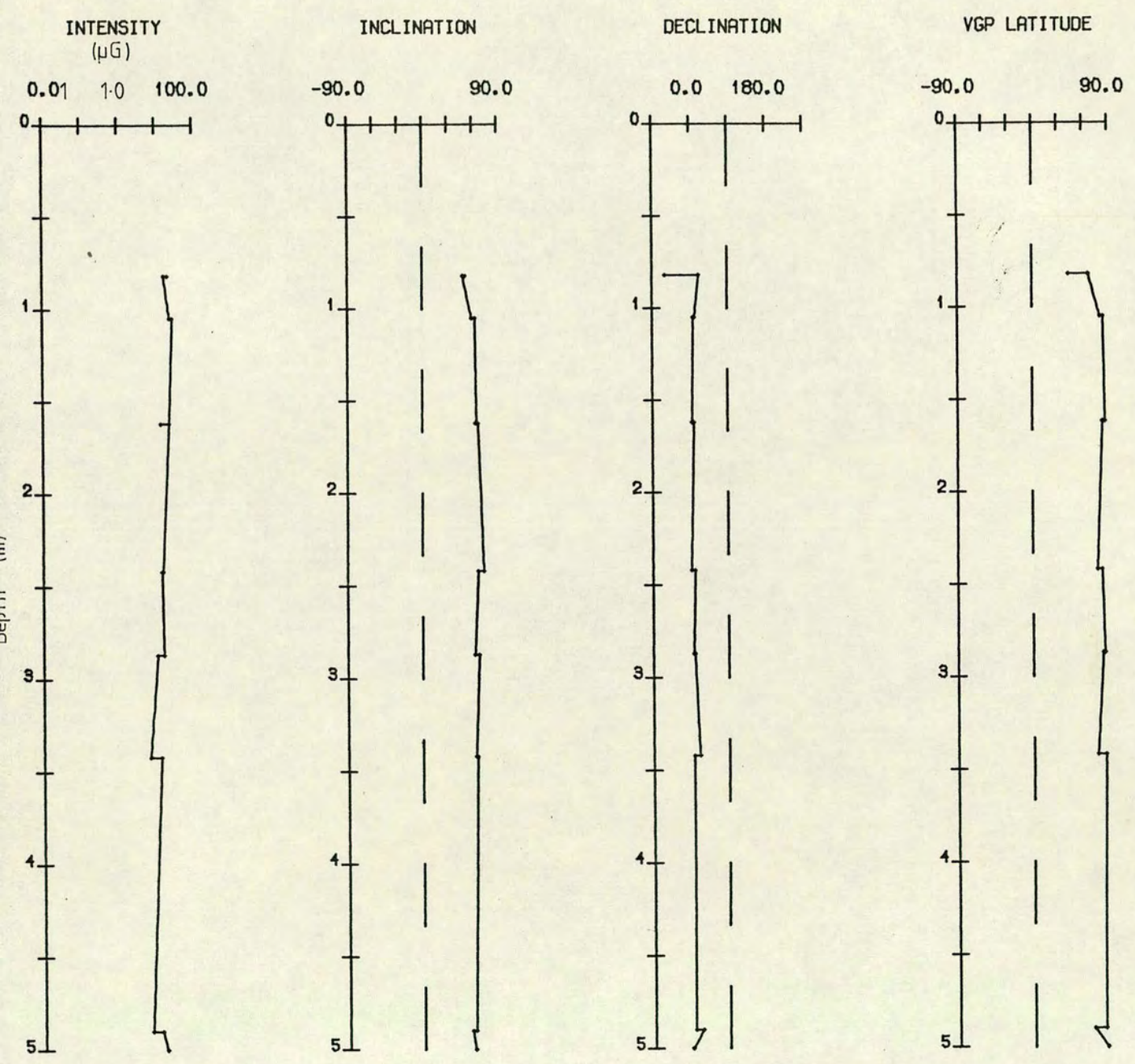
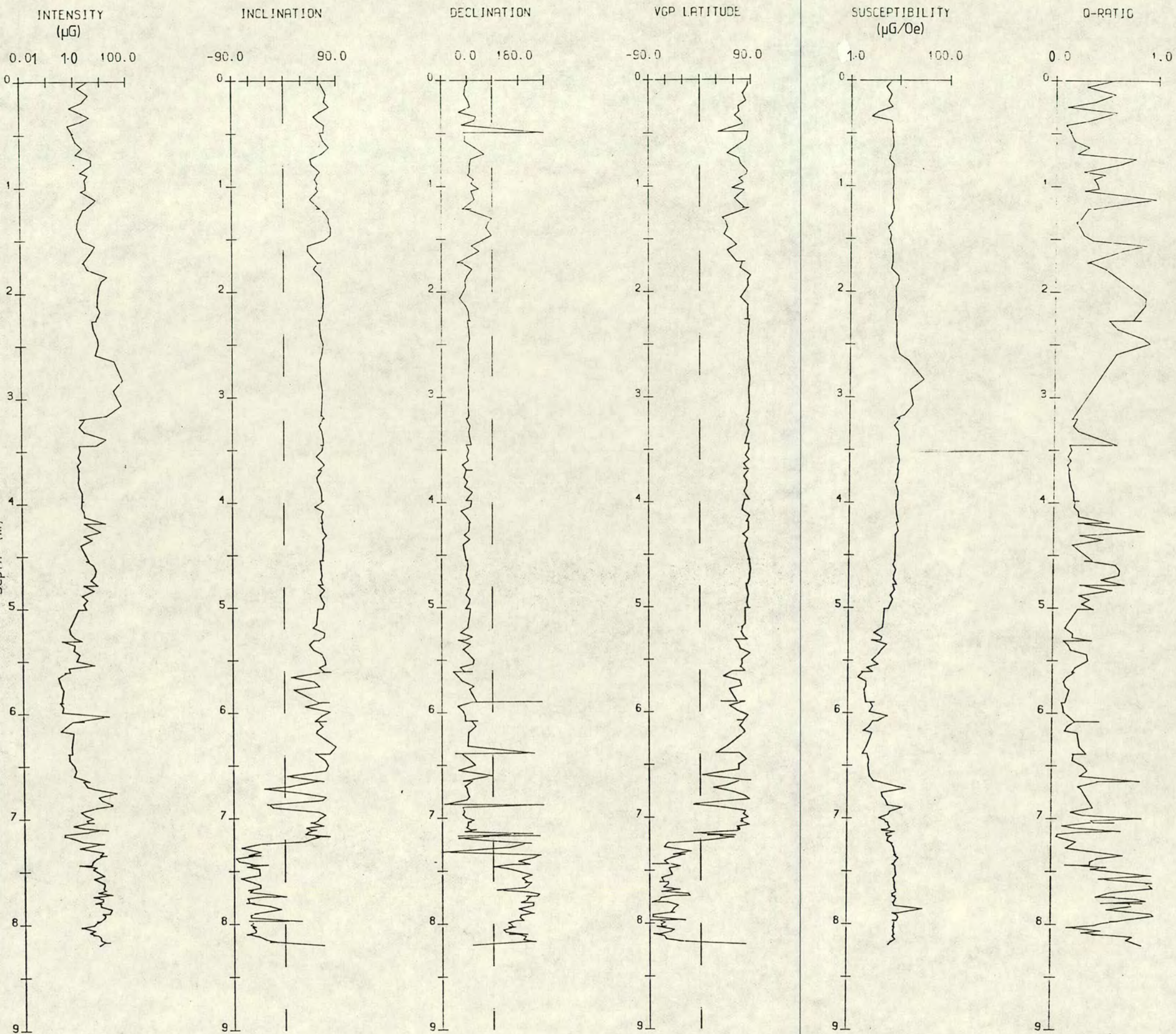


Figure 102. NRM Results for Section 8



possessed a stable remanence, carried by grains with a range of coercivities (Figure 103). Median destructive fields are generally between 300 and 500 Oe, however occasional samples at the top of Units 6a and 6b, and near the transition are softer (e.g. BS42 at 13cm, and BG80" at 711cm). Reversed samples do not show the presence of a normal overprint resulting from viscous remanence (BG97': 441cm). Most samples show no change in direction apart from the development of a spurious magnetization at 400 Oe or above. Samples in the transition zone show a small amount of movement: BG84' (719cm) changes from normal to intermediate, the softer component representing a younger magnetization.

The results after blanket demagnetization are shown in Figure 104. Intensity has been reduced by only 15% to an average of 4.4 ± 6.5 μ G, and shows a pattern similar to that seen at NRM. The lowermost samples are reversed, showing a fair degree of scatter. A reversed to normal transition occurs between 724 and 713cm, above which samples are normal apart from an excursion at 687 to 688cm, coinciding with Unit 7. The results show a large amount of scatter between the transition and about 5.60m, above which there is little variation. However between 1.30cm and 1.61cm there are low latitude VGPs caused by an eastward swing in declination. The decrease in scatter away from the transition is reflected by alpha 95 values for the averages of samples at the same level. These are less than 10° in the upper 2m, below which they increase to around 20 to 40°. Demagnetization does not improve the alpha 95 values except for the metre of sediment below the transition. It does, however, sometimes increase the latitude of low latitudes poles away from the transition zone, for example the palaeolatitude given by BG64' (660cm) changes from 3.7° to 37.0° with demagnetization.

Figure 103. Examples of
Pilot Demagnetization
from Section 8

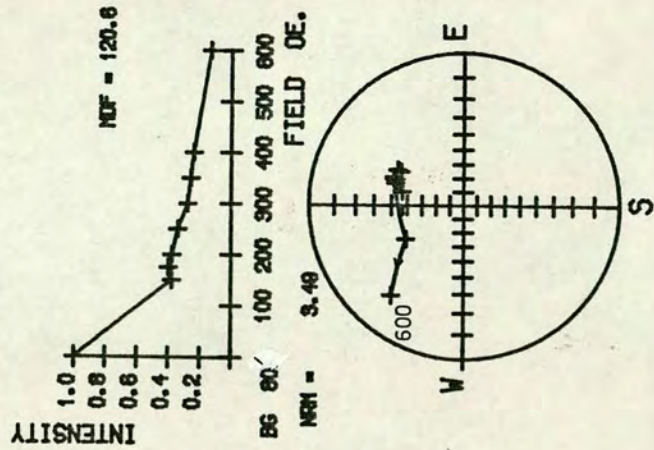
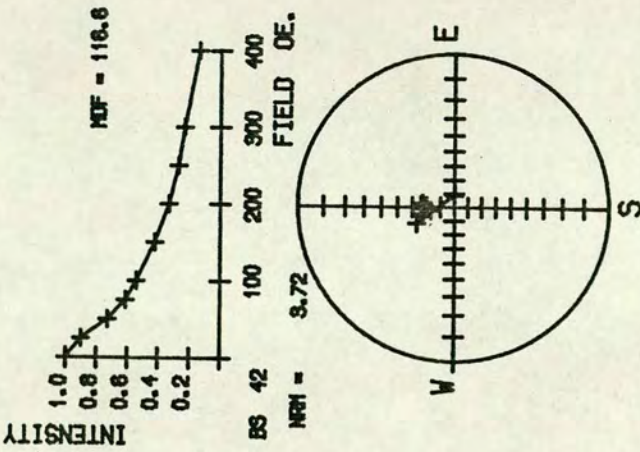
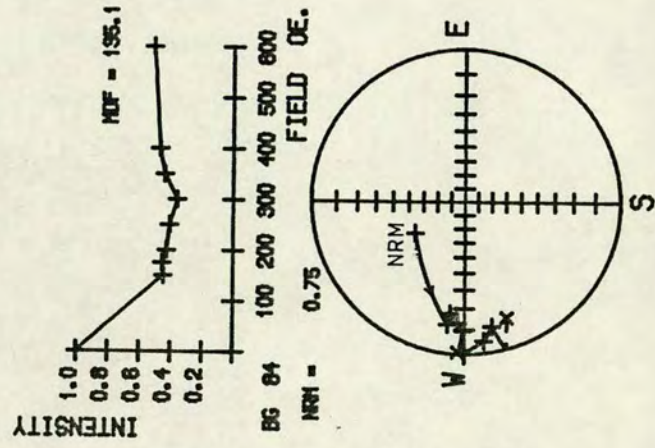
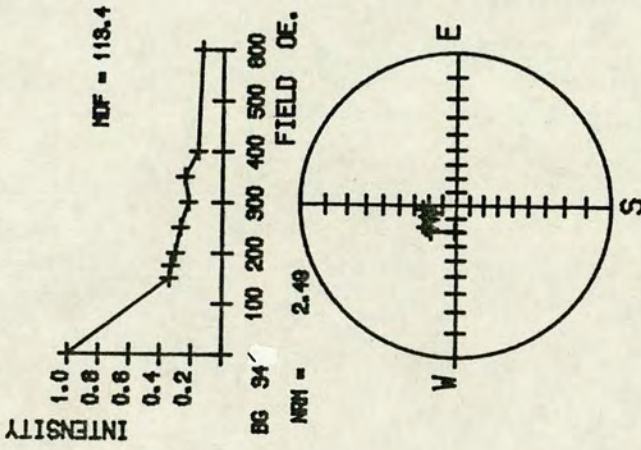
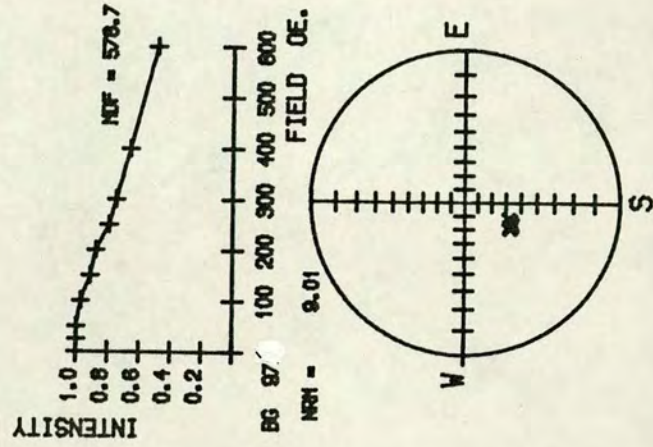
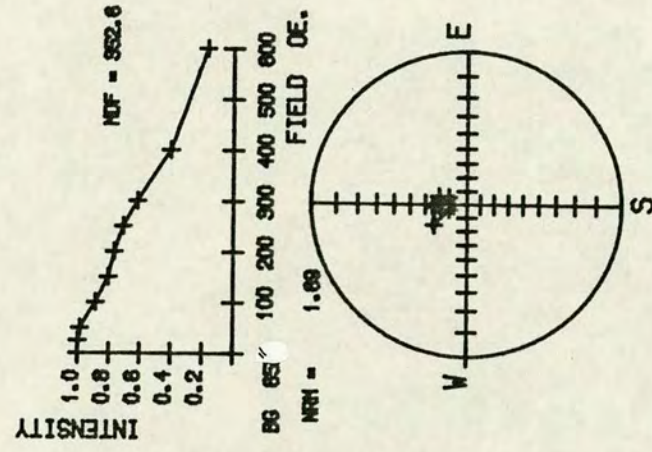
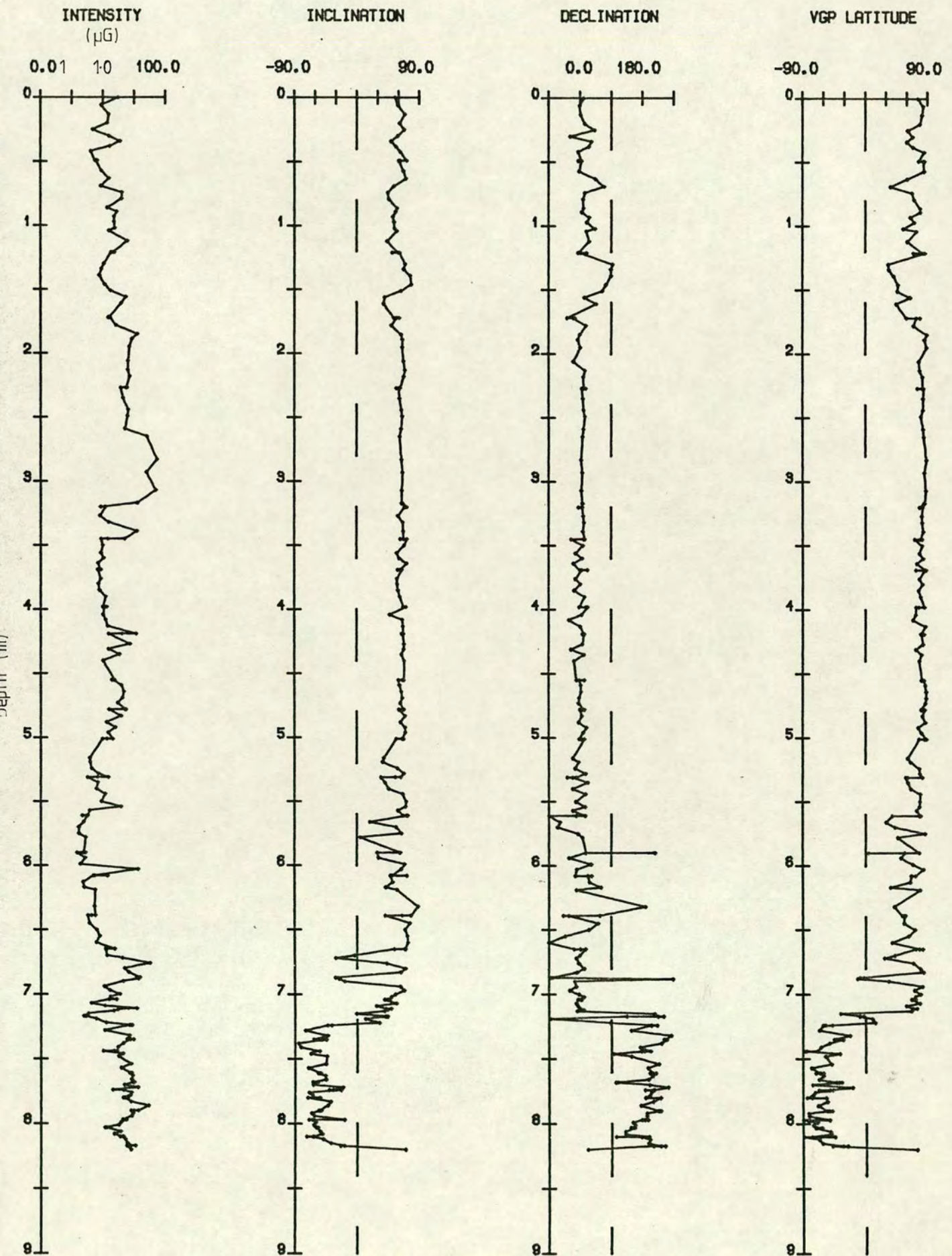


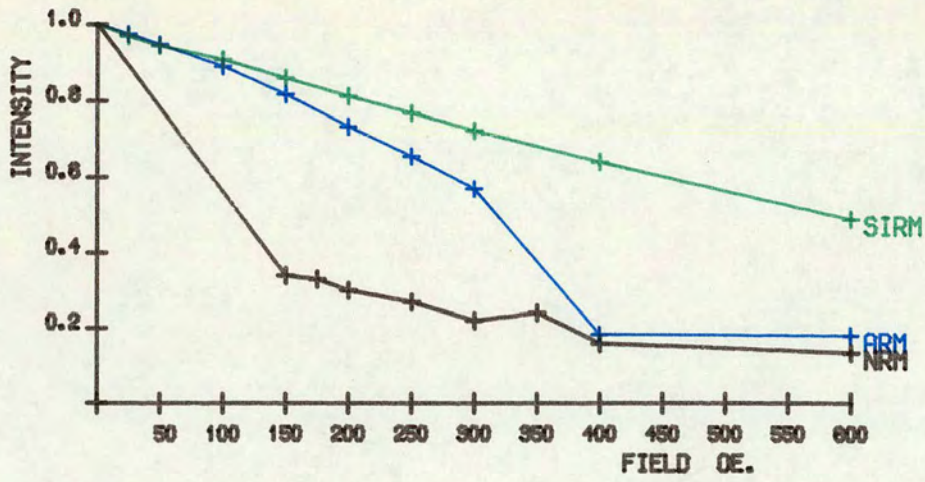
Figure 104 Results for Section 8 after Demagnetization (150 Oe)



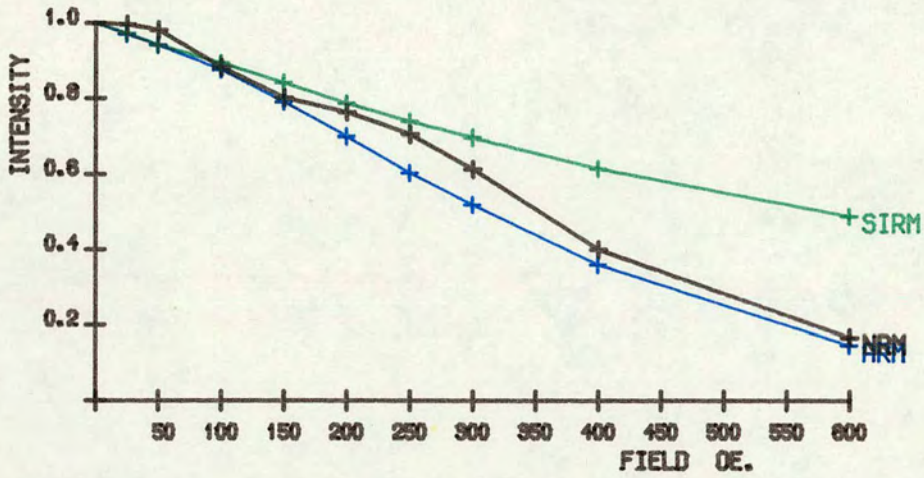
Synthetic magnetizations, which were given to the 1981 samples only, in general reflect the main variation in NRM intensity. Both ARM and SIRM averages are greater than at Section 9, and both show large variations ($20.7(\pm 21.6)\mu\text{G}$ and $670(\pm 710)\mu\text{G}$ respectively). SIRM is harder than ARM, median destructive fields for SIRM ranging from 400 Oe to greater than 600 Oe, and for ARM ranging from 280 Oe to 380 Oe (Figure 105). The difference between SIRM and ARM becomes more marked above 710cm. The hardness of NRM varies, in some cases being much softer than both ARM and SIRM (BG34', 501cm) and in other cases being harder (BG97', 761cm). Normalization of NRM by ARM or SIRM produces scattered values which are relatively low in the transition zone, higher between 25cm and 50cm above and below the transition, then low again further away. The transitional values are not significantly lower than the mean for the upper part of the section. The higher values bracketing the transition are not necessarily indicative of geomagnetic behaviour as it cannot be shown that the same range of grain sizes carries the natural remanence and the artificial remanence.

Hysteresis curves for IRM at section 8 (Figure 106) show that coercivity of remanence lies between 500 and 850 Oe, with S values of 0.19 to 0.73. Samples below BG91' (740cm) reach saturation by 2000 Oe; samples above BG75' (700cm) do not show signs of reaching saturation by 10,000 Oe. S values at the top of the section are lower than at section 9, however the coercivities of the carriers of the natural remanence and the colouring of the clays themselves suggest that any haematite present in Section 8 is of minor importance in the natural remanence.

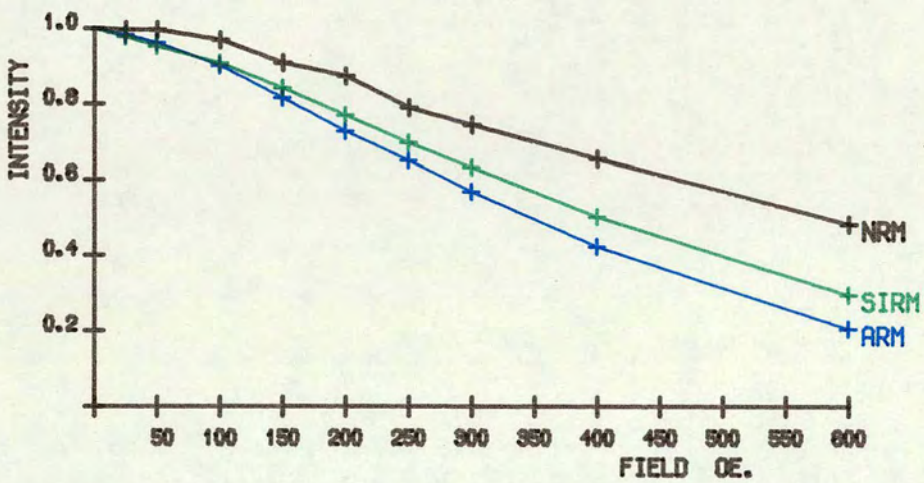
The resampled section of the transition, about 10m away from this section, consisted of alternating sands, silts, and clays. The coarse woody bed which was used as a marker was observed to be con-



BG 34A



BG 65B



BG 97A

Figure 105. Demagnetization of NRM, ARM, & SIRM at Section 8

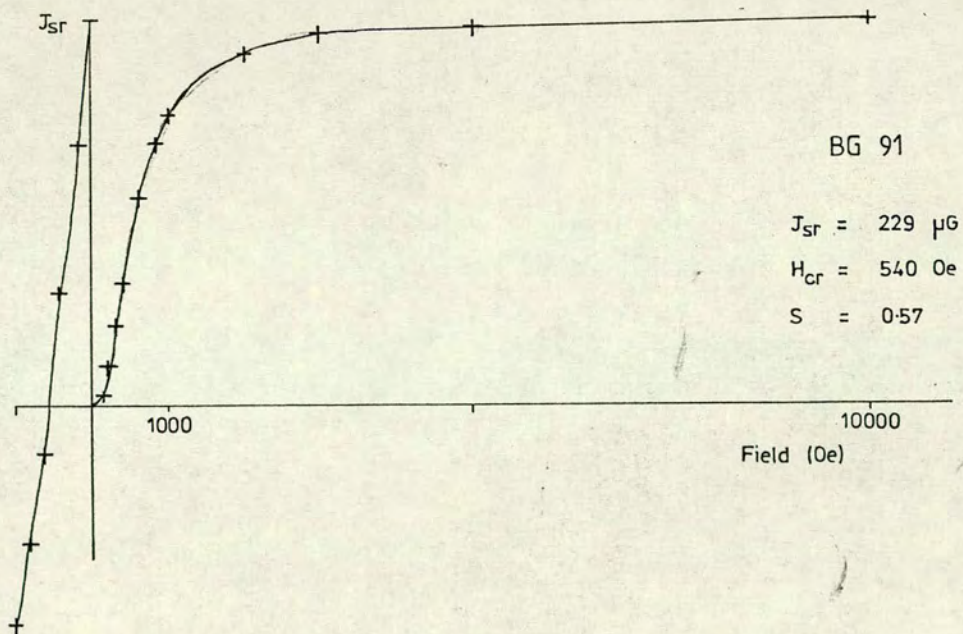
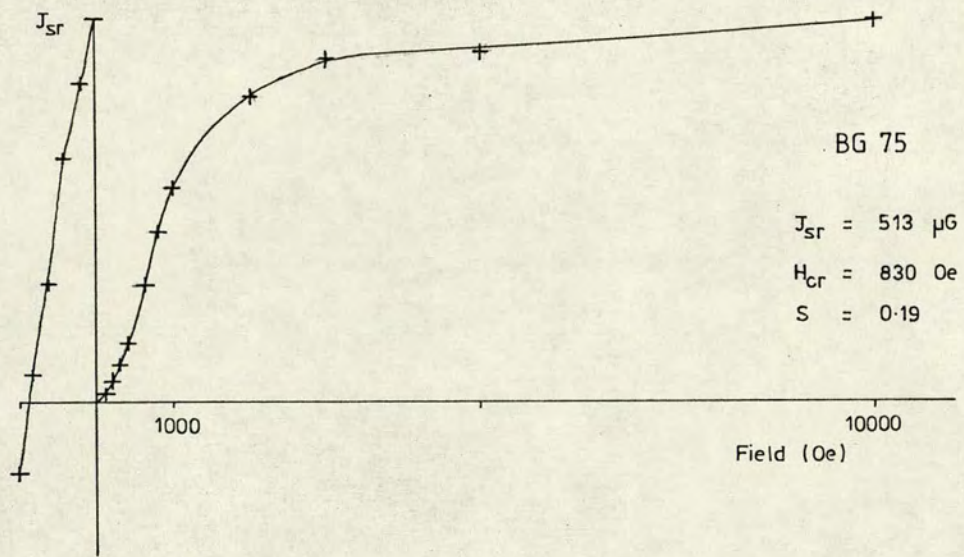
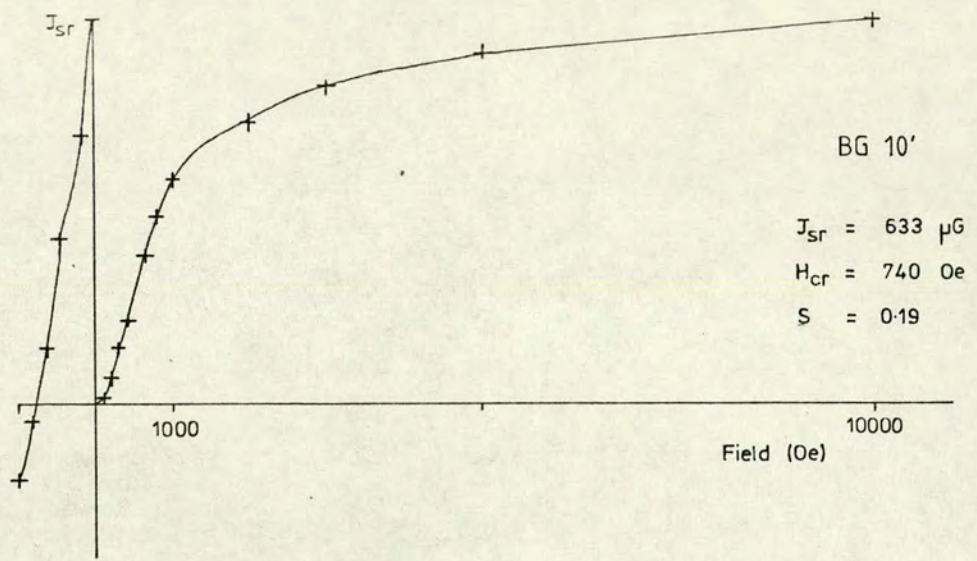


Figure 106. Examples of Hysteresis Loops for Section 8

tinuous between the two sections. At section 8 the transition occurred about 30cm beneath this bed. NRM results for the re-sampled section are shown in Figure 107. These are markedly different to Section 8 where the transition occurred within 10cm. Most of the inclinations are reversed and declination is mainly southerly, giving negative or intermediate poles.

Pilot demagnetization shows that most samples are stable, like those at Section 8 with median destructive fields of 250 to 520 Oe. Blanket demagnetization does not lead to any large change in direction. Only one sample (BS23, 15cm below the woody bed) is definitely normal. compared with an interval of about 25cm (9 samples) between the transition and the woody bed at Section 8, see Figure 108. The overall pattern is the same, that is a transition and an excursion so the most probable explanation is that the increased sand content at the second site has blurred the signal.

2. Section 9.

The NRM directions for section 9, together with the remanent intensity, susceptibility, and Q-ratio are shown in Figure 109. Intensity shows a step in values coinciding with the first visible signs of oxidation at 113cm (more complete oxidation is seen above 98cm). Below the step intensity averages $4.6(\pm 3.3)\mu\text{G}$, above 113cm average intensity drops to $0.2(\pm 0.1)\mu\text{G}$. Susceptibility is only slightly lower above 113cm but not significantly so, the average throughout the section is $7.9(\pm 1.8)\mu\text{G}/\text{Oe}$. Low values are seen between 98cm and 113cm, reaching a minimum of $3.4\mu\text{G}/\text{Oe}$ at 103cm. Q-ratios reflect the step seen in the intensity curve, averaging $0.5(\pm 0.4)$ in the blue clays, and $0.03(\pm 0.02)$ in the brown-orange clays.

The direction of the natural remanence shows a marked change

Figure 107. NRM Results for the reampled transition

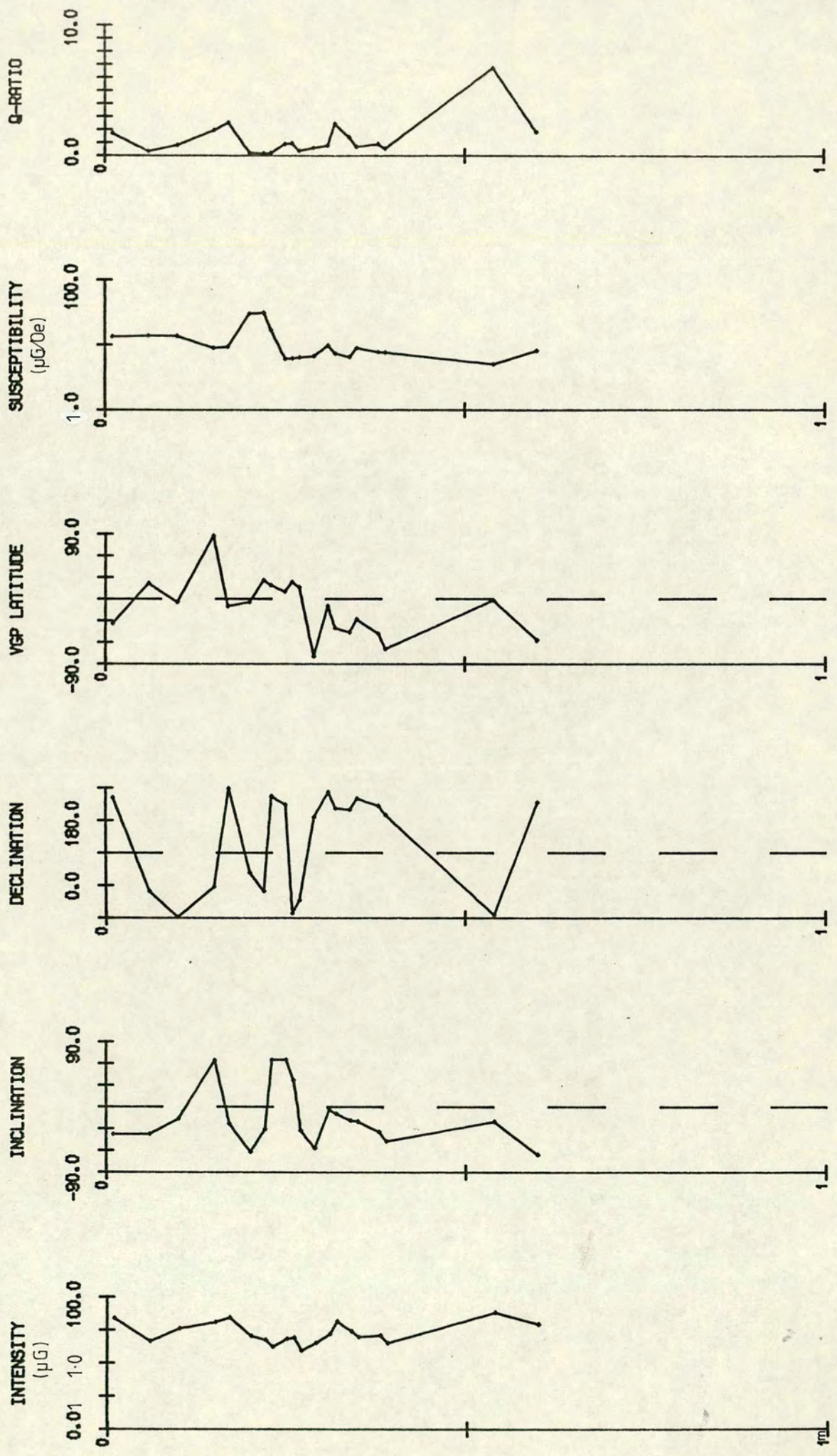


Figure 108. Comparison of two records for the transition after demagnetization

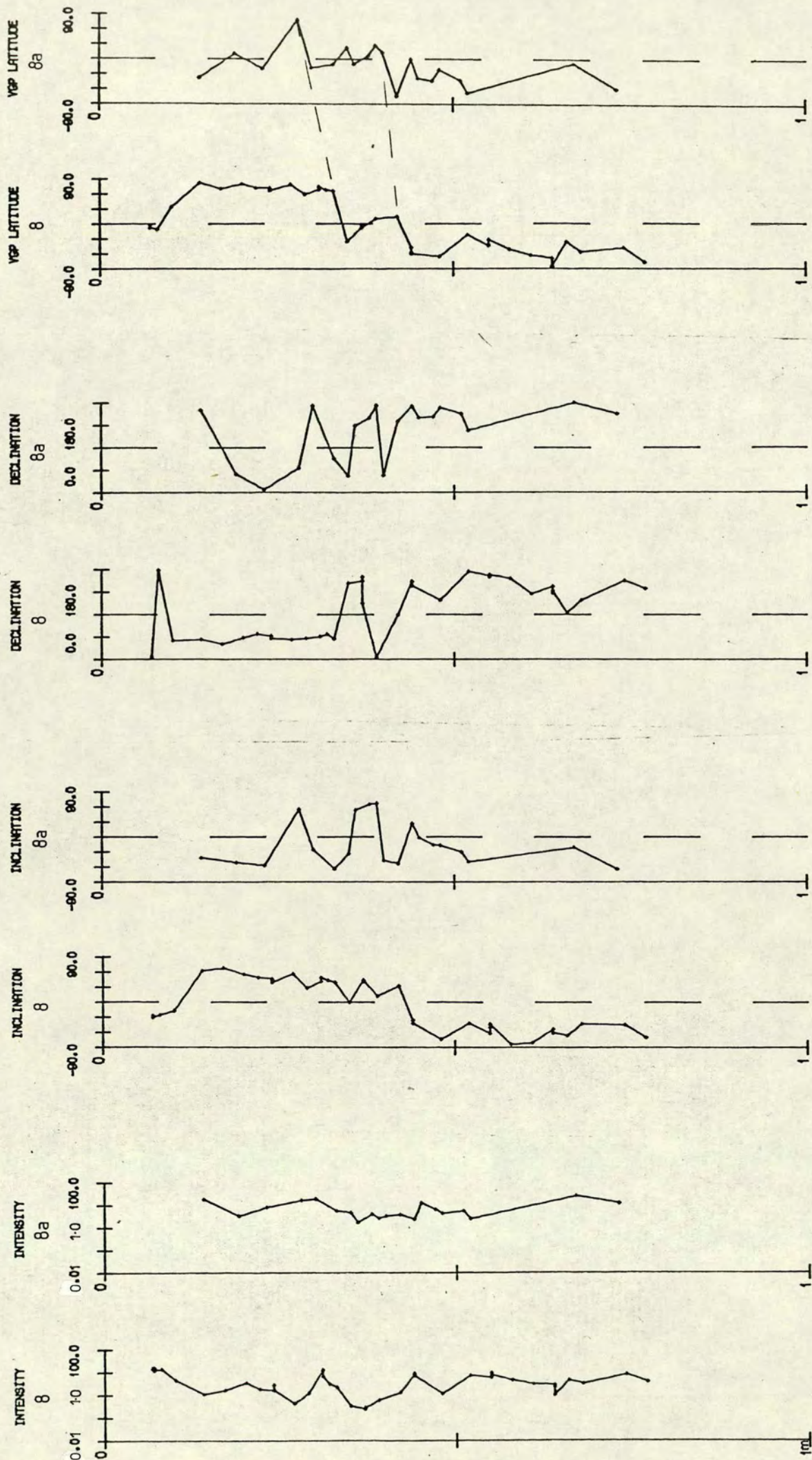
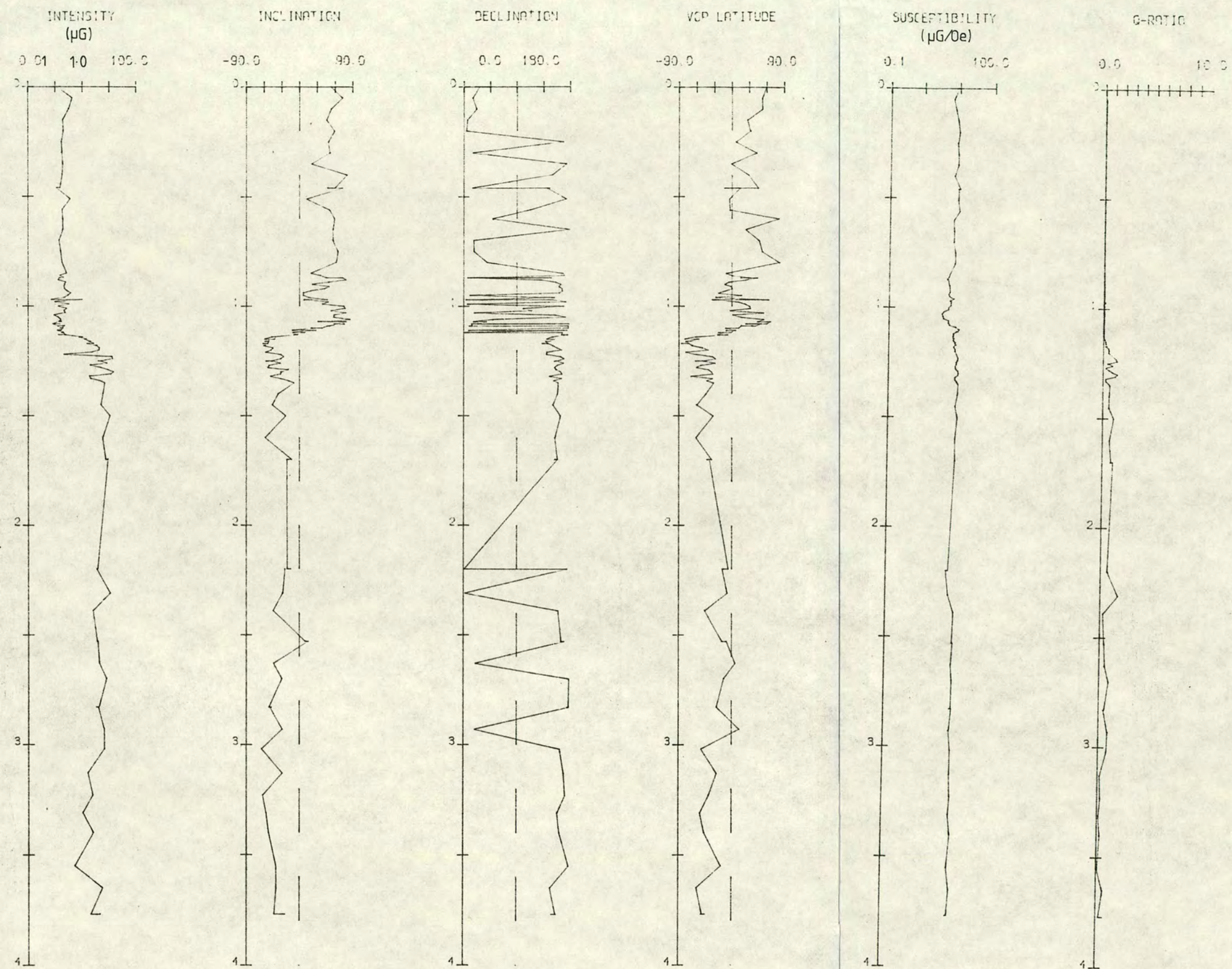


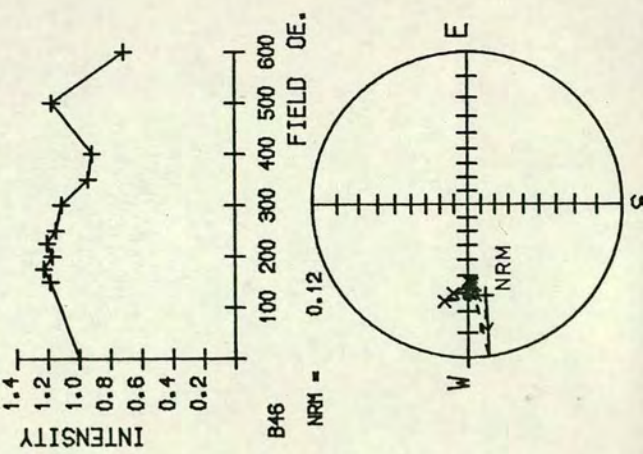
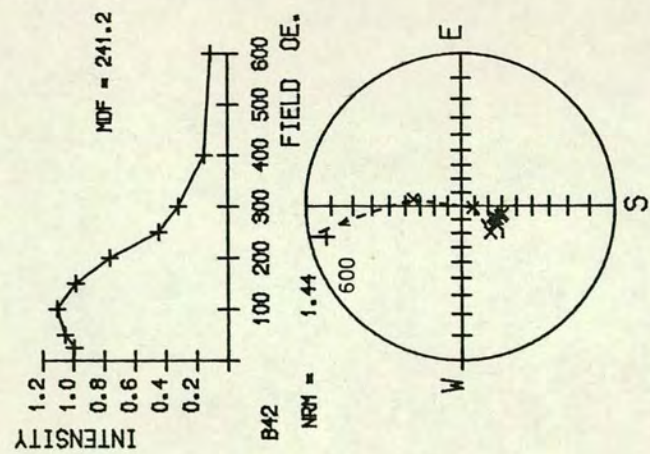
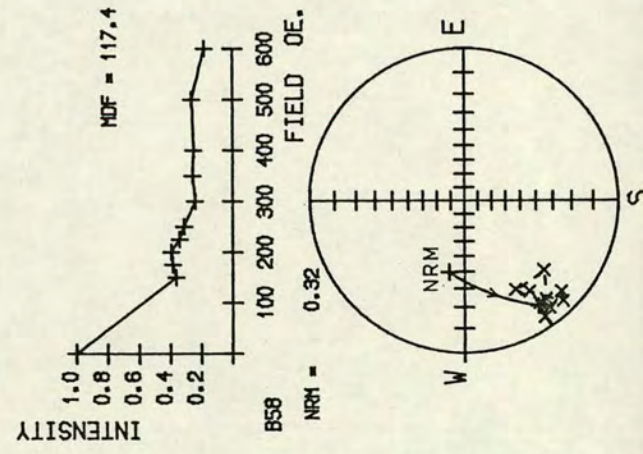
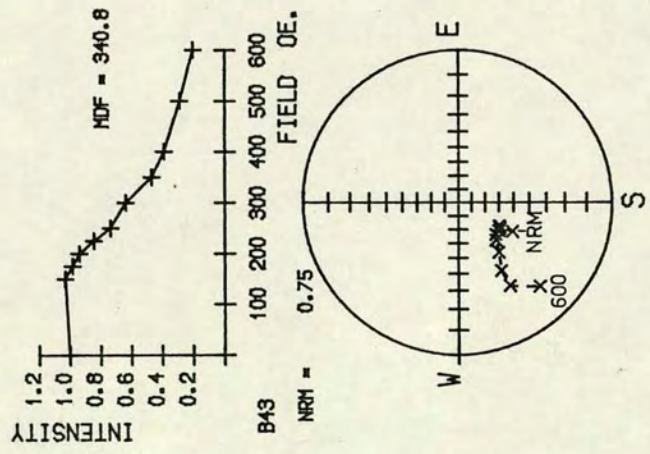
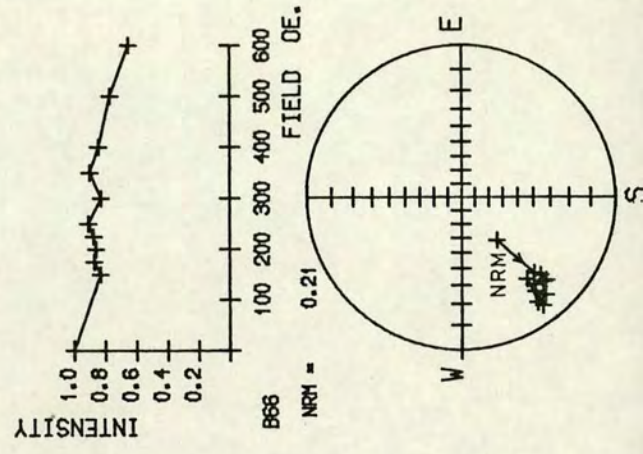
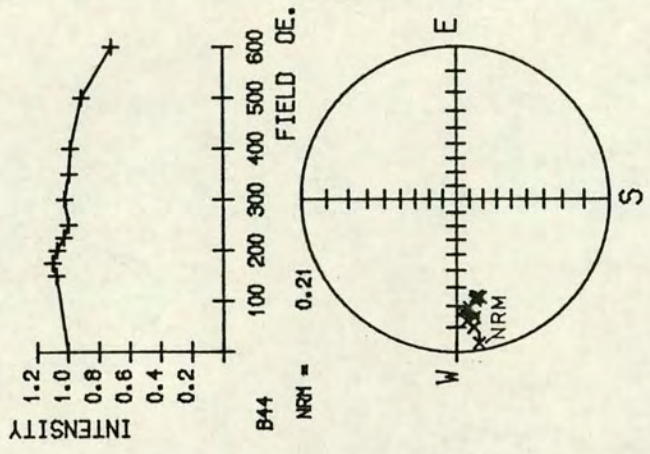
Figure 109. NRM Results for Section 9



coinciding with the change in intensity at 113cm. Inclination is mainly negative below this averaging $-39.4(\pm 15.1)^\circ$ between 113cm and 107cm inclination becomes positive, and averages $45.1(\pm 23.4)^\circ$ in the upper part of the section, although low inclinations are seen between 93 and 97cm. Declination is reversed below 113cm, most values lying to the west of south. Above 113cm the scatter of values becomes much greater, with rapid oscillation between normal and reversed directions. The quality of the results can be analyzed by studying the alpha 95 values for averages of groups of three samples taken at the same level. Below 113cm alpha 95 values lie between 3.0° and 18.0° ; between 113cm and 97cm they vary between 18° and 108° , above which they are more constant at 32° to 48° . Virtual geomagnetic pole (VGP) latitudes for the NRM directions reflect the step in inclination, changing in general from southerly latitudes to northerly latitudes, however the pole does not reach high normal latitudes in the upper part of the section, and show a large amount of scatter.

Demagnetization characteristics can also be classified into two groups: those of oxidized and unoxidized samples. Below 113cm samples are generally stable, with little or no change in direction, and median destructive fields of between 240 and 590 Oe (Figure 110). Sample B42 (115cm) shows a slight increase in intensity up to 100 Oe, which is indicative of a normal viscous remanence superimposed on the reversed primary remanence. In the oxidized clays, low intensity causes larger scatter in directions between demagnetization steps because of the relative increase in noise. The samples generally change direction between 1 and 150 Oe, then remain more or less stable (e.g. B46 at 111cm and B66 at 91cm). Intensity sometimes decreases between 0 and 150 Oe if a change in

Figure 110. Examples of
Pilot Demagnetization
from Section 9



direction occurs. After 150 Oe there is very little change in intensity (compare B44 at 113cm with B43 at 112cm). Median destructive fields are generally either lower than 150 Oe (B58 at 99cm) or greater than 600 Oe (B44). The general trend for this upper set of samples is toward a direction with low inclination and usually southerly or southwesterly declination.

The directions after blanket demagnetization (Figure 111) show a step in inclination at 113cm as at NRM, but while the lower samples have a similar value to NRM ($-39.9(\pm 16.3)$) the upper samples have decreased to $21.5(\pm 18.7)$. Declinations are mainly between 180 and 270° throughout the section giving VGP latitudes of 60° S to 30° S in the lower part, and 30° S to 0° in the upper part. The decrease in intensity after blanket demagnetization is proportionally greater in the upper part of the section (35% compared with 10%) indicating that a greater percentage of the remanence in the oxidized samples is carried by grains with low coercivities. The grouping of samples at the same level is not generally improved by blanket demagnetization; between 110 and 117cm alpha 95 values drop slightly but above this they increase somewhat.

The intensity of ARM averages $15.0 \mu\text{G}$, and is higher in the lower part of the section, though not significantly so ($24.8(\pm 13.2)\mu\text{G}$ c.f. $8.4(\pm 4.3)\mu\text{G}$). SIRM averages $350 \mu\text{G}$ showing a more marked decrease from $531.7(\pm 405.5)\mu\text{G}$ to $145.7(\pm 53.1)\mu\text{G}$ above 113cm (see Figure 112). SIRM is more resistant to demagnetization than ARM, however at 113cm (B44) the curves are similar up to 250 Oe (Figure 113). Median destructive fields are 300 to 500 Oe for SIRM, 250 to 300 Oe for ARM, both becoming lower nearer the top of the section. According to the modified Lowrie-Fuller

Figure 111. Results for Section 9 after Demagnetization (150 Oe)

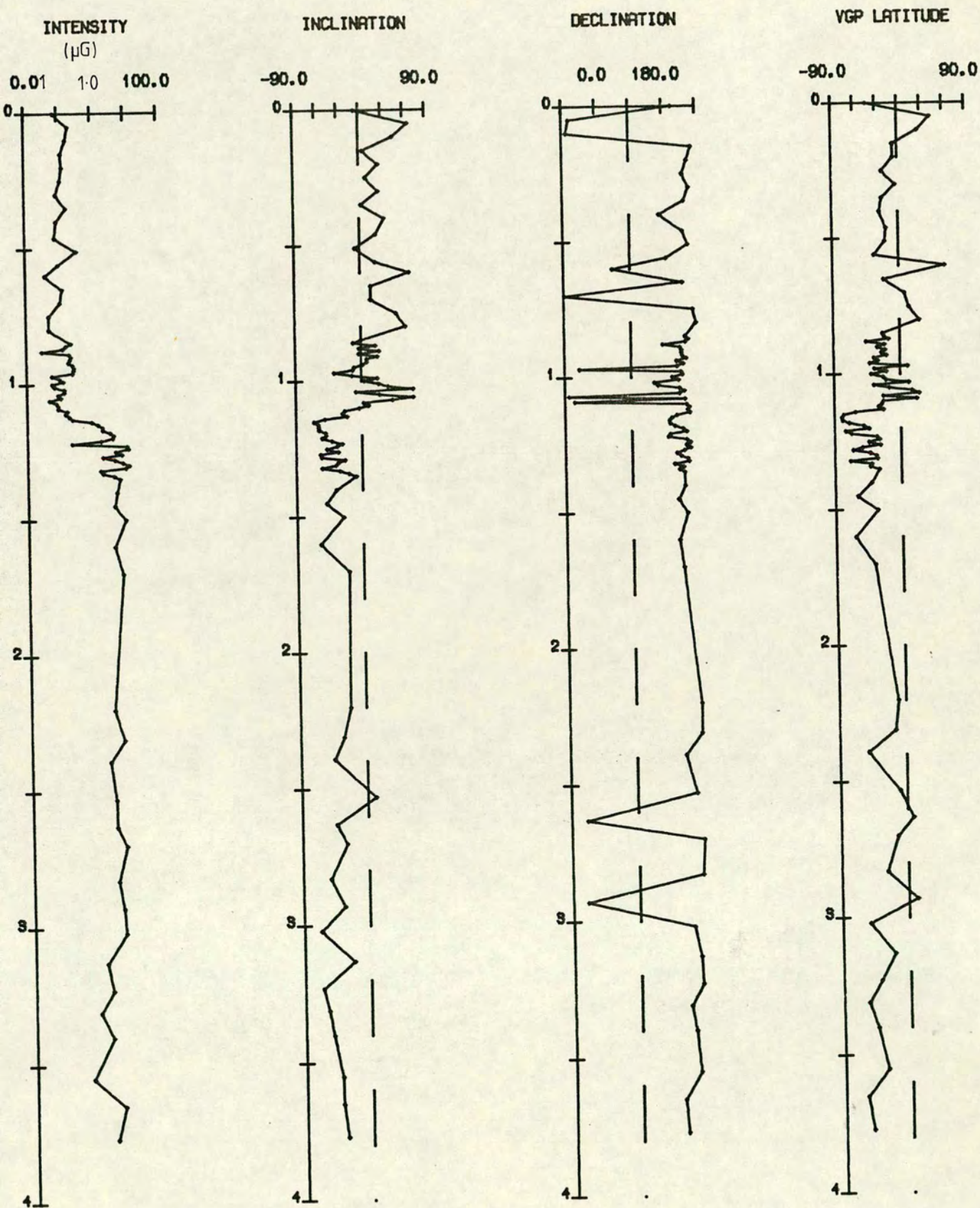
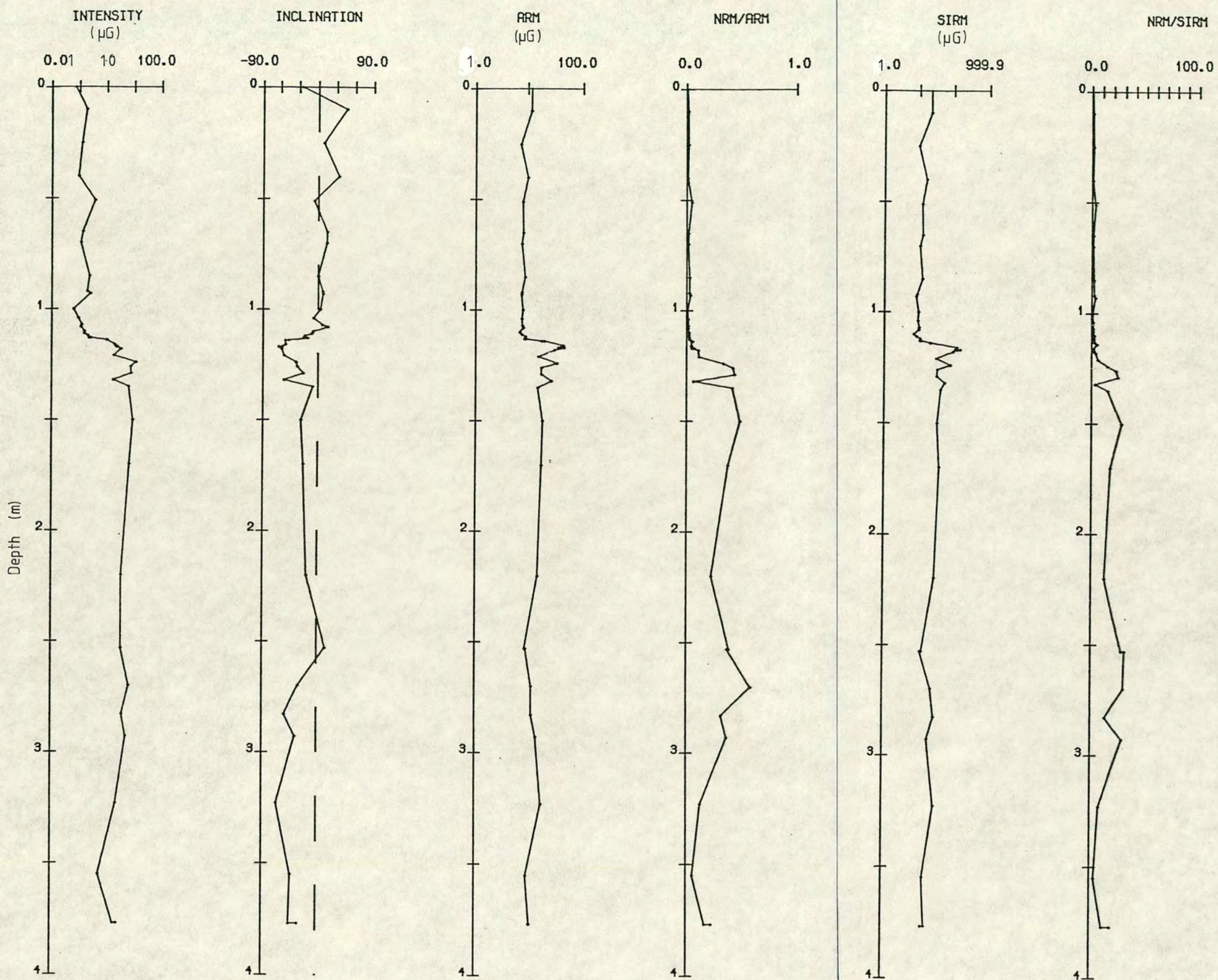
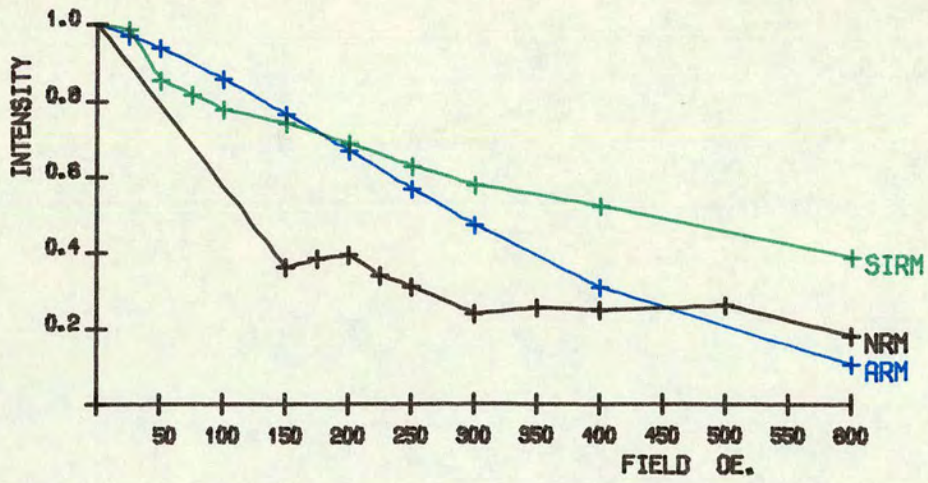
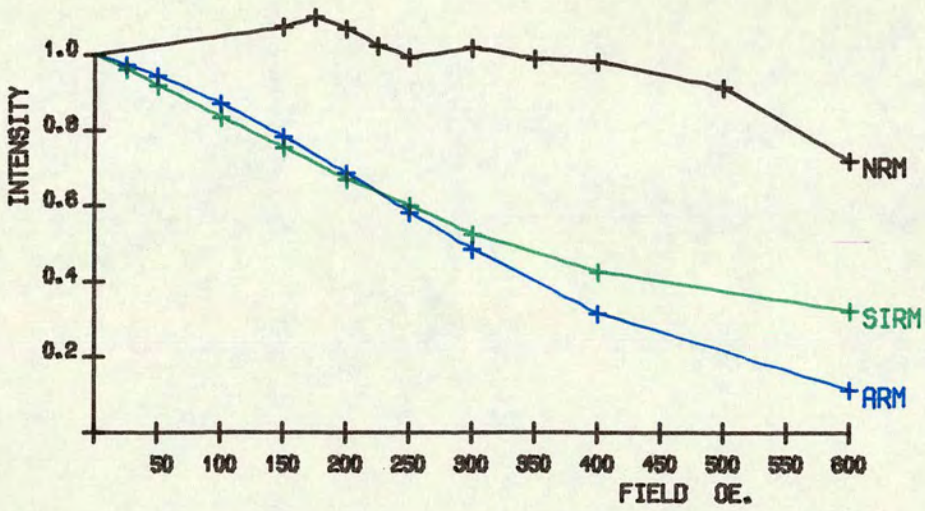


Figure 112. Normalised intensity for Section 9

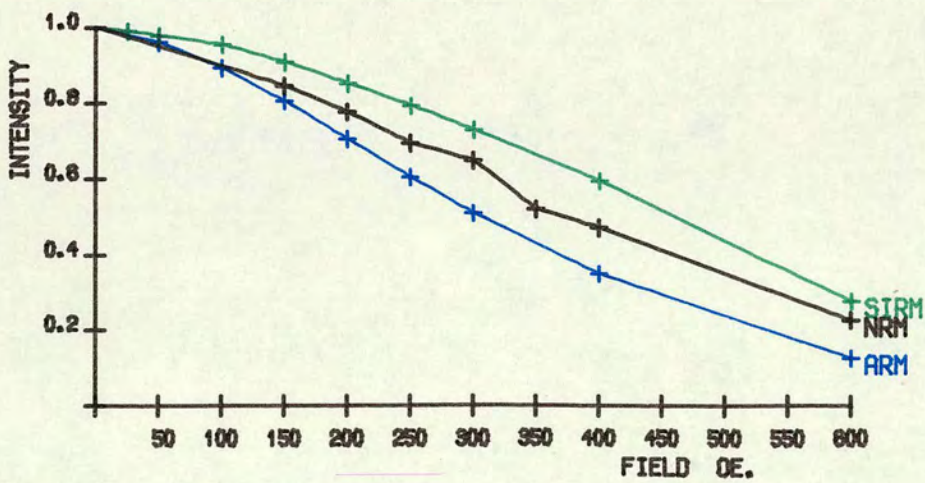




B58



B44



B40

Figure 113. Demagnetization of NRM, ARM, & SIRM for Section 9

test (Johnson et al, 1975) a harder SIRM when compared with ARM indicates that coarser, multi-domain grains are more abundant than finer, single domain grains. The NRM demagnetization curves show variation in comparison with synthetic magnetizations above 113cm the NRM has two components, one very soft and one very hard. Below 113cm the NRM is sometimes softer, sometimes harder than SIRM, but always harder than ARM. Towards the bottom of the section the NRM and SIRM curves coincide up to 200 Oe. Due to the variety of magnetic carriers displayed by the NRM, it is not, however, possible to normalize intensity using artificial magnetizations, the dominant feature of the normalization curves (both initially and after blanket demagnetization) is the decrease above 113cm.

Study of IRM hysteresis reveals that none of the samples become saturated at 1000 Oe, and samples above 113cm (B50' to B89') do not show signs of becoming saturated at 10,000 Oe (Figure 114). Coercivity of remanence is between 540 and 770 Oe, with S values ranging from 0.13 to 0.64. In general S decreases up the section with a step from 0.5 to 0.6 below 113cm down to 0.3 to 0.5 above 113cm. Values of S of less than 0.6 indicate the presence of large quantities of haematite in the section, this conclusion is supported by the coercivity of NRM above 113cm and by the decrease in SIRM. Attempts to determine the grain size of magnetite in the section by comparing susceptibility of ARM and low field susceptibility could be hampered by the presence of haematite; however the results suggest a decrease in size up to 113cm, than a return to larger grain sizes above, (Figure 115).

The palaeomagnetic history of Section 9 at Bagaggera can be interpreted as follows. The lowermost 2.87m of blue-grey clay were deposited at a time of reversed polarity, recorded by the natural

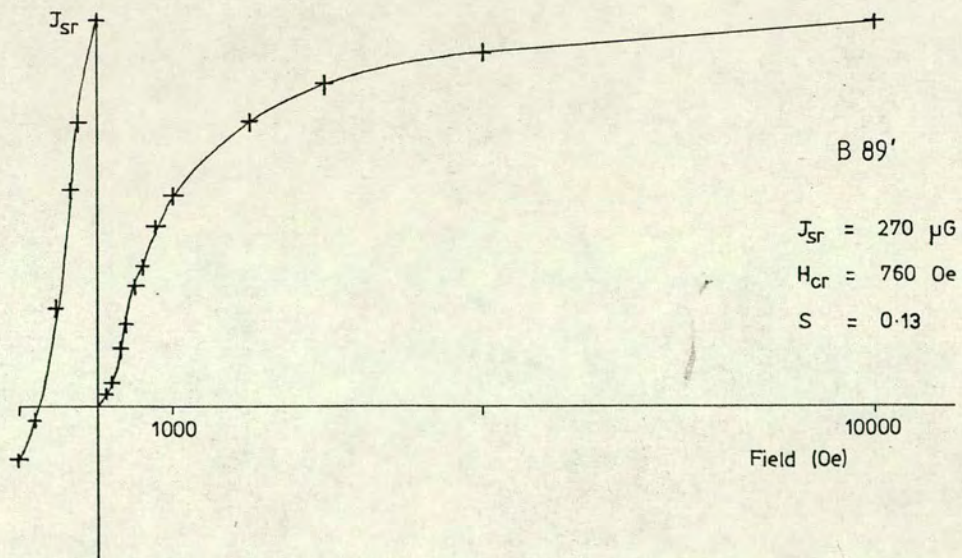
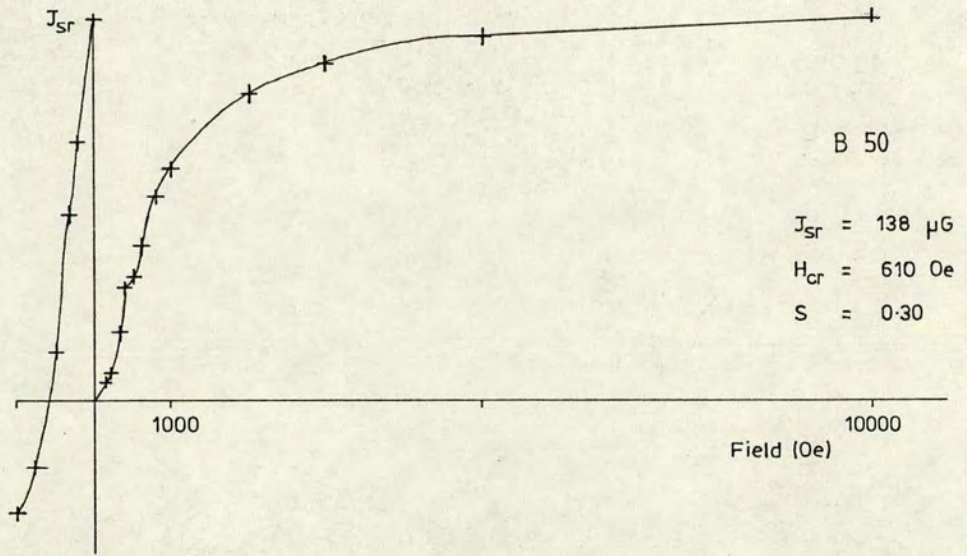
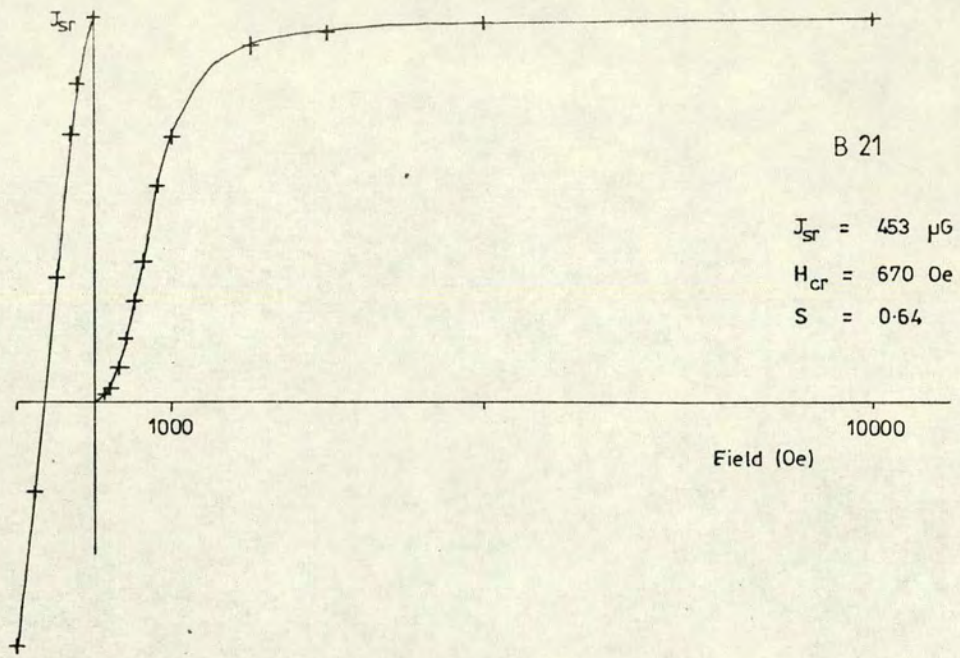


Figure 114. Examples of Hysteresis from Section 9

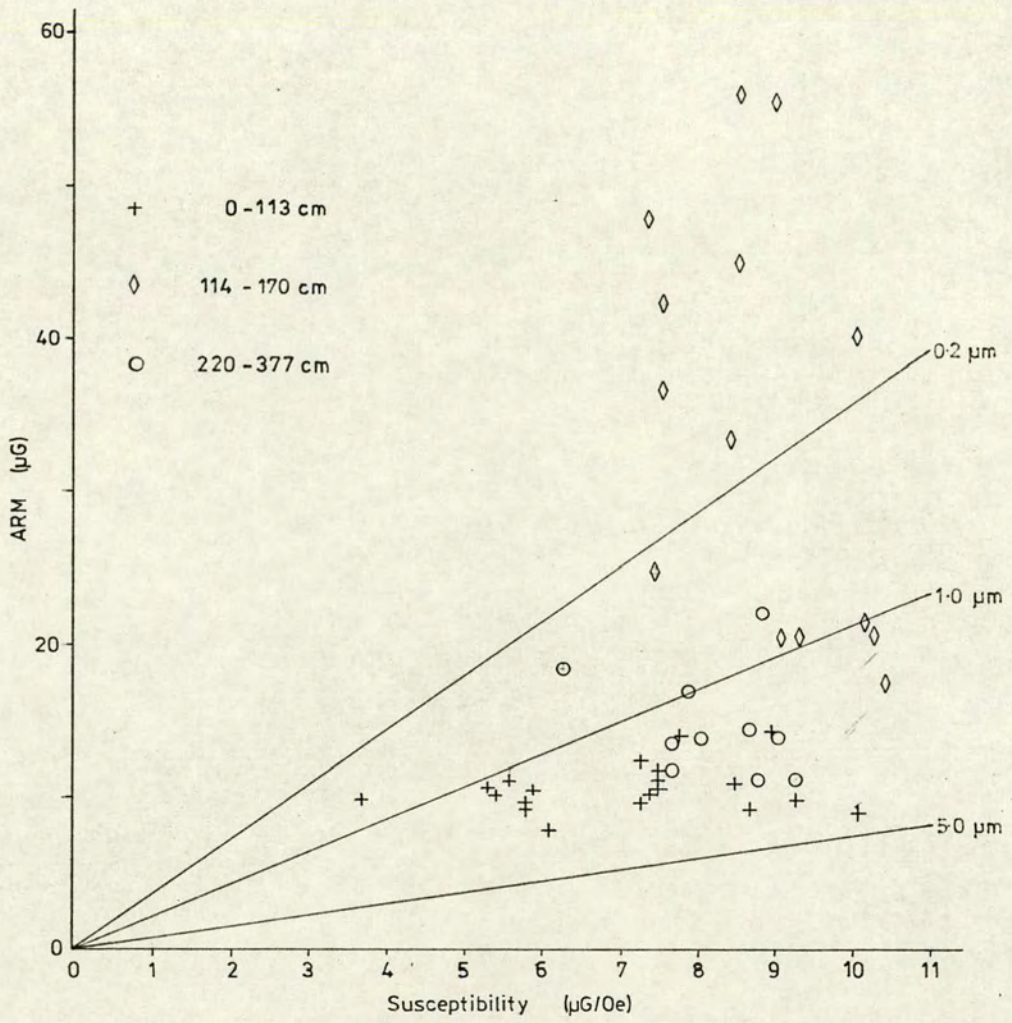


Figure 115. ARM versus Susceptibility at Section 9

remanence. The clay above a depth of 113cm was deposited during a polarity transition and during the period of normal polarity which followed. The initial remanence was probably carried by similar grains to those in the lower part of the section. Some time after deposition the upper 113cm of the section were subjected to chemical alteration resulting in the formation of a chemical remanent magnetization. The alteration preferentially attacked the smaller grained magnetite, giving rise to haematite as shown by the colour of the section which is blue-grey below 113cm and brown-orange above, and the coercivity spectrum of NRM which changes with the removal of a component whose coercivity is represented by alternating field demagnetization between 200 and 600 Oe, and its replacement by a component still present above 600 Oe. In addition hysteresis experiments show that S values as defined by Stober and Thompson (1979) show a decrease above 113cm which is indicative of haematite in the oxidized clays. Demagnetization of these oxidized samples involves a change in direction from normal to intermediate between 0 and 150 Oe, usually with a drop in intensity. The initial drop in intensity is due to the removal of a normal component carried by less finely grained magnetite, which is not greatly affected by oxidation (susceptibility, which generally reflects the amount of larger grained magnetite is more or less constant above and below the level of oxidation). This normal vector is probably a primary remanence similar in nature to that seen in the lower half of the section. The intermediate directions carried by the haematite imply that the oxidation took place when the ambient field was other than normal. The directions may represent the true field at the time of oxidation, in which case the field was either partly through a reversal, or undergoing an excursion. Alternatively the

directions represent a mean between the ambient field direction and the primary remanence recorded before alteration, in which case the ambient field may have been stable and reversed. When difference vectors are calculated for the oxidized samples, for the component removed up to 150 Oe, the inclinations are high and positive and, although declinations are scattered around north (largely due to the increased error involved in finding difference vectors), the VGP latitudes above 113cm are positive.

Bucha and Sibrava (1977) were able to sample a more extensive section near Section 9, including unit 6 above the erosion surface which forms the limit of sampling for this work. From their Figure 2 it would appear that directions in this part of the section are consistently normal, suggesting that the reversed oxidation is not present in these deposits. The sediments of Unit 6a in Section 8 are slightly oxidized, but show no signs of overprinting. This oxidation was prevented from extending below the clay between Units 6a and 6b. The heavy oxidation at Section 9 was possibly due to an earlier event, which took place in a reversed epoch before deposition of Unit 7. This does not explain the absence of oxidation in the lower part of section 8, so perhaps the erosional and weathering history is more complex than appears at first sight.

TRANSITIONAL PATHS

The age of the transition recorded in Sections 8 and 9 must be at least 730,000 years, the age of the Matuyama-Brunhes transition (Mankinen and Dalrymple, 1979). The presence of reversed oxidation above the transition suggests that this reversal may be the base of the Jaramillo Event (970,000 yr. B.P.) or older. It is, however possible that reversed polarity occurred during the Brunhes either

at 110,000 years during the Blake Event (Emian) or at 465,000 years b.p. during the Emperor Event (Holsteinian) although Units 6 and 7 were probably deposited after this first phase of oxidation.

The record of the transition at Section 9 is confused by the reversed overprint. At NRM the path passes northward through South America and the Western Atlantic, with a lot of variation in the second half of the transition. When demagnetized the directions give VGPs clustered around the South American continent, never reaching high northerly latitudes. In an attempt to improve the resolution difference vectors were calculated for the component of the natural remanence removed up to 150 Oe. These results suggest that the transition took place between samples B43' (114cm) and B44' (113cm). The nature of the transition zone cannot be clearly decided from the results of Section 9, but there is a suggestion of bias towards South America (Figure 116).

The results from Section 8 probably represent a much more accurate record of the ambient field during the transition. The mean directions of samples in the upper 2m lie within 5° of the axial dipole directions and have alpha 95 values of between 5° and 10°. There is no obvious change in sediment below these samples suggesting that the increased amount of variation with depth is a true reflection of large geomagnetic variation both before and after the transition. The increase in divergence between samples apparently recording the same time interval may be due to variations in magnetic grain size.

The NRM directions of transitional samples give poles concentrated in the North Atlantic. However demagnetization suggests that this includes a normal vector which is removed below 150 Oe. Whether this is a viscous overprint, or the result of acquisition of

Figure 116. Transition at Section 9



After Demagnetization



Before Demagnetization

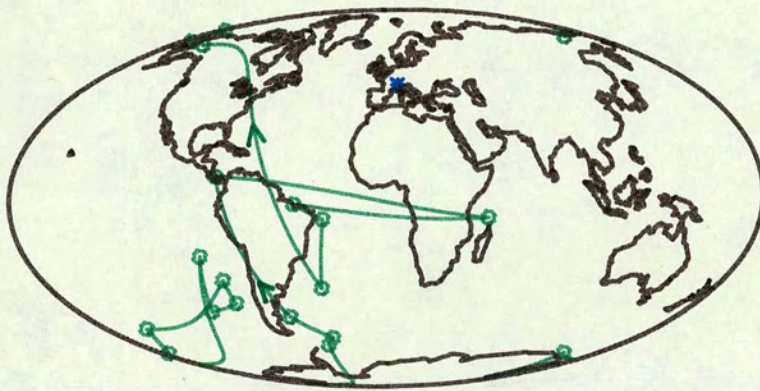


Difference Vectors

the primary remanence over a period of time is not clear, however Tucker (1979) suggests that softer magnetic grains, being larger should generally be trapped in position in a sediment before smaller, harder grains.

The pole moves first towards India (BG85, 402cm) then across to the Caribbean and the South Atlantic (BG84 to BG82: 399-395cm), and finally through North America to Alaska (BG81 at 393cm), see Figure 117. Three samples at 397cm have a cone of 95% confidence about the mean direction with a half angle of 60° , however this still gives a near-sided path, slightly biased towards the west. The diagram uses great circles to join the poles, but the poles for BG85 and BG84 are almost 180° apart so there is little control on this part of the path. The Indian pole may represent an excursion before the reversal, it may be part of the transition with westward drift between 90° E and 90° W, or it may represent the transition, with the Atlantic loop being an excursion. Without this pole the path is more longitudinally confined.

Following the transition, for about 1.50m, the virtual geomagnetic poles oscillate in latitude within the northern hemisphere before settling down within 5° of the geographic pole above 2.40m. Only once does the pole cross the equator after the transition: at 687 and 688cm, when an excursion to the eastern Pacific is seen. Both this excursion and a smaller one shortly later are far-sided as shown in Figure 118. The three samples recording the larger excursion are tightly grouped suggesting rapid development and collapse of a short term anomalous field rather than drift of a strong non-dipole field. The upper excursion (BG66 and BG67: 670 to 672cm) may in fact be due to low fidelity recording of the ambient field in the coarser, woody bed.



Without
Indian Pole



All Samples

Figure 117. Transition at Section 8

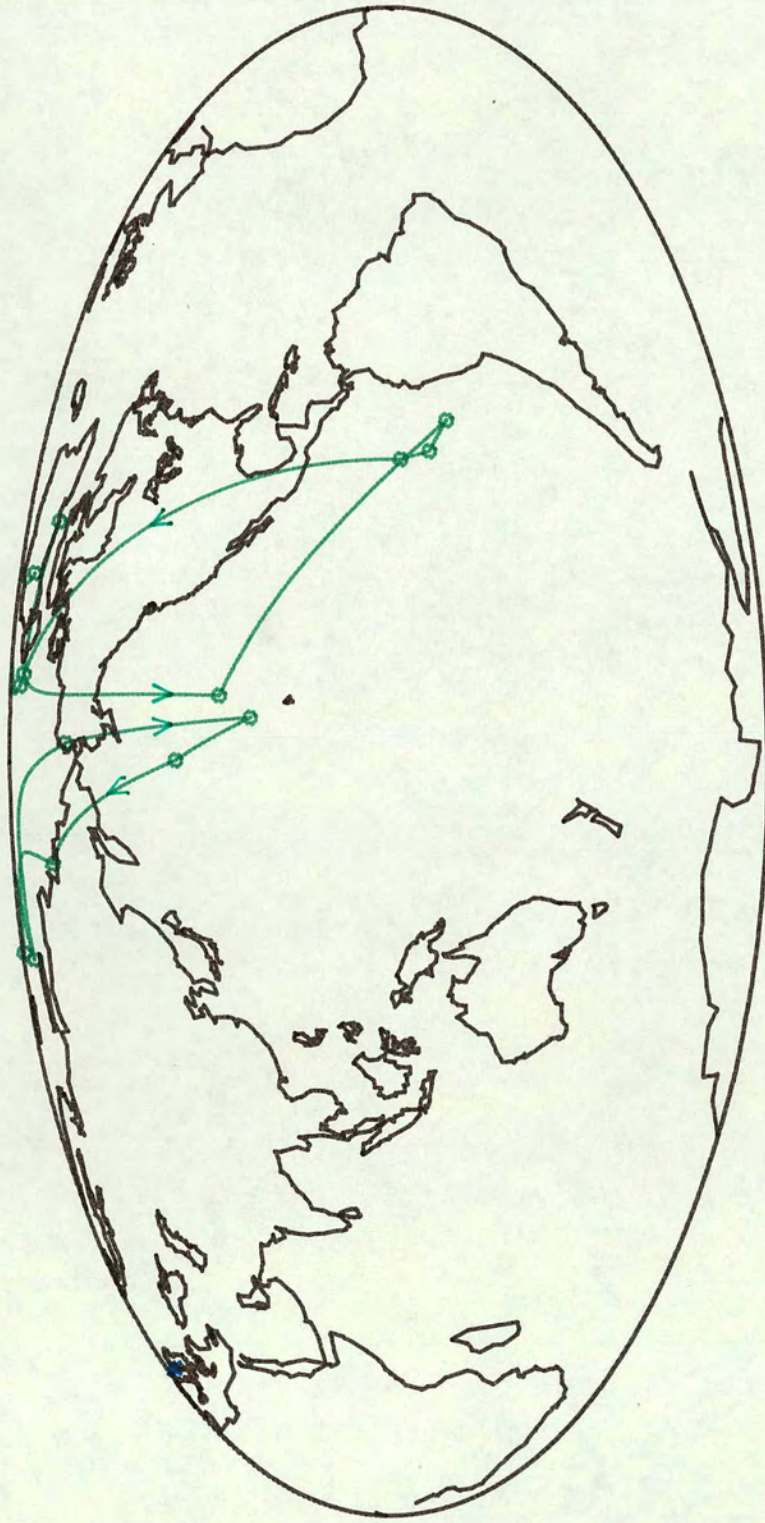


Figure 118. Excursion at Section 8

Although the results from Section 8a are not as good as those at Section 8 the transitional poles appear to be concentrated around the Americas, though with a loop to Africa, suggesting that the Indian pole is unimportant (Figure 119). Billard et al (in print) studied two parallel sections of this reversal, both giving paths through America (c90° W of the site) without any excursions to the east (Figure 120).

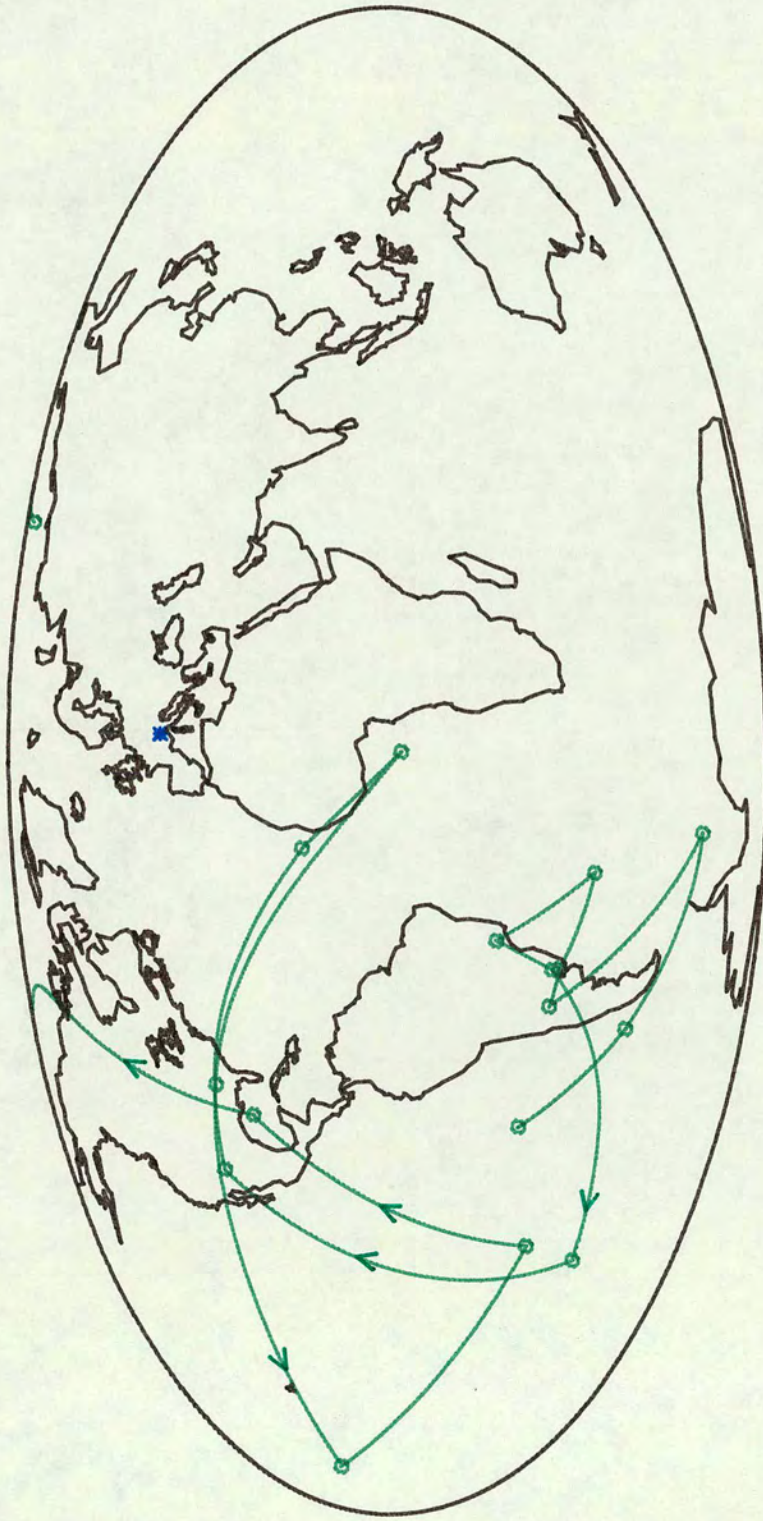


Figure 119. Transition at Section 8a

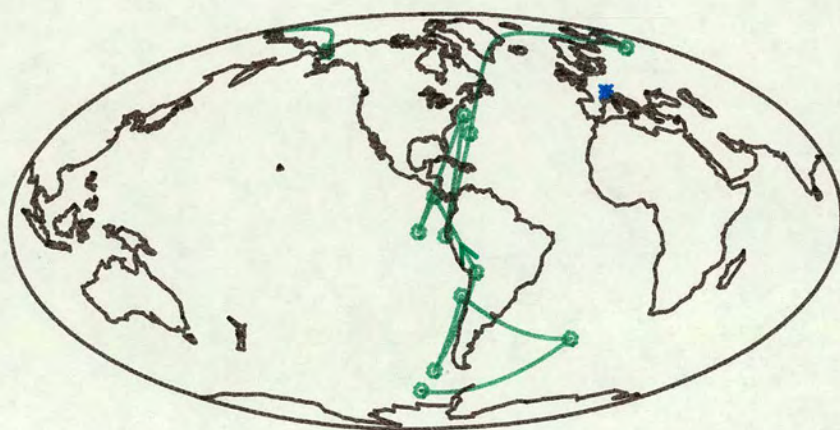


Figure 120. Transition from Billard et al (1983)

PART II PONTIDA

The deposits of Pontida accumulated in an ice-dammed lake sandwiched between the hills of Monte dei Frati and M. Chignoletti near the town of Pontida on the main Como to Bergamo road, 15km west of Bergamo, just to the east of the Adda river (Map 33 III S.O.: NR 381651).

GEOLOGY

At least 60m of laminated lacustrine clays and silts were deposited in the Pontida basin, which trends east-west, between hills formed of Cretaceous flysch (Figure 121). The valley is blocked by moraine to the east, however little moraine is seen at the western end of the valley, suggesting that the lake was dammed directly by the Adda glacier (Alessio et al, 1978).

Twenty metres of lacustrine sediments are exposed in quarries on either side of the Como to Bergamo road, with a further 40m proved in a borehole. The deposits rest directly on the Cretaceous flysch bedrock, and consist of silts and clays which presumably accumulated very quickly, with occasional sand lenses. Towards the top of the sequence the clays are oxidized. Locally delta foresets are seen, often at the edge of the basin, or in a position that was probably very near the ice. The lake clays are overlain by fluvial sands and gravels deposited after the lake had been drained. Vegetation remains at a depth of about 10m have been dated at $17,700 \pm 360$ years by radiocarbon, which probably represents the end of the Würm glaciation (Alessio et al, 1978).

A six metre section, consisting mainly of clay, but split by 1m of sand between 2.75 and 3.75m, and by other smaller sand levels was sampled during September 1980. The top of the section sampled

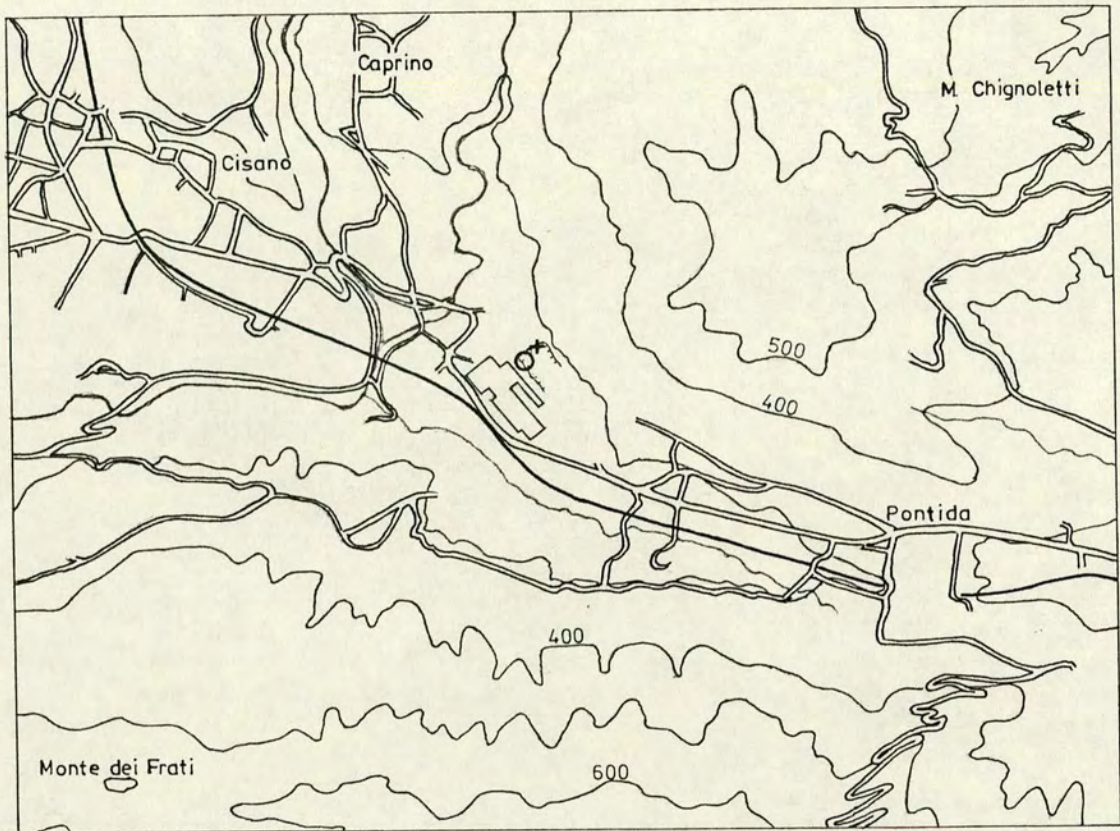


Figure 121. Map of Pontida showing Sampling Sites
(⊙ Palaeomagnetic samples ⊕ Radiometric samples)

500 m

is about 1m above the interval dated at 17,700 years.

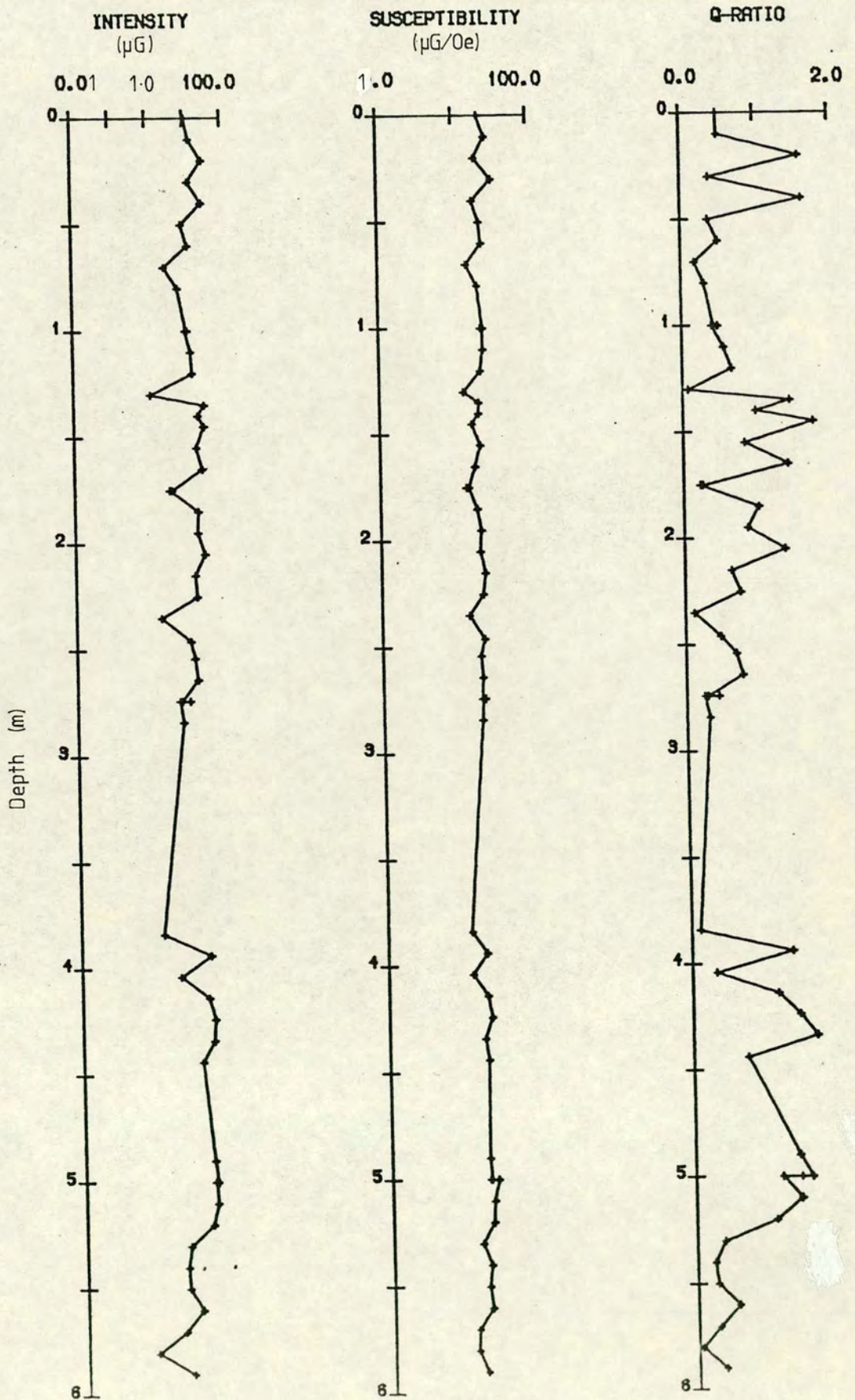
RESULTS

Intensity at NRM (Figure 122) is relatively high (the mean is $15.46(\pm 10.39)\mu\text{G}$). There is a large amount of variation, with occasional isolated samples having intensities of only 1 or 2 μG . Susceptibility is more constant throughout the section, averaging $20.44(\pm 4.03)\mu\text{G}/\text{Oe}$, which gives high Q-ratios ($0.7(\pm 0.5)$). In fact Q-ratio is often in excess of 1, which is higher than at any other site. High Q-ratios probably reflect very still conditions of deposition allowing complete orientation of grains, as contrasted with the much lower Q-ratios seen in marine and fluvial sediments (where susceptibility is almost the same). At Pontida Q-ratio is higher between 1.35 and 2.15m and between 4.14 and 5.30m; this may result from change in water depth and thus a change in current action or from change in geomagnetic field intensity.

Samples from Pontida were very stable when subjected to alternating field demagnetization (Figure 123). Both P10 (500cm) and P39 (100cm) showed little change in direction with demagnetization, having median destructive fields of about 245 and 235 Oe respectively.

After blanket demagnetization at 150 Oe, very little change had taken place; direction had hardly changed at all, and intensity had decreased by 35% to $10.07(\pm 7.86)\mu\text{G}$ (Figure 124). Declination is very close to zero, but inclination is low: $31.0(\pm 15.4)^\circ$ after demagnetization, giving VGP latitudes of 60°N , lying near Alaska. This represents an error in inclination of 30 to 35° , which is much greater than reported elsewhere ($f=0.3$ compared with 0.85 to 1.0 at Bagaggera). The high Q-ratio suggests that these deposits

Figure 122. NRM Results for Pontida



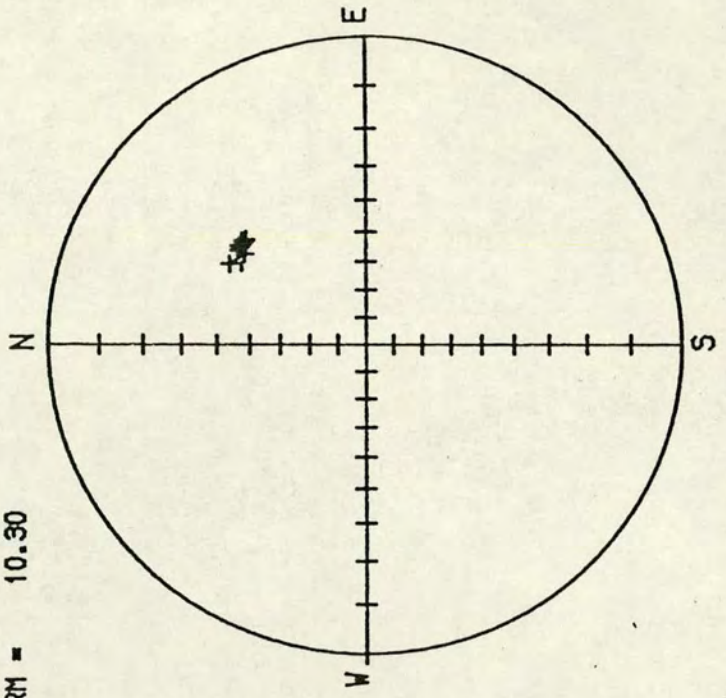
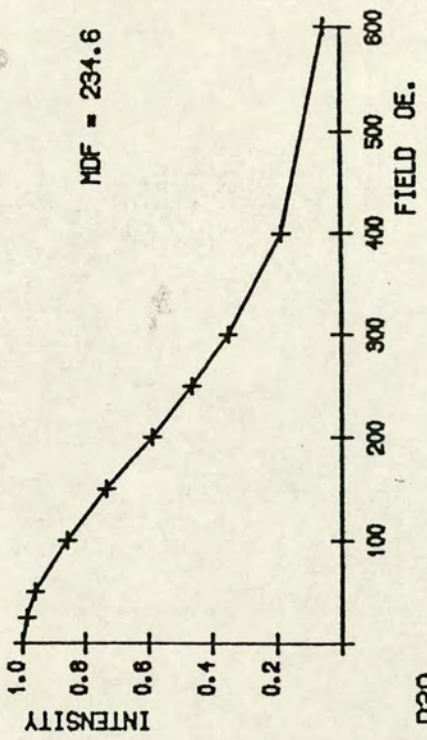
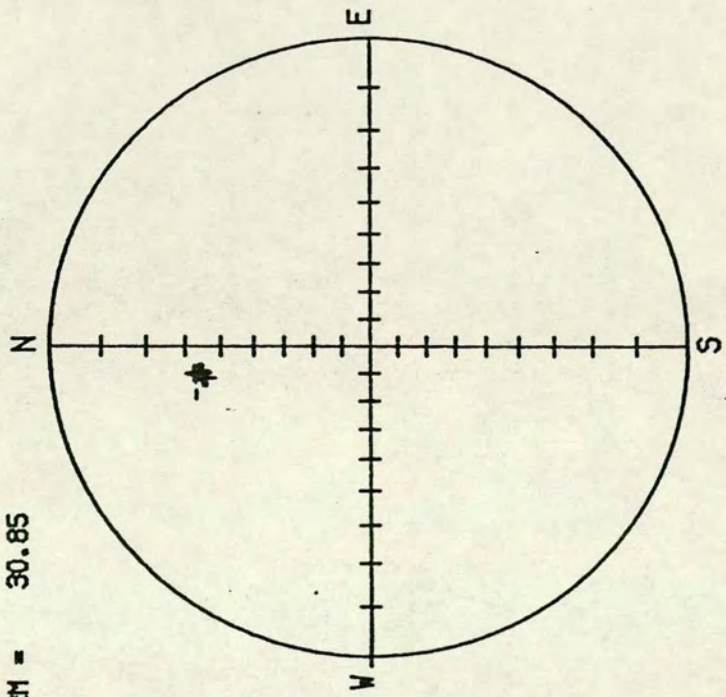
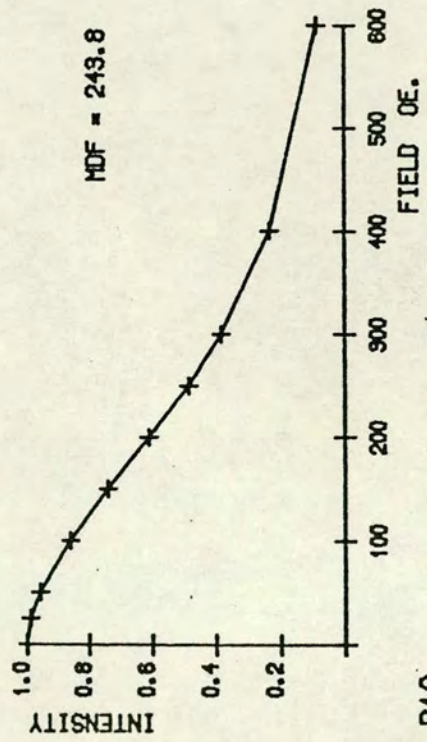
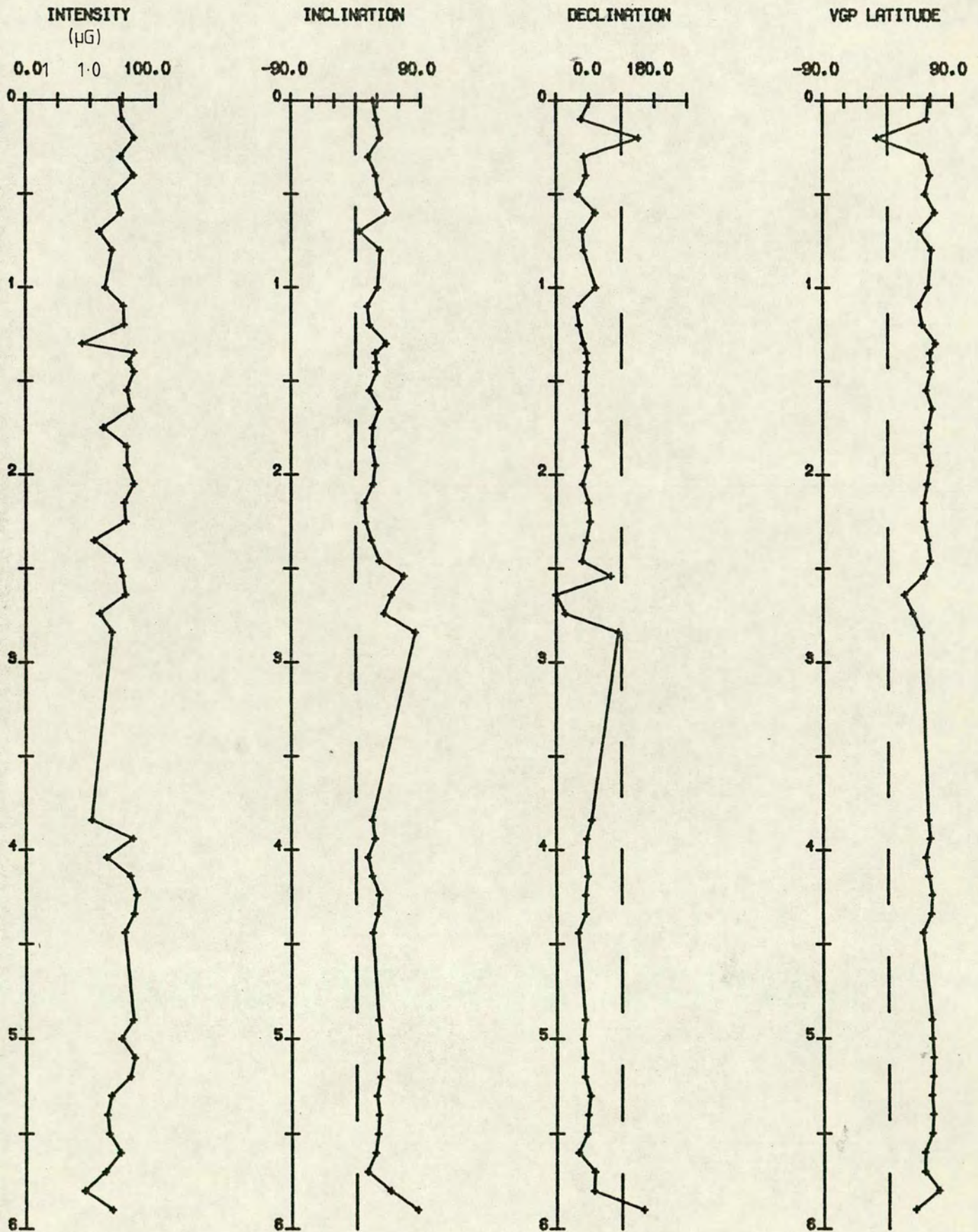


Figure 123. Examples of Pilot Demagnetization from Pontida

Figure 124 Results from Pontida after Demagnetization at 150 Oe



record the geomagnetic field with high fidelity, the beds are clearly not dipping, nor is there any indication of deposition on a slope, which may also give rise to inclination error. Alpha 95 values are low; generally less than 10° , apart from in an interval of 30cm just above the thick sand bed where an apparent excursion takes place. In this interval inclination increases while declination swings first to the east, then to the west, and finally back to the east before returning to zero. The VGP traces a clockwise loop through Asia to eastern America, then an anticlockwise return loop following the same path, maintaining a latitude of between 40° and 20° N. (Figure 125). Although this excursion occurs just above the sand there is no indication that this excursion is caused by any sedimentological phenomena.

It would appear that the sediments of Pontida were deposited during a period when the VGP had drifted 30° from the pole towards Alaska, and maintained this position for some time. It is interesting to note that no viscous overprint with a steeper inclination is seen — a fact also noted in the reversed clays at Bagaggera. An excursion of the field took place while the pole was in this anomalous position, consisting of clockwise and then anticlockwise looping of the pole. The length of time represented by the 6m of clay is not known, however the excursion (and indeed, the period of low inclination) can be dated at around 18,000 years B.P.

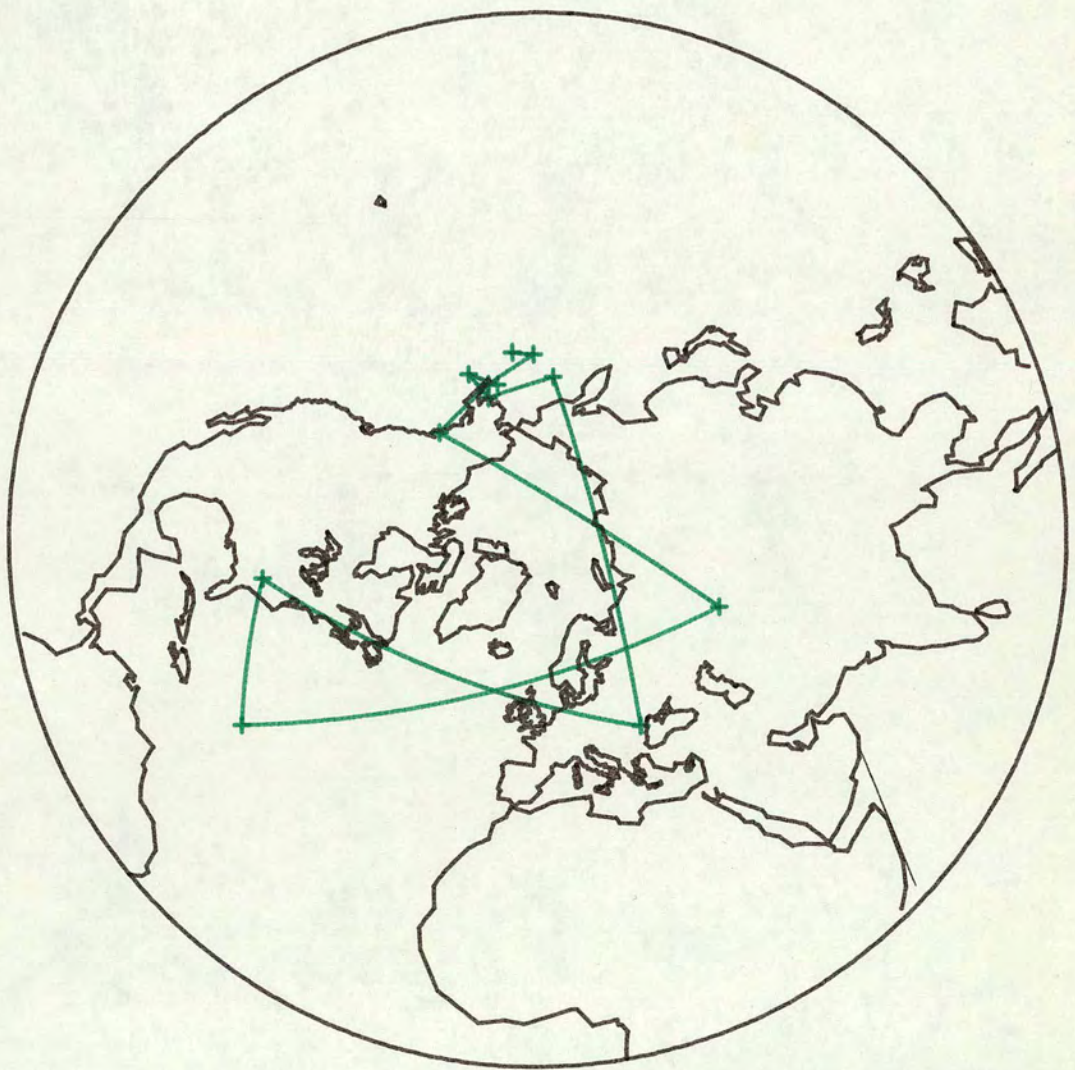


Figure 125. VGP path for Excursion at Pontida

PART III LEFFE

The deposits of Leffe are situated in the Bergamo prealps, 14km west of Lago d'Iseo and 22km northeast of Bergamo. The sections studied were a small exposure on Tappetificio Hill in the grounds of a carpet factory, at a height of 500m above sea level (NR 68887343) which represents the top of the sequence, and a cutting of the River Re at a height of 420m a. s. l. (NR68177330) which is towards the base of the series of (Figure 126, see Map 33 II N.E.).

Altogether there are about 100m of lacustrine sediments at Leffe, mainly consisting of fine grey-green silts and clays, but with numerous lignite layers. An Upper Villafranchian fauna has been found in the uppermost deposits, which Arias et al (1982) correlate with the Olivola and Farneta Mammal Zones (that is between 2.5 and 1.0 m.y.).

Due to restricted access, only a limited number of samples could be taken: a 2.30m section of clays on Tappetificio Hill capped by a thin red soil representing a river terrace, and a 4m section of orange-brown clays overlying grey-green clays in the River Re, just below two lignite layers. Most of the samples from the lower section were taken as large blocks and cut into 2cm cubes at Edinburgh.

RESULTS

The NRM results for section 1 are shown in Figure 127. Intensity is high in the soil (5-10 μ G), below which the clay averages 0.59(\pm 0.36) μ G. Susceptibility is similarly higher in the soil (c 15 μ G/Oe) but does not show as much variation in the lower deposits (4.11(\pm 1.58) μ G). Q-ratio averages 0.2, and is slightly higher in the soil. The directions are normal at the top, in the soil and in

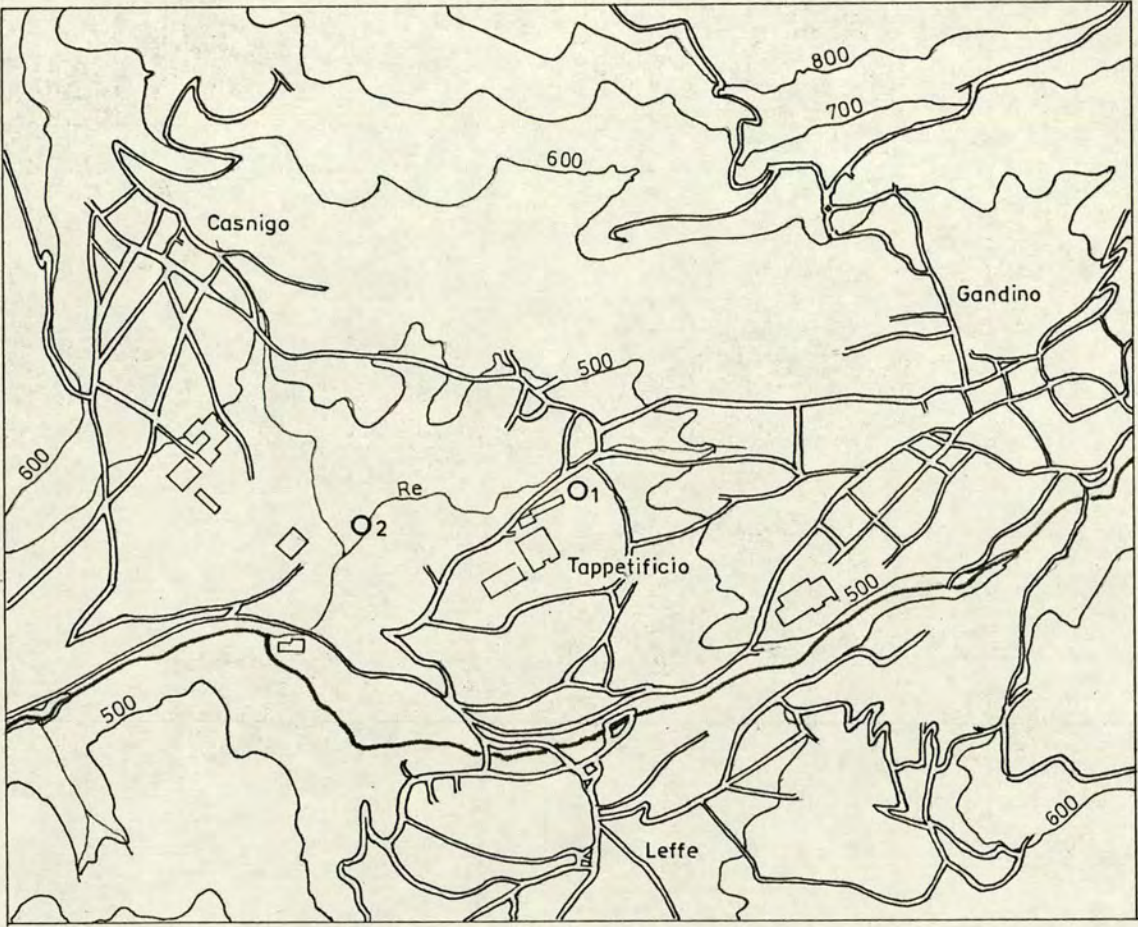
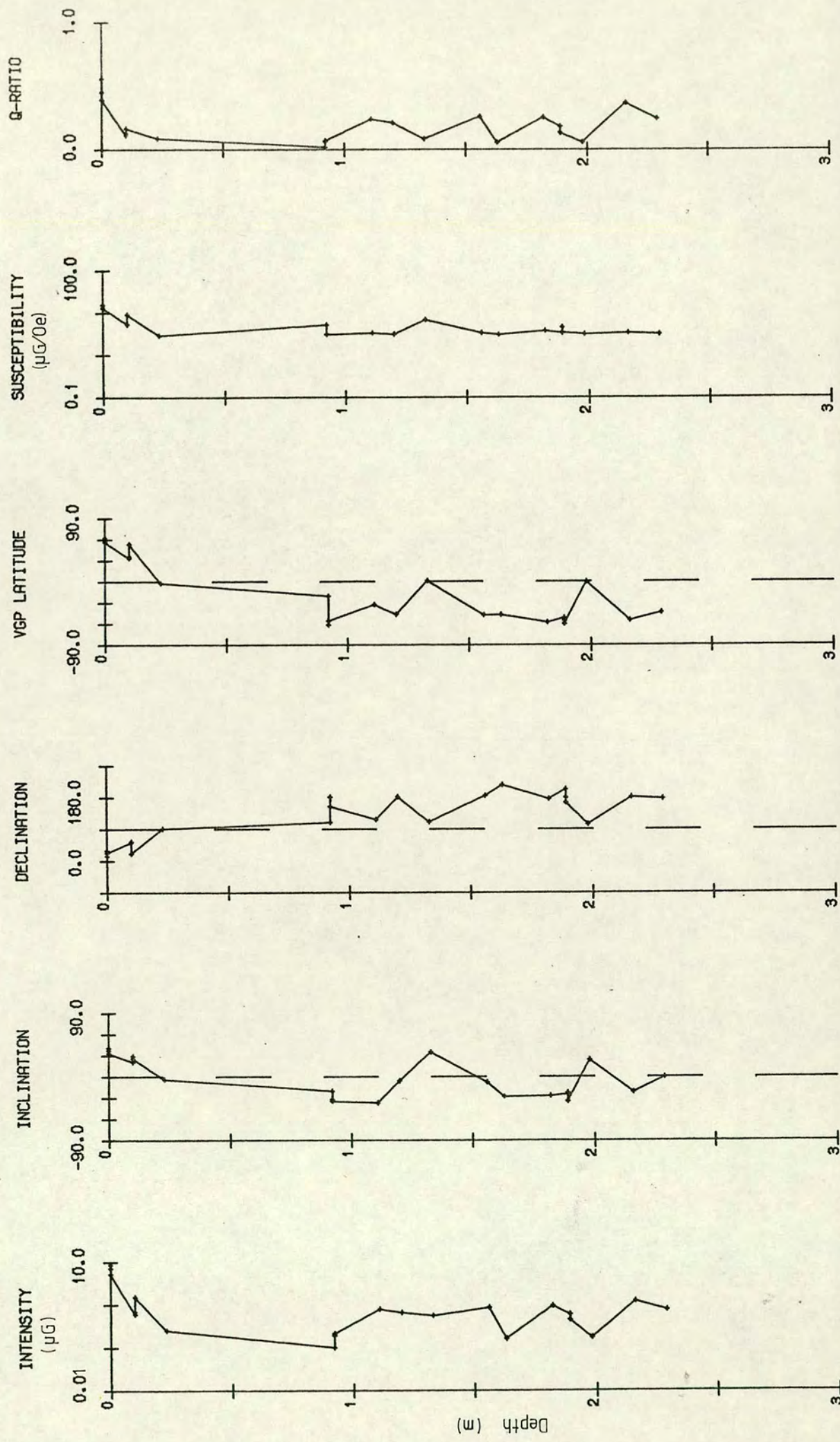


Figure 126. Map of Leffe showing Sampling Sites

500 m

Figure 127 NRM Results for Section 1 at Leffe



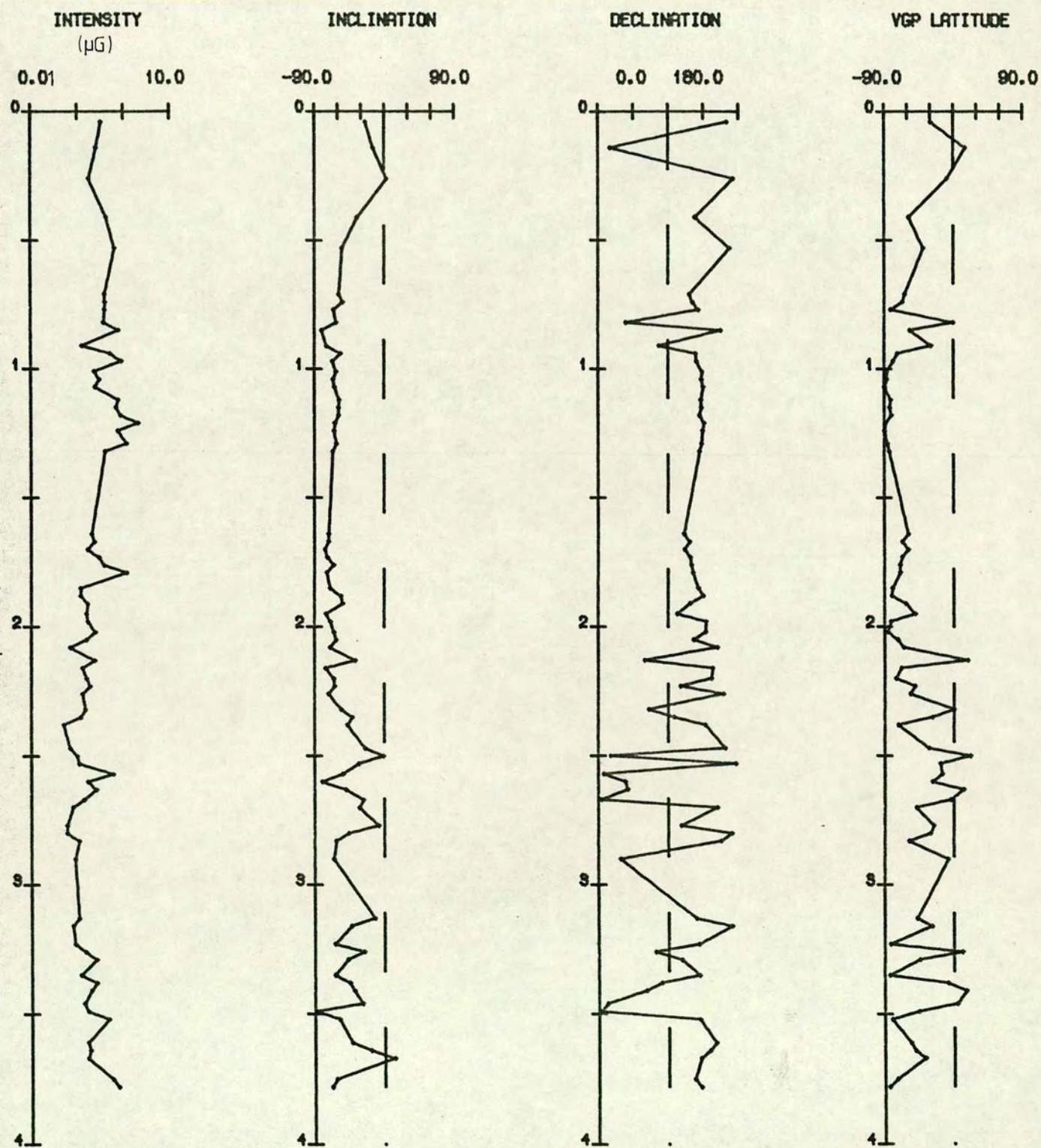
the upper 20cm of the clays; but with declinations of 20° to 50° and inclinations of only 20° to 40°. Below this the directions are more or less reversed, however inclinations are shallow (-20° to 40°) giving low VGP latitudes.

Section 2 (Figure 128) has an average intensity of around 0.5 μ G. This is slightly higher in the upper two metres of the section than below, coinciding with a change from orange-brown silty clay to grey-green silty clay (0.57(\pm 0.47) μ G cf. 0.19(\pm 0.16) μ G). The directions are mainly reversed, however the lowermost samples show much variety, both in declination and inclination, giving generally low VGP latitudes. In addition there is an apparent excursion in declination at 82 to 94cm, with no coincident variation in inclination, giving VGPs approaching the equator.

Examples of pilot demagnetization from Leffe are shown in Figure 129. Some of the more intensely magnetized samples are stable with demagnetization (e.g. L30A2, 1.21m) while others show a tendency to drift above 100 Oe: L40B1 (2.60m) and L50B3 (3.78m). There is no general pattern to the directional change: L40B1 develops a normal magnetization but L50B3 varies around its initial direction. Median destructive fields for Leffe samples vary from 90 to 170 Oe.

Blanket demagnetization gives rise to a very small decrease in intensity in section 1 to 0.54(\pm 0.32) μ G while the soils have a remanence of about 4.0 μ G (Figure 130). The directions are much more consistent after demagnetization with positive inclination and northerly declination in the soil, and negative inclination and southerly declination below. In both intervals inclination is low, averaging about 40°, giving VGP latitudes of 60° North or South. Nevertheless the clays clearly record an interval of reversed polarity while the overlying soil developed during normal polarity.

Figure 128 NRM Results for Section 2 at Leffe



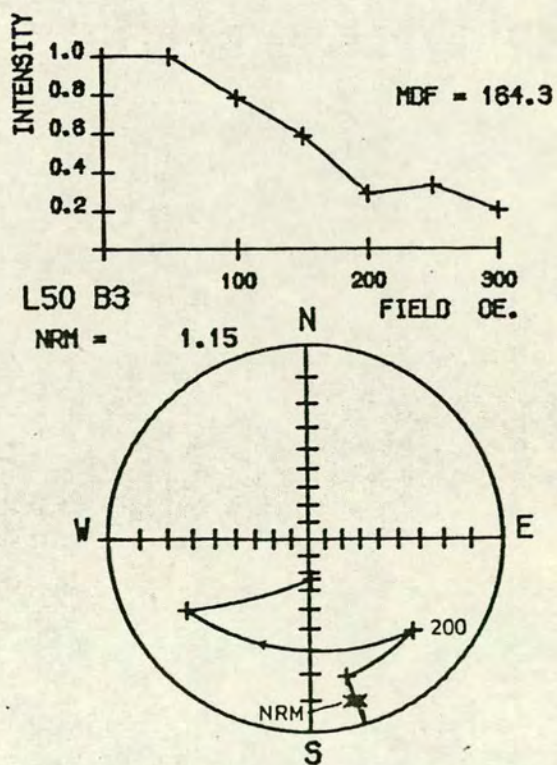
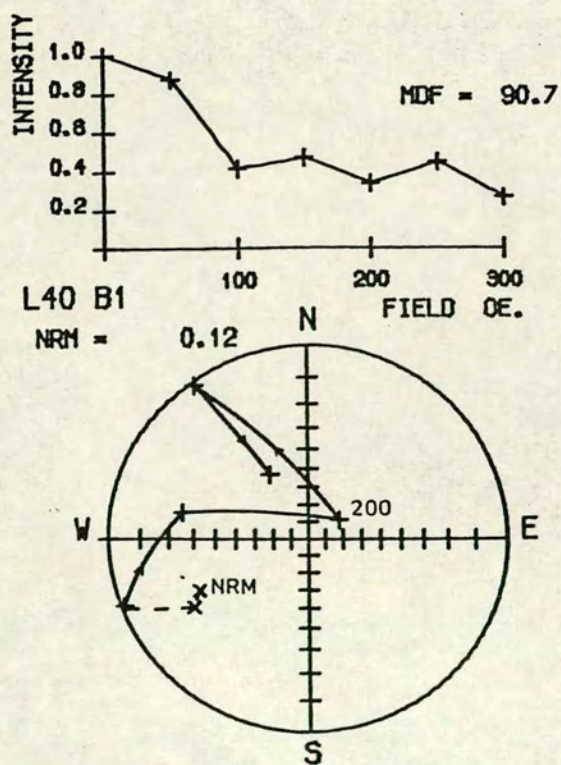
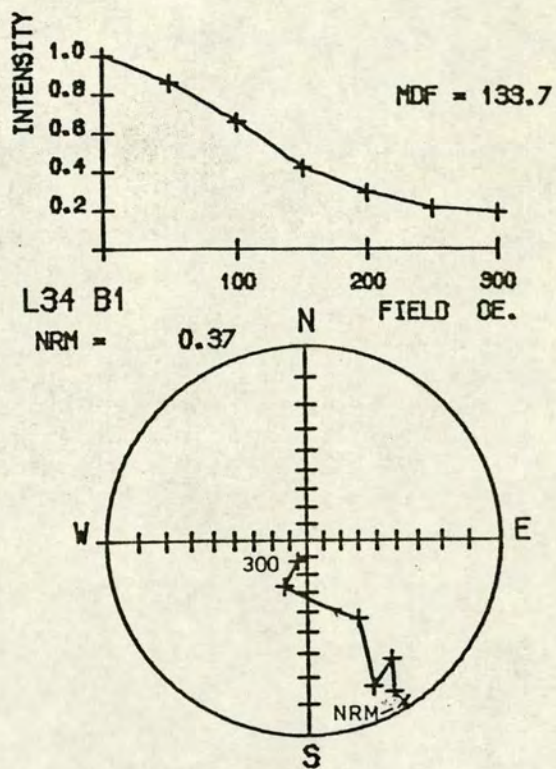
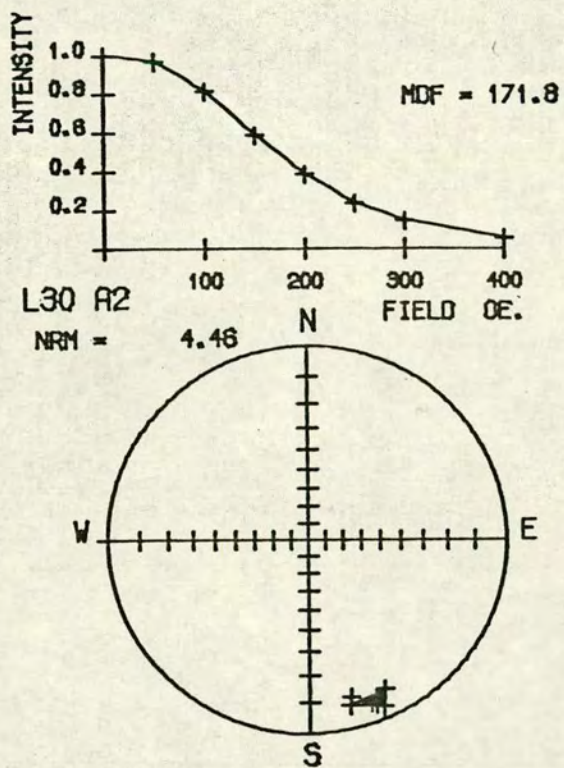
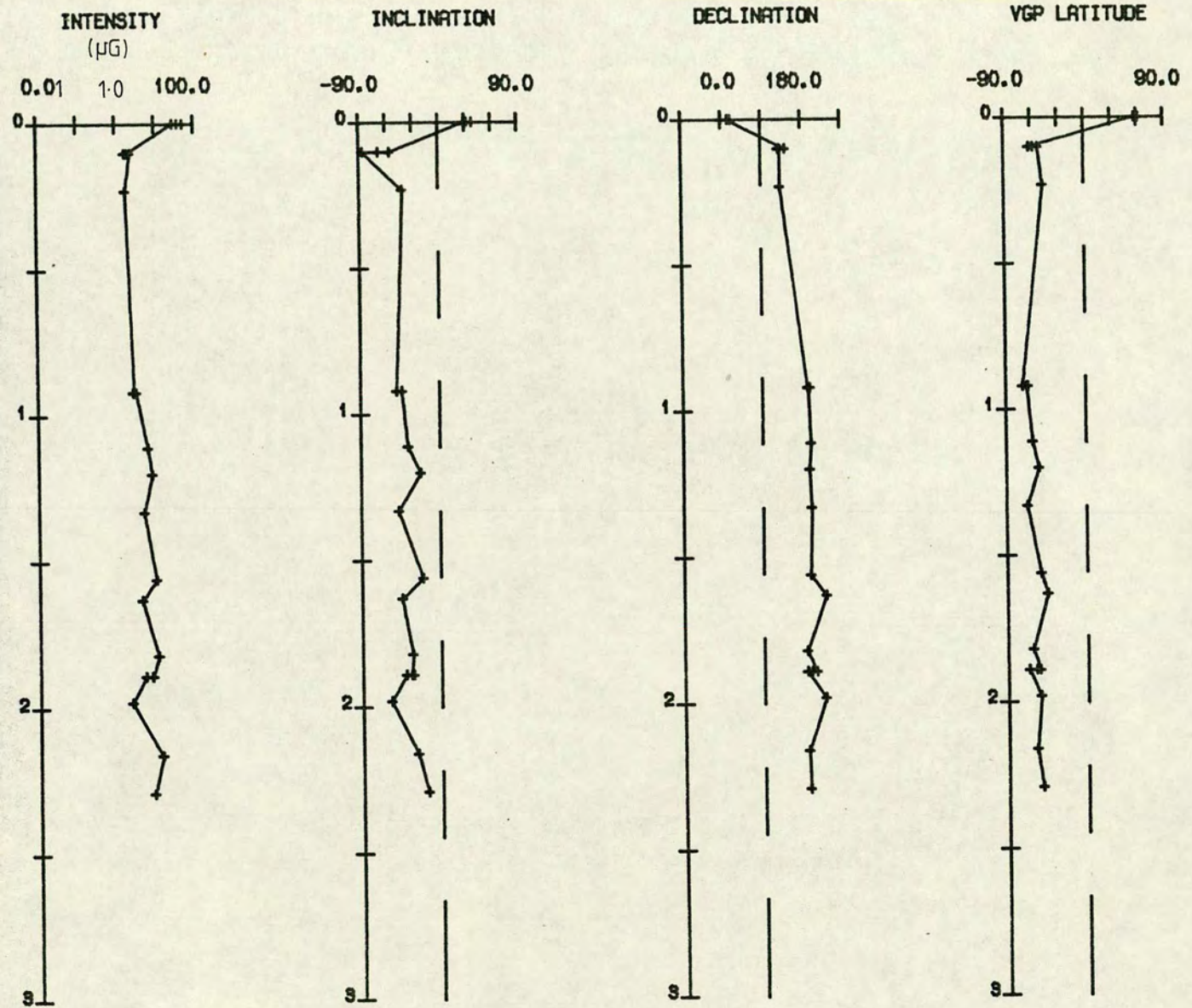


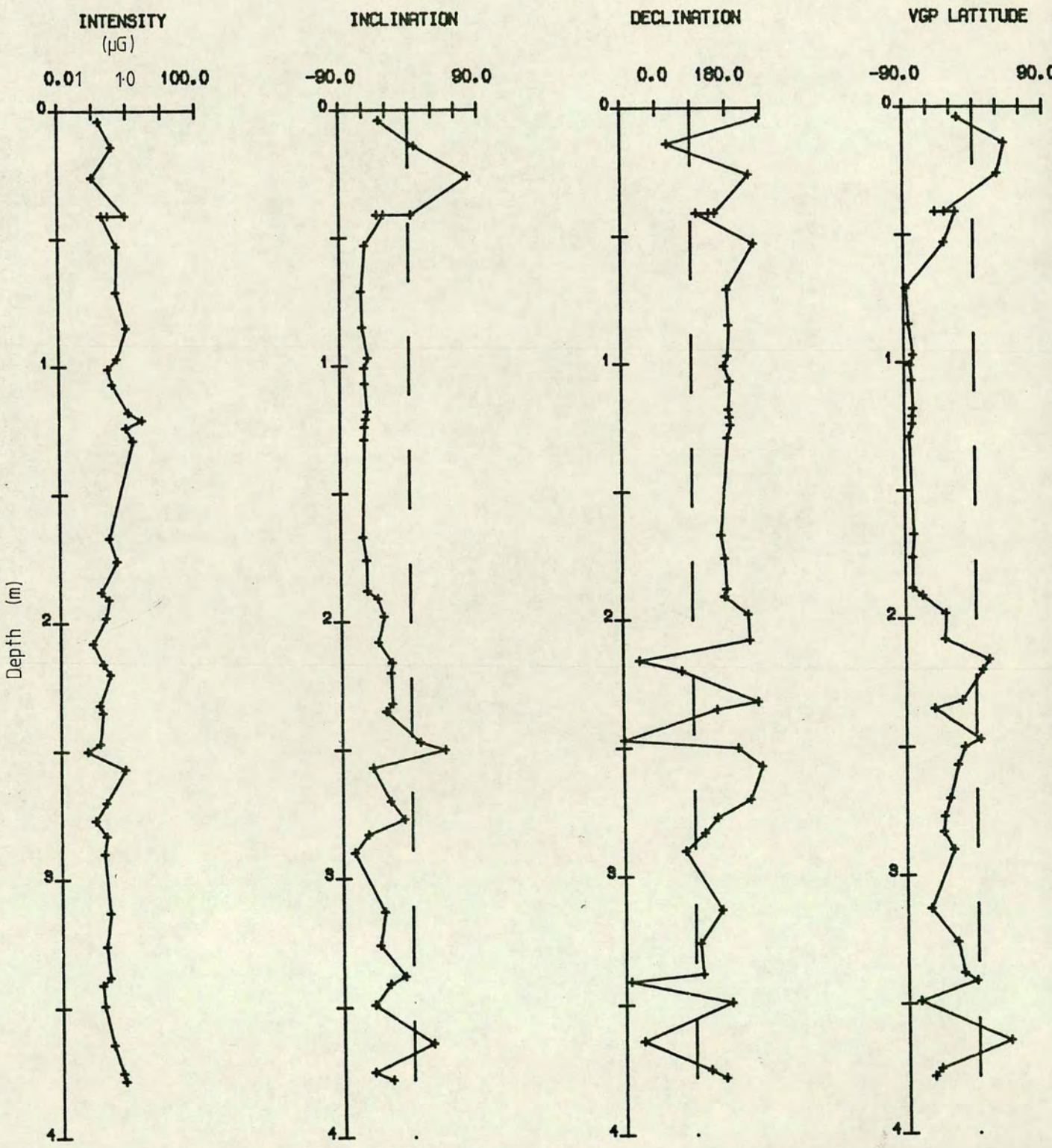
Figure 129. Examples of Pilot Demagnetization from Lefte

Figure 130 Section 1 results after Demagnetization at 150 Oe



Section 2 shows a small decrease in intensity with demagnetization to $0.43(\pm 0.46) \mu\text{G}$ (Figure 131). The directions remain mainly reversed, however below 2m the inclinations are generally more shallow (averaging 36° compared with 50°) which coupled with the variation in declination gives low VGP latitudes in the southern hemisphere. Two samples at the top of the section have VGPs in the northern hemisphere: one with a high positive inclination and southerly declination, the other with low inclination and northerly declination. Again the section records a reversed interval, however there may be an interval in which normal polarity is obscured by an overprint. The samples do not stand up to further demagnetization so it is not possible to resolve this question. The correlation of both sections with the Matuyama does not contradict the palaeontological evidence.

Figure 131. Section 2 results after Demagnetization at 150 Oe



PART IV PIANICO

The deposits of Pianico are exposed in the Borlezza river which flows into Lago d'Iseo near the town of Lovere, 30km northeast of Bergamo (Figure 132, see Map 34 III N.O.). At least 70m of calcareous marls, clays, deltaic sand and gravel are present, deposited in a lacustrine environment. These sediments have a varved appearance with layers 1 to 10mm thick, though it is not known whether these layers represent yearly variations or not. The deposits are attributed to the classic Riss-Würm interglacial on the basis of palaeontology, stratigraphy, and geomorphology (Alessio et al, 1978). They are covered by Würmian glacial till and contain much organic debris, this has been dated at greater than 43,000 years using the radiocarbon method, which does not conflict with the traditional dating.

A 6m section was sampled in the river bank at NR 805742, taking blocks approximately 20cm x 20cm x 10cm which were cut down to 2cm cubes at Edinburgh. The section consists of 2.75m of grey silts and sands, 1.75m of grey-green alternating clays and silts, with 1.50m of alternating cream and dark grey silts at the base.

Apart from a black clay layer at 4.5m, NRM intensity is low, averaging $0.30 \pm 0.60 \mu\text{G}$ (see Figure 133). Lower values occur in the bottommost deposits (around $0.05 \mu\text{G}$), while in the black clay layer intensity is 10 to 20 μG . The directions are all normal with inclinations of about 45° which indicates an inclination error of about 15° . The lowermost light cream varves have more variation in direction. VGP latitudes are between 60 and 70°N .

The samples all have low median destructive fields (for example SS7A1 at 1.42m: 100 Oe, and S15B3 at 4.43: 90 Oe, see Figure 134). Most of the samples appear stable, but those with low intensity soon

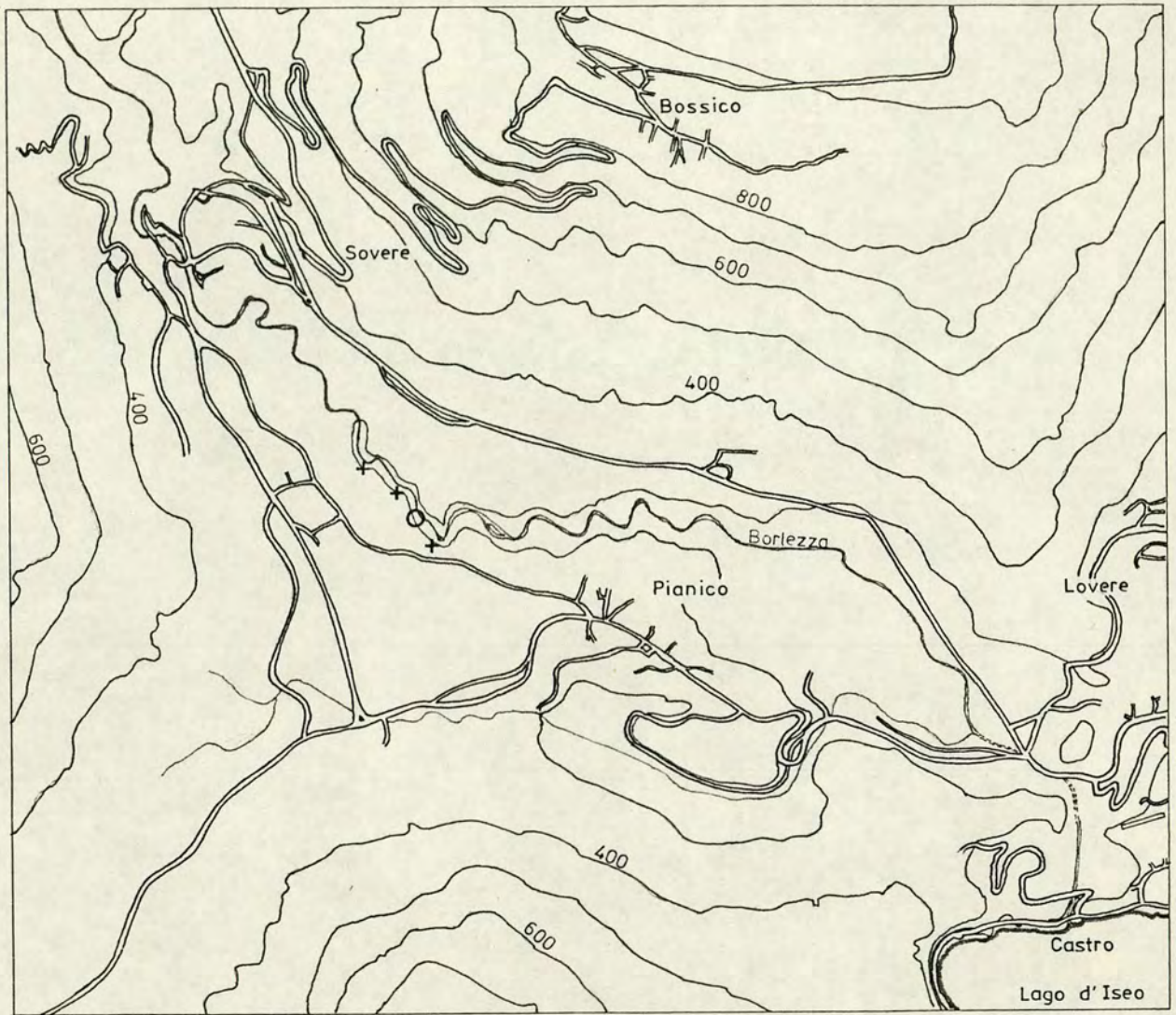
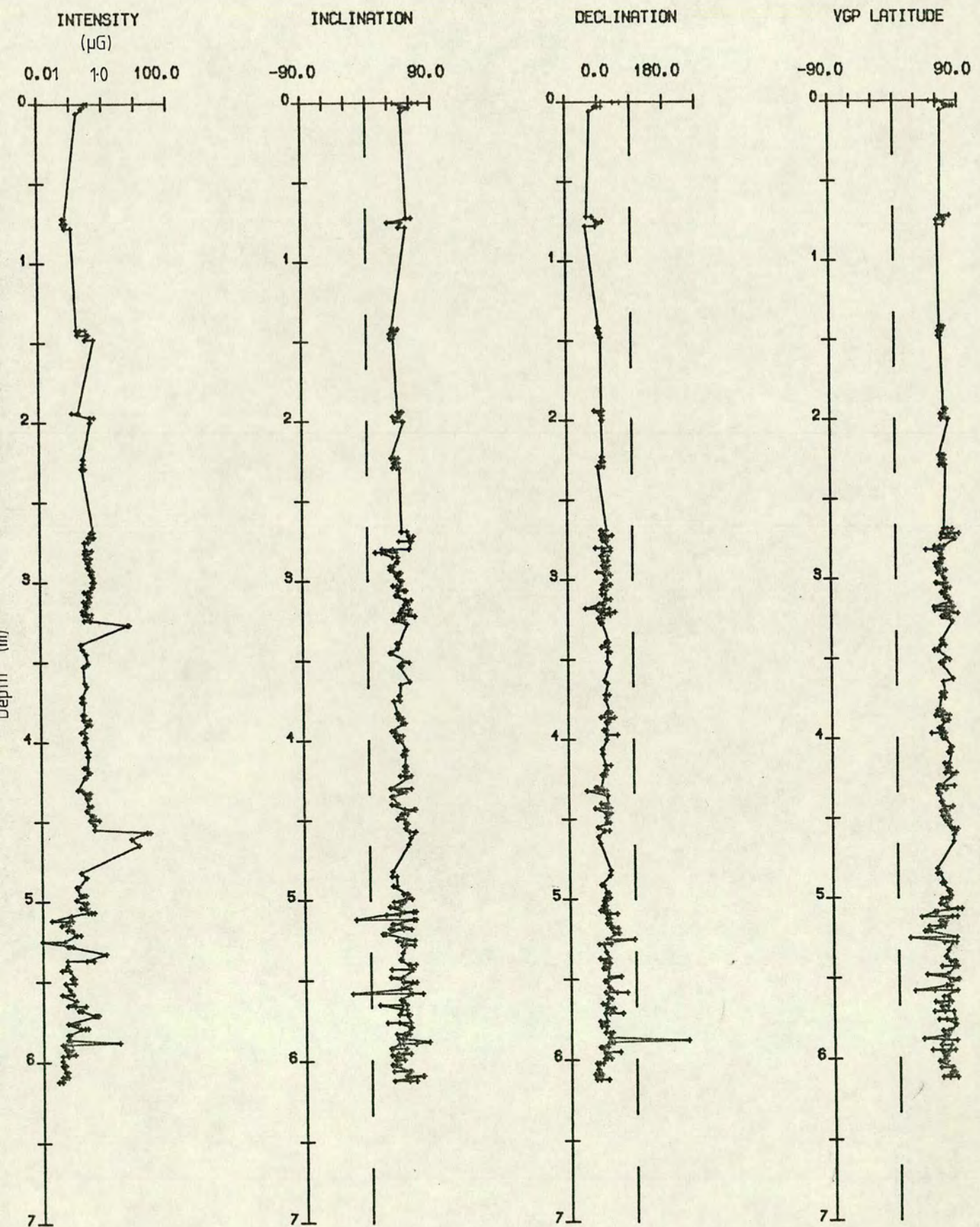


Figure 132. Map of Pianico showing Sampling Sites

500 m

Figure 133 NRM results from Pianico



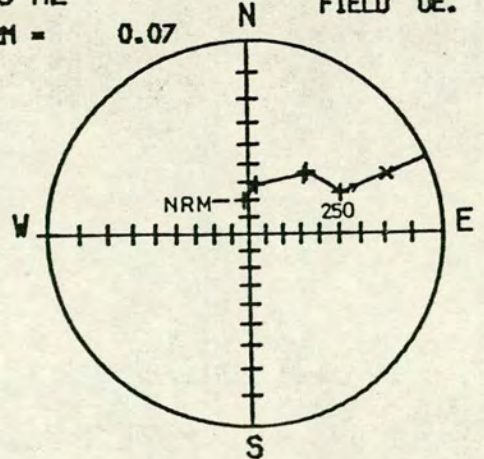
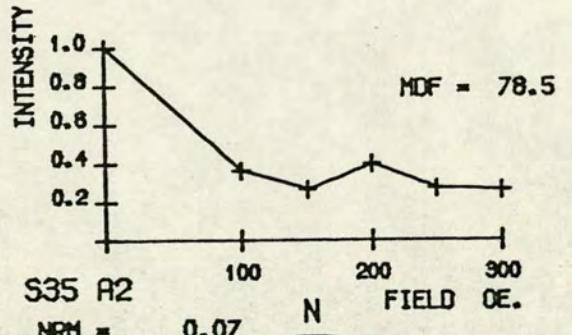
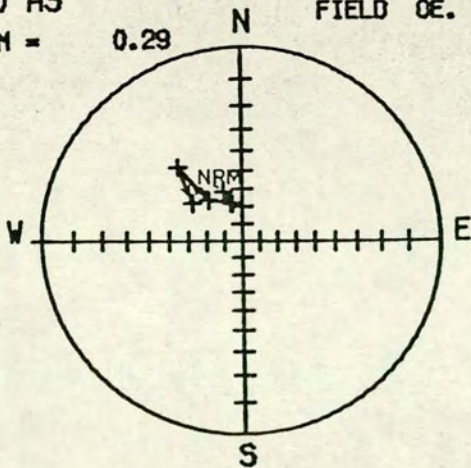
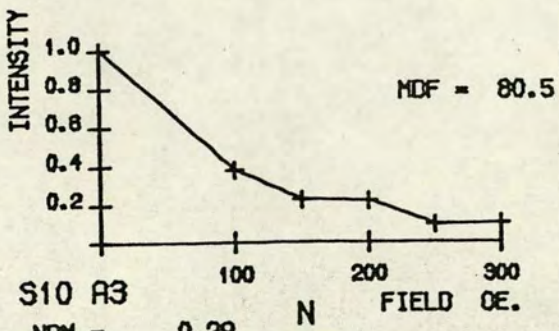
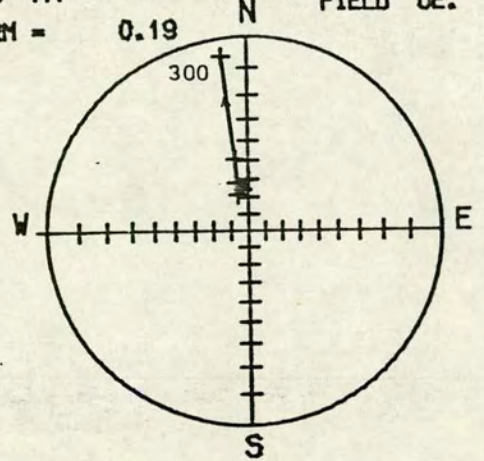
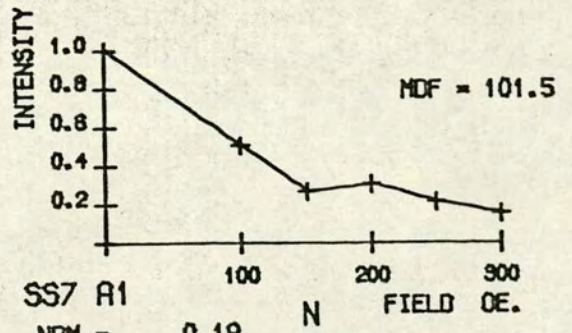
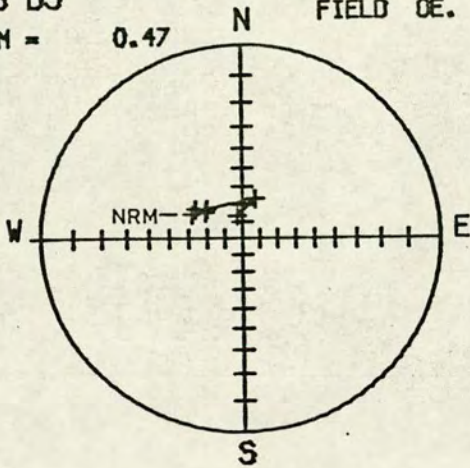
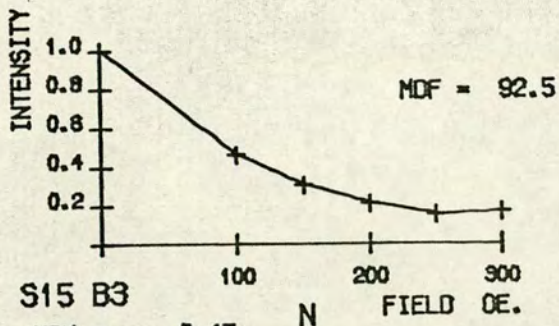
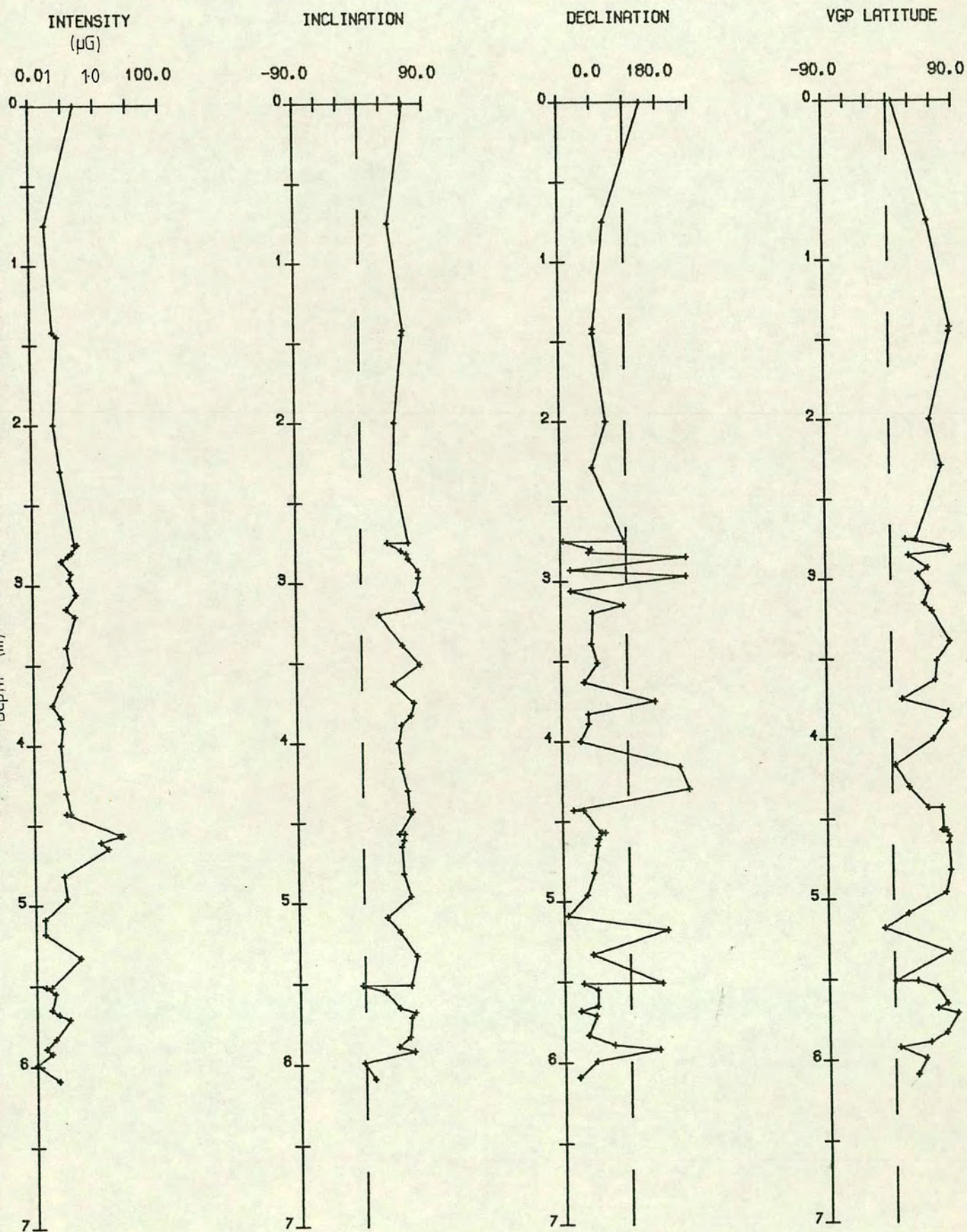


Figure 134. Examples of Pilot Demagnetization from Pianico

reach the noise level of the magnetometer (e.g. S10A3 at 3.83m, and S35A2 at 5.89m). The result is that blanket demagnetization at 150 Oe gives rise to a scattering of directions (Figure 135). Intensity drops by 66% as a whole to $0.10(\pm 0.07) \mu\text{G}$, the black clays drop to between 2 and 5 μG . Inclination averages 55°; but declination is often southerly (though not consistently so), giving occasional low latitude VGPs.

The NRM directions are probably a more accurate representation of the ambient field at the time of deposition, although there is a large inclination error. The deposits are all normal, and do not contradict the classic date of Riss Würm interglacial (which is within the Brunhes Epoch). Declination appears to be biased slightly east of north, but neither declination or inclination show any marked periodic variation. The deposits represent at least 1000 years of deposition, but may not represent a period long enough to display large secular variation swings which are seen in Holocene lake sediments.

Figure 135. Results from Pianico after Demagnetization



PIOMBINO

The sediments of Piombino were taken in five boreholes drilled along an east-west line between the towns of Piombino and Follonica in central Italy (namely MT0, MT1, MT2, MT3, and MT4 from east to west, see Figure 136). The boreholes penetrate up to 130m of continental and marine deposits dating back to the Middle Pliocene, resting on Oligocene formations. Each core section of up to 1m was individually orientated with respect to geographic north.

The lowest geological unit encountered (Unit E of Aquater, 1978) is a thin continental or lagoonal deposit, seen only in cores MT0 & MT2, see Figure 137. This is followed by a transgression and deposition of about 20m of calcareous blue-grey clays (Unit D). These represent a shallow sea environment, usually littoral, occasionally neritic, with a water depth of up to 100m. On the basis of nanoplankton this unit can be placed in the D. tamalis sub-zone of the D. broweri zone, i.e. about 2.5 to 3.0 million years old, representing the base of the Upper Pliocene. Unit C consists of about 10m of lagoonal or littoral sediments followed by a regression which Aquater dates at probably Upper Pliocene. This is followed by up to 85m of continental clays, silts, sands, and gravels ascribed to Unit B. Above Unit B there is an alternation of continental and marine sediments (Unit A') before a full marine transgression and deposition of up to 30m of littoral clays. These are overlain by a thin layer of Wurmian continental deposits.

PREVIOUS WORK

Palaeomagnetic investigation of these five cores has been carried out by Creer et al (1979) and by Readman and Evans (1979).

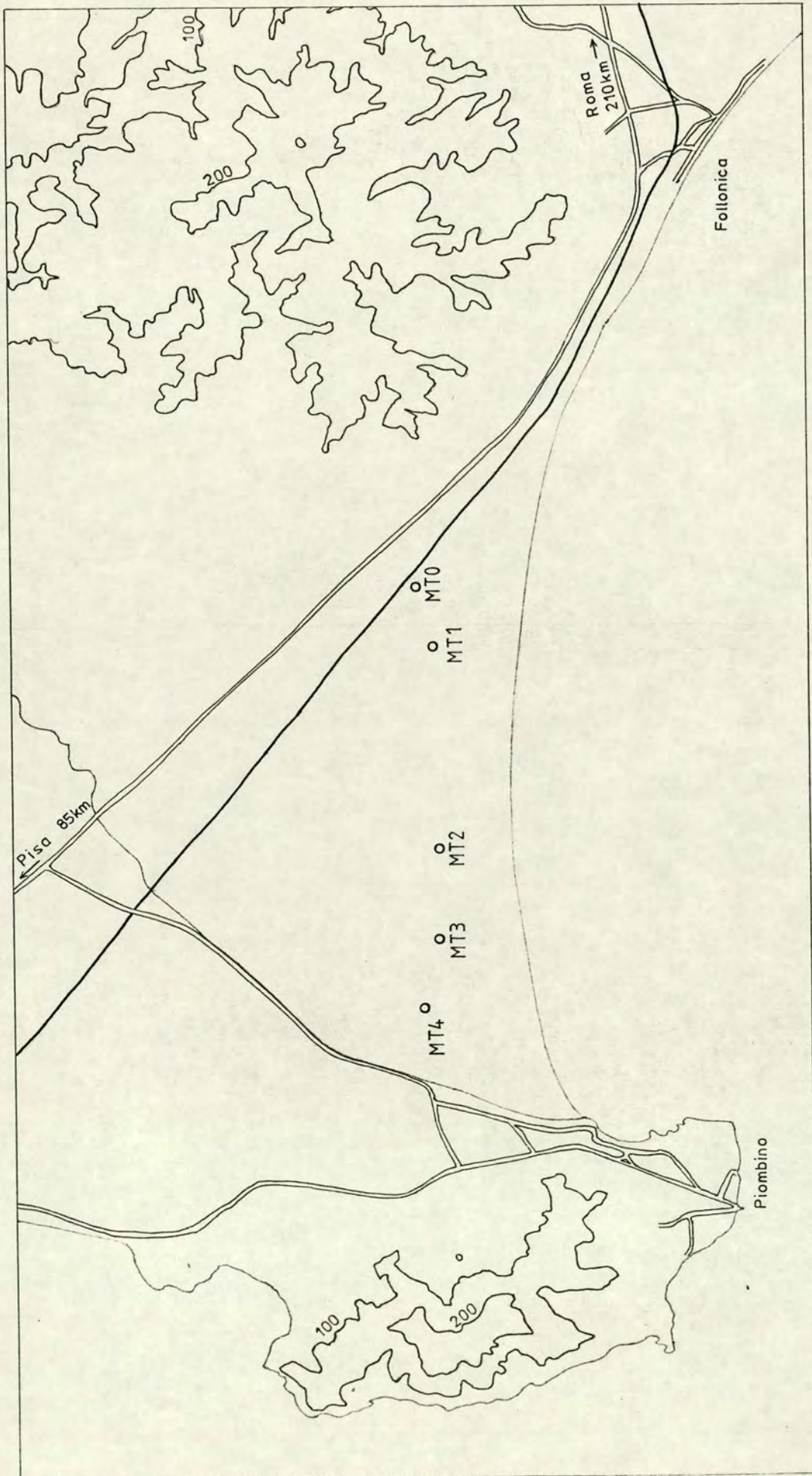


Figure 136. Map of Piombino Core Sites 500 m

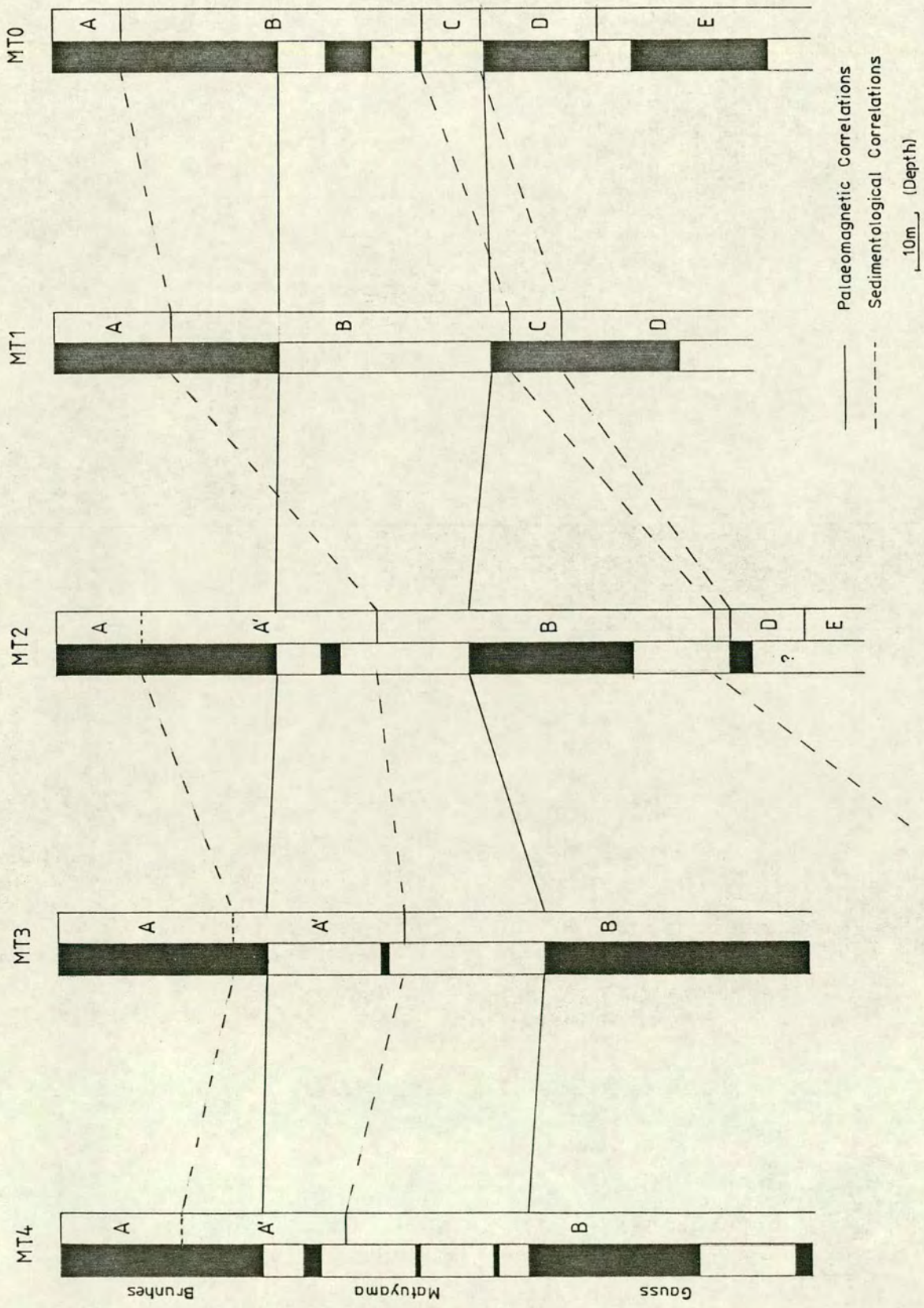


Figure 137. Correlation of Piombino Cores by Creer et al (1979)

The cores all date back to at least the middle of the Gauss Epoch (c3.0my) although identification of the Matuyama Epoch is difficult due to a strong normal overprint. The stratigraphic boundaries proposed by Aquater are diachronous, the regression at the base of Unit B occurred first in the west (i.e. MT2, 3, and 4), but the transgression of Unit A apparently also occurred first to the west (Figure 137), suggesting that the western end of the section has moved both up and down with respect to the east.

MT0

In core MT0, the Matuyama-Brunhes transition was initially placed at 18m (Creer 1977), then later at 39m (Creer et al, 1979), to coincide with the level in the other cores. The Gauss-Matuyama transition is at 74m, with the Gauss-Gilbert at 122m.

The Brunhes is represented by an interval of normal inclination and northerly declination to a depth of about 18m below which directions are more scattered, though still mainly normal. Readman and Evans (1979) studied the stability of samples from the Brunhes in MT0 and showed that between 9m and 20m the directions were stable. Between 39 and 47m declinations are southerly, and inclinations are negative (averaging about -30°), then occurs a further 7m of normally magnetized sediment correlated with the Olduvai Event. Between 54 and 61m declinations are mainly southerly, with inclinations of between 70° and -40° . The remaining 13m of sediment ascribed to the Matuyama, belonging to Unit C, have scattered, mainly normal inclination and scattered declination.

The top of the Gauss coincides with the top of Unit D. Inclination is high and positive apart from two intervals correlated with the Kaena-Mammoth Event, and the Gilbert Epoch. Similarly declination is uniformly northerly apart from scattered directions at the

top and southerly declinations in the two intervals noted with negative inclination. Although much of what is assumed to be Matuyama has scattered directions, Core M10 is the only one of the five Piombino cores with definitely reversed directions.

MT1

In core MT1 the Matuyama-Brunhes transition occurs at 39 m with the Gauss-Matuyama at 75m. The Brunhes is normal to a depth of 20m apart from an excursion at 15m. There is then a 10m gap below which directions are scattered to a depth of 63m. In this interval most inclinations are positive and declinations are mainly northerly, apart from the interval 39m to 48m. Below 63m directions are mainly normal, becoming more closely grouped below 75m. Within this period ascribed to the Gauss three excursions are seen (termed α , β , & γ). The α excursion involves only a change in declination, the other two involve both negative inclination and southerly declination.

Readman and Evans (1979) studied the stability of a number of intervals and showed that the Brunhes Epoch at 5m was stable but had low median destructive fields (100 Oe). The Matuyama at 57m and 67m was also stable and appeared to remain normal, again with low median destructive fields suggesting that this may in fact be a normal interval. The Upper Matuyama at 45m became reversed with demagnetization in some cases. In the Upper Brunhes there appears to be a long period secular variation with a period of 50,000 to 100,000 years. There is also an excursion at 15m which remains after demagnetization and features a clockwise loop of the VGP. The age is estimated by Readman and Evans to be 400,000 years, and the duration only 5,000 years.

MT2

The Matuyama-Brunhes boundary is placed at about 40m in Core MT2, with the Gauss-Matuyama transition at 71m. The Brunhes is mainly normal, but with some scatter in directions. The Matuyama between 40 and 55m is represented by positive inclinations (between 0° and 85°) and northwesterly declinations. The remainder of the Matuyama consists of very scattered directions: declinations are distributed about the entire 360°, while inclinations are slightly biased towards positive directions. The Gauss begins with 4m of normal sediment, but is then interrupted by a gap in sampling to a depth of 96m. The remaining 24m have directions scattered around normal and may belong to the Kaena or Mammoth Event.

MT3

In Core MT3 Creer et al (1979) place the Matuyama-Brunhes transition at 36m and the Gauss Matuyama transition at 83m. The Brunhes is similar to that in MT2 with a large degree of scatter about the normal direction, and again interrupted between 18 and 25m. All of the sediments assigned to the Matuyama Epoch give scattered directions, however the Gauss has fairly consistent normal inclination and declinations centred around zero. Three excursions may occur in the Gauss Epoch, the first represented by southerly declination only, the other two involving low positive or negative inclination.

MT4

MT4 has mainly normal polarity to a depth of 35m which is ascribed to the Brunhes. The Matuyama between 35m and 91m consists of very scattered directions with a slight positive bias in inclinations. The Gauss is also scattered, but inclinations are mainly

normal to a depth of 110m which may represent the top of the Kaena Event.

In general the Piombino sediments are poor recorders of the magnetic field. The Matuyama is almost always overprinted (only in MTO are true reversed directions seen). The epoch boundaries are defined by the amount of scatter - often the Gauss has directions closely grouped about a normal field direction, perhaps because any normal overprint does not conflict with the primary magnetization. Creer et al (1979) note that higher scatter coincides with higher susceptibility which may reflect that the poorer magnetic recorders have coarser grained magnetite, reflecting either a lack of alignment or a readiness to acquire viscous magnetizations. In the Brunhes sediments between about 20m and 40m in the cores the scatter must be due to sedimentation because there is no possibility of a reversed viscous overprint developing.

SAMPLING

In the summer of 1981 various intervals in each of these five cores were resampled to study Gauss excursions, the Gauss-Matuyama transition, and also the effect of demagnetization on some sediments from the various magnetic intervals. Each core is divided into two halves, and two types of sampling were used: round mini-cores were cut with a special tool from the upper half of each core section and extruded into 1cm cylindrical sample holders; samples from the bottom half of each section were taken using plastic boxes in the normal way. The sediment is often hard, so using square plastic boxes often leads to distortion of the sediment which is avoided using the former method. The smaller round samples can be selectively taken to avoid areas of oxidation, so in all cases the round samples probably give a more accurate record of the remanent magnetization.

RESULTS

MTO

Eight intervals from Core MTO were resampled, these were Sections 28 and 29 (22 to 24m) representing the lower Brunhes in which there was much scatter, Sections 78 and 79 (67 to 68m) representing the lower Matuyama, two intervals (Sections 82 and 86; 70m and 74m) which may record the Gauss-Matuyama transition, three intervals which may record excursions in the Gauss at 79m, 83m, and 87m and finally a section at 105m which recorded very consistent normal directions attributed to the lower Gauss.

NRM results for these intervals are shown in Figure 138. The Brunhes section, recorded in square samples only, has an average intensity of $7.06(\pm 7.32)\mu\text{G}$. Inclinations are mainly normal, but show a large amount of variation. Declinations vary between 0° and 180° giving a wide range in VGP latitudes. The section from the lower Matuyama has lower average intensity ($0.76(\pm 0.79)\mu\text{G}$). Four separate polarity intervals are recorded: two normal and two reversed, with VGPs alternately reaching high northerly and southerly latitudes. The upper normal zone shows slightly more variation than those below. The first reversal occurs between sections 78 and 79, the others all occur in section 79.

The five intervals sampled between 70m and 90m all have mainly positive inclination, though with much variation. The declination in the uppermost of these sections (70-71m) varies between 90° and 180° , and between 78 and 80m is around 90° . The other three intervals have mainly northerly declination. VGP latitudes also show much variation they are mainly southerly between 70 and 71m, but in the other intervals they vary from 10°S to 80°N . Average intensity in each of these intervals varies from 0.1 to 10.0 μG . The final

Figure 138. NRM Results For Square Samples From MTO

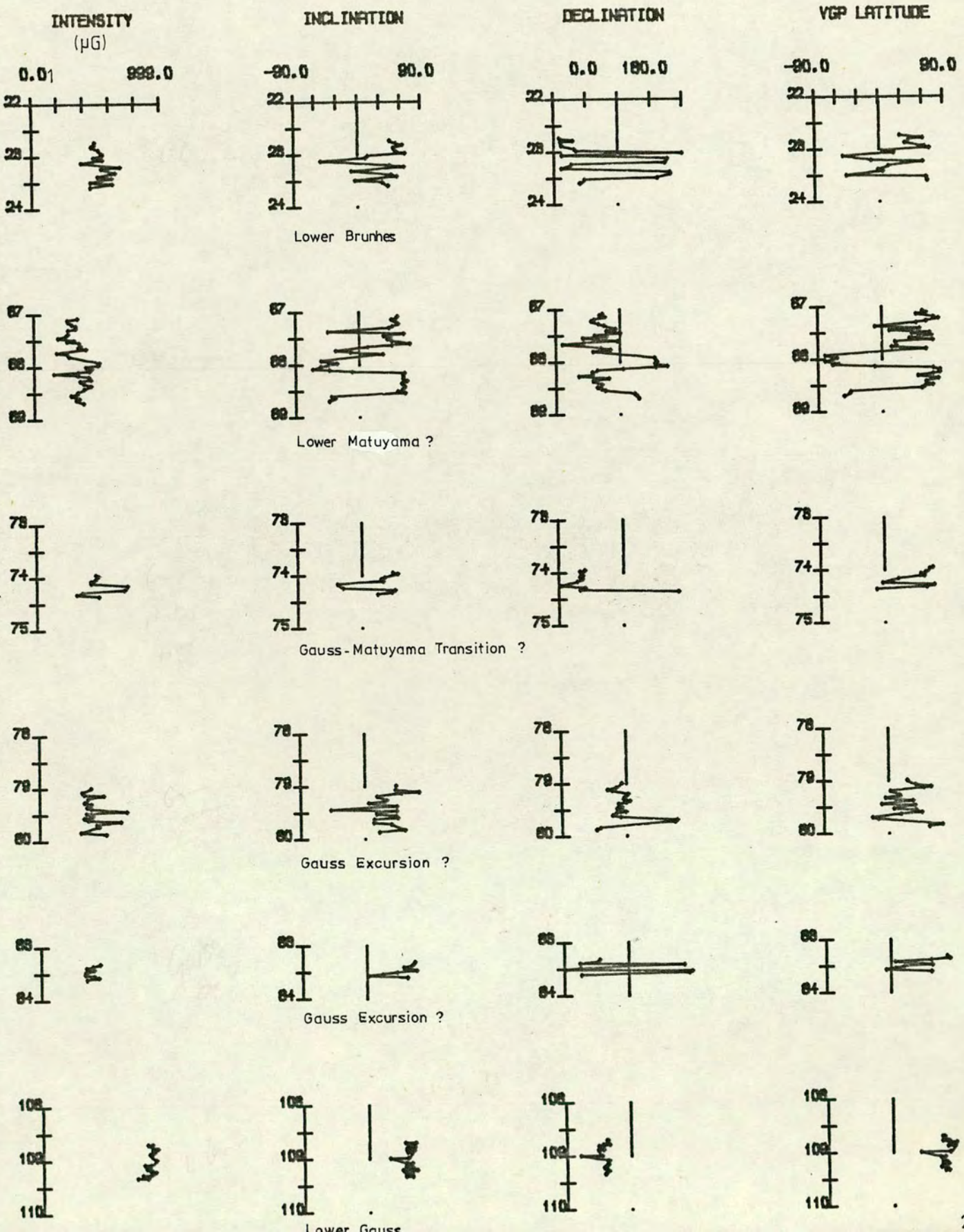
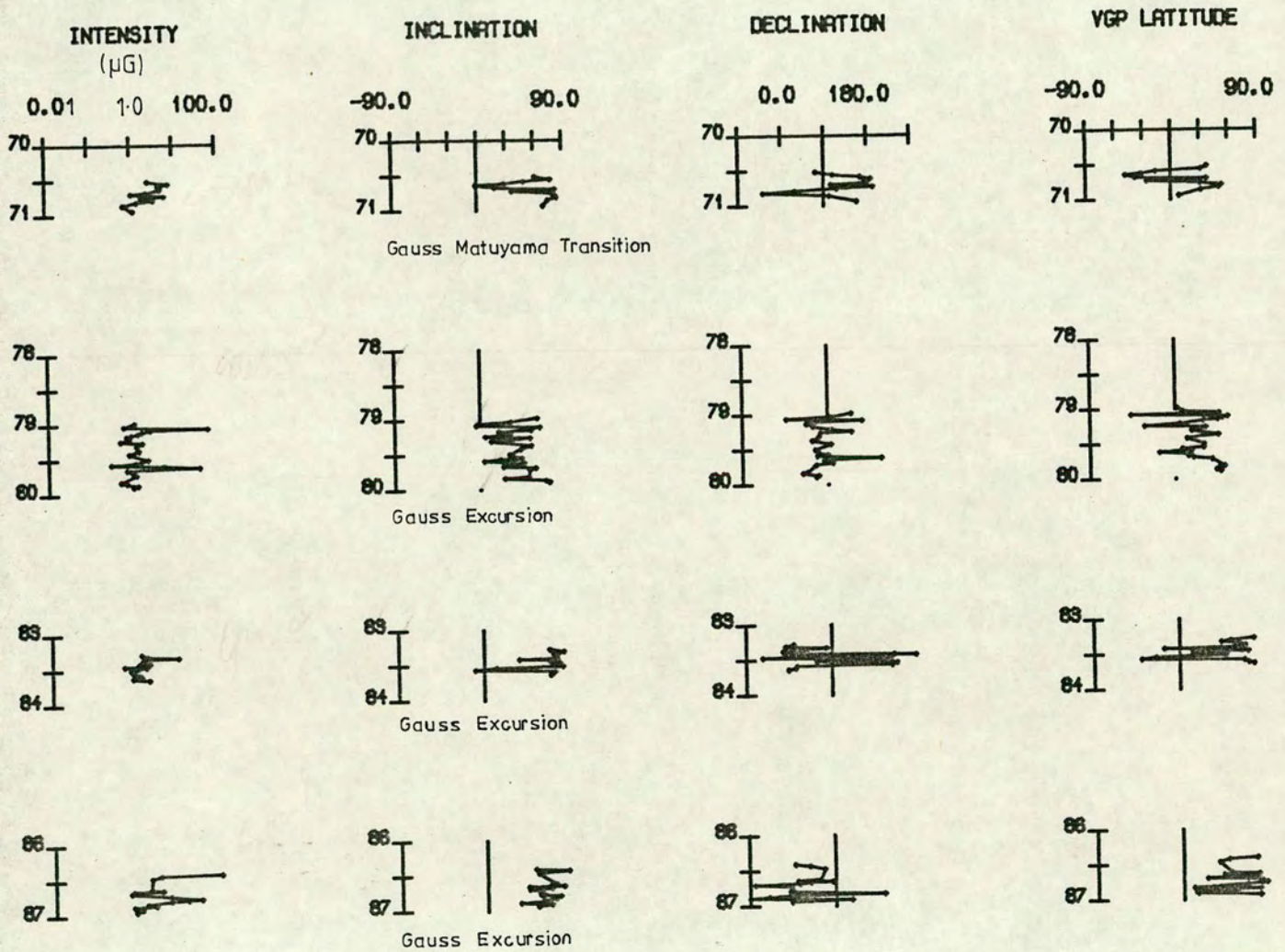


Figure 138 NRM Results for Round samples from MTO



section (105m) consists of consistently normal directions and has a very high intensity (184.5 ± 646) μG).

Examples of pilot demagnetization for samples from MTO are shown in Figure 139. Those of the Brunhes samples which were initially reversed remain so, while those initially normal become reversed (MTO All: 23.02m, MTO A15: 22.81m). Both of these samples show normal overprints, median destructive fields are 240 and 210 Oe respectively. The Matuyama samples vary in stability: some are very stable, with high median destructive fields (e.g. MTO B5: 68.51m), others show some variation about an initial direction before developing an anomalous direction above 250 Oe (e.g. MTO B32, 67.37m). Nevertheless it would appear that most samples record stable directions.

Samples from the Gauss are generally stable, with median destructive fields of between 220 and over 500 Oe. Only sample 82-16 (70.71m) shows any marked change in direction with demagnetization, developing a higher inclination. Samples from the lowermost section were demagnetized as part of the ARM versus RRM study (see Chapter 2). As noted earlier all the samples were very stable, and had high median destructive fields.

After demagnetization at 150 Oe, section A in the Brunhes had become reversed. Directions remain constant between 150 and 250 Oe (Figure 140). Intensity has dropped by 63% to 2.64 ± 1.91 μG at 150 Oe, and by a further 17% to 1.28 ± 0.44 μG at 250 Oe. This behaviour is different to that noted by Readman and Evans (1979) for sediments above 20m, so these sediments may belong to a Brunhes Event, or, more probably, to the Matuyama Epoch.

The second section (67-69m) retains the pattern seen at NRM, but with slightly more variation in the upper normal interval.

Figure 139. Examples of
Pilot Demagnetization
from MT0

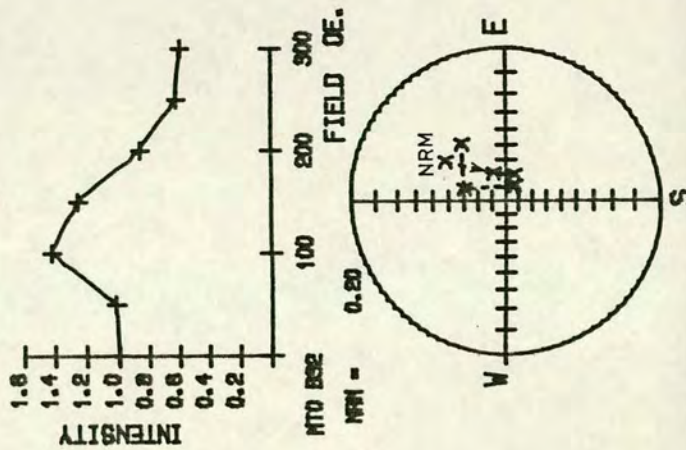
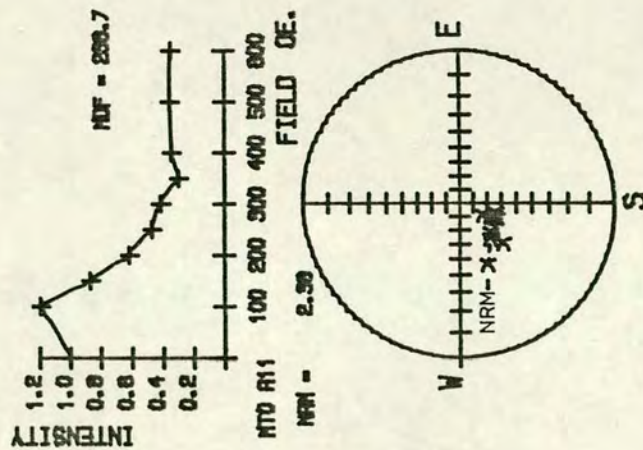
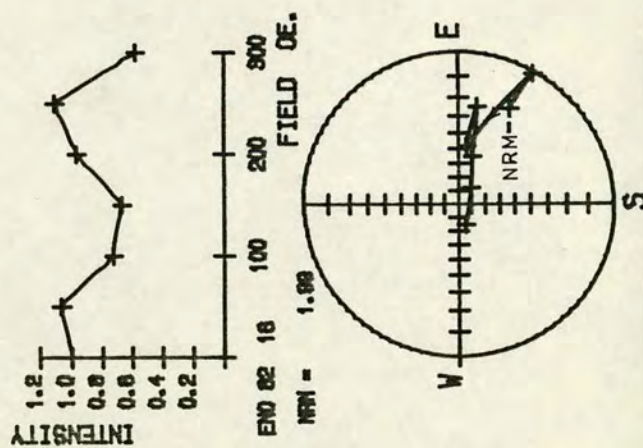
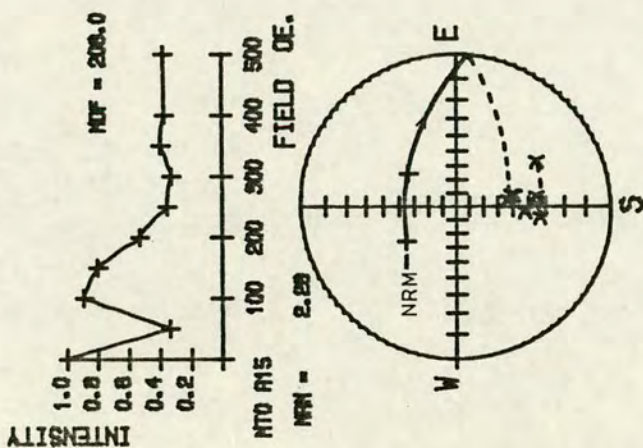
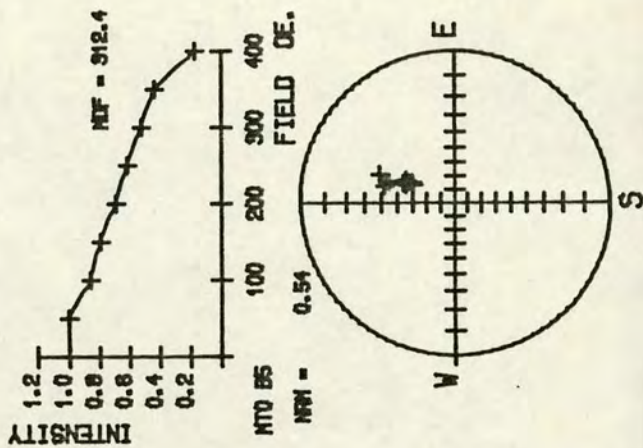
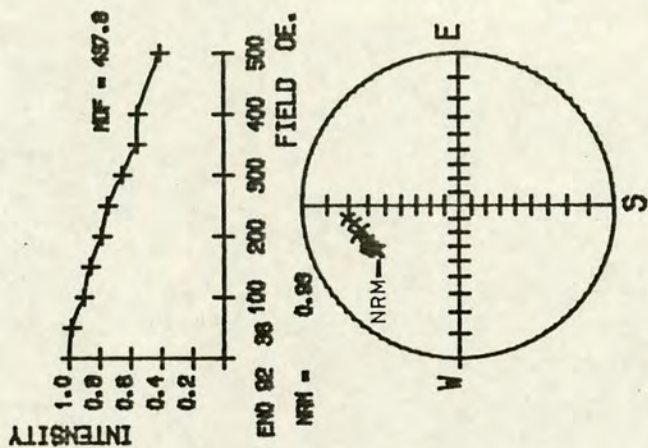


Figure 140 Results for MT0 after Demagnetization
(Square Samples)

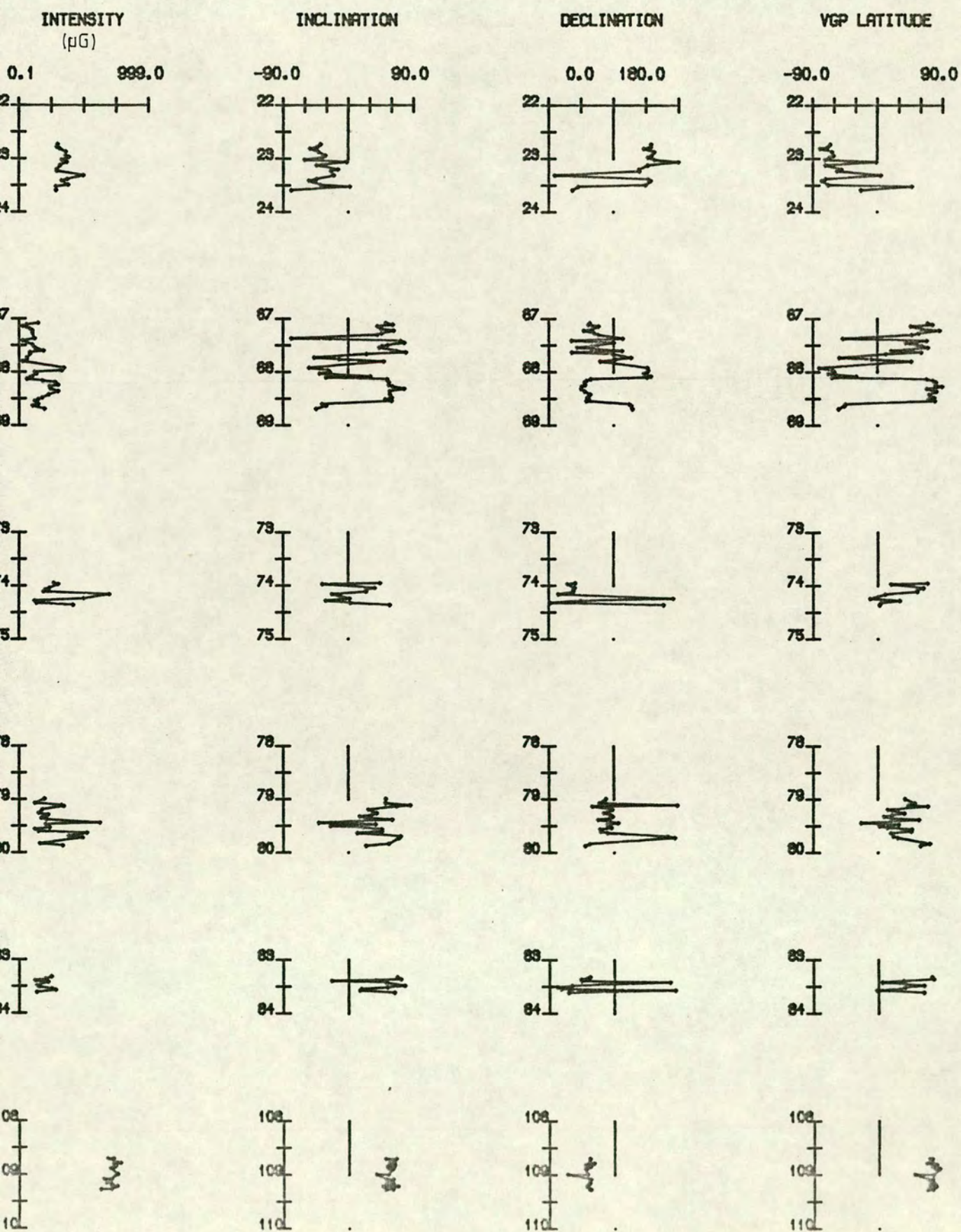
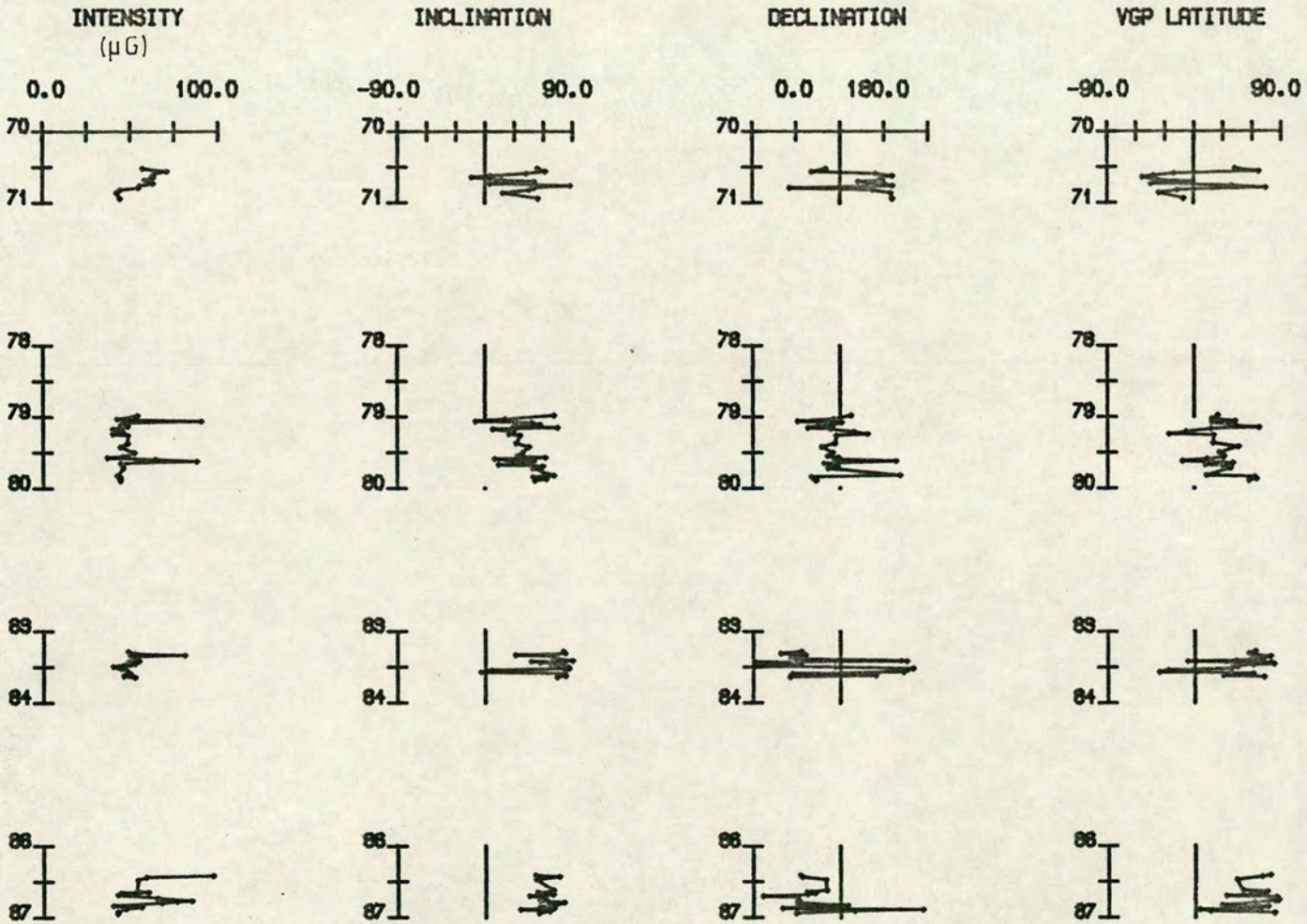


Figure 140 Results for MTO after Demagnetization

(Round Samples)

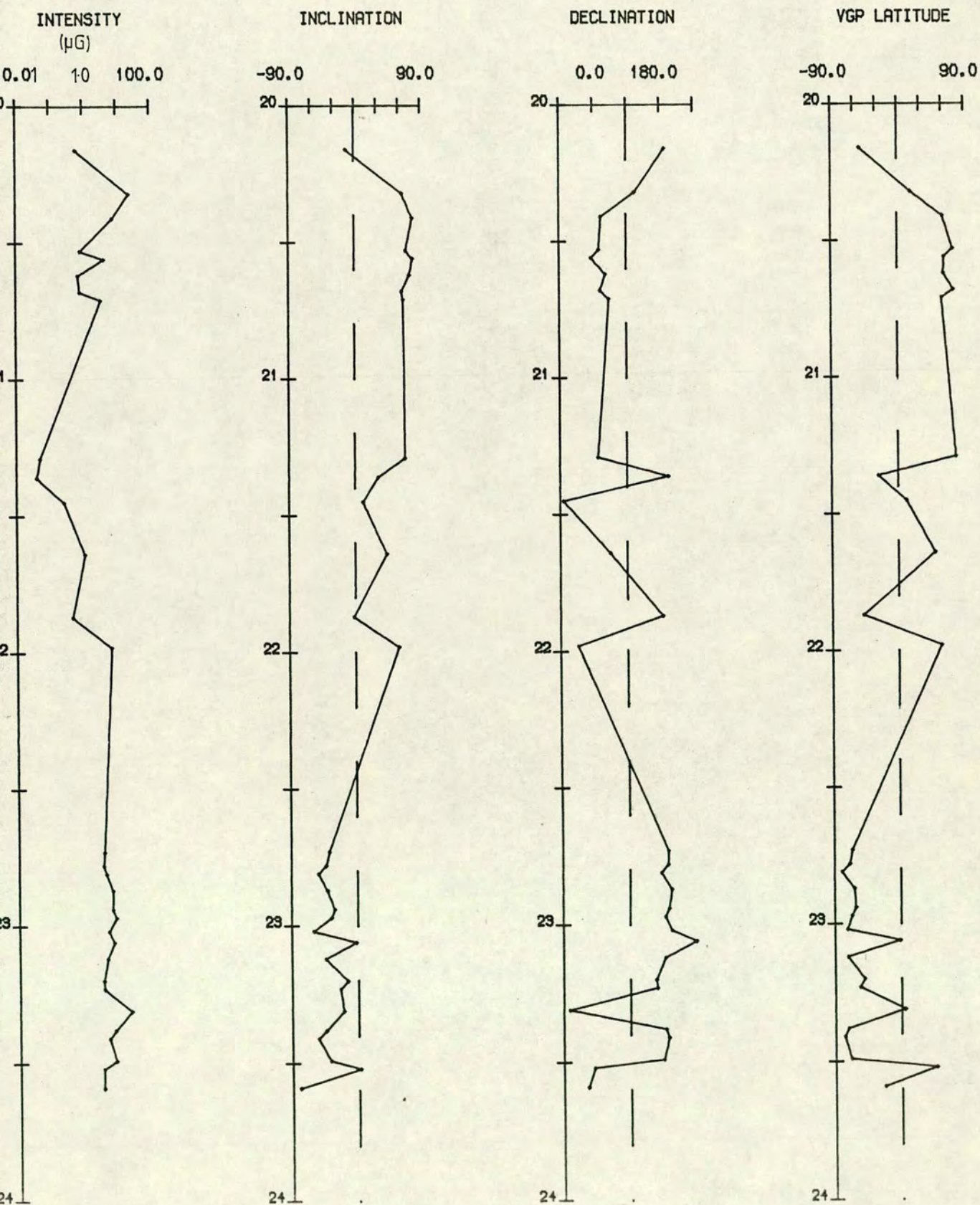


Intensity in this section fell by 32% to $0.52 (\pm 0.56) \mu\text{G}$ after 150 Oe, and by a further 11% to $0.44 (\pm 0.51) \mu\text{G}$ after 250 Oe. Two of the reversals occur within section 79 and probably reflect true geomagnetic behaviour. The most likely interpretation is that the normal intervals correspond to the Reunion Events.

The Gauss sections retain their scattered directions after demagnetization. The sediments are fine grained clays and silts so the direction is probably an accurate reflection of the field during times of erratic VGP movement. The section 70 to 71m still had positive inclination and southerly declination, and may represent overprinted Matuyama, though there is little indication of removal of an overprint between 0 and 150 Oe. The sections at 78 to 80m, 83 to 84m, and 86 to 87m may record excursions, but before this can be stated definitely, it has to be shown that the remainder of this section of the Gauss records stable normal directions. The section at 105m showed a drop of only 2% after demagnetization at 150 Oe. Directions remained normal, although declinations are all east of north. This may, however, be due to a slight error in orientation of the core sections, Figure 2 of Creer et al (1979) shows that the easterly bias is seen throughout the Lower Gauss.

Re-examination of the 'Brunhes' between the sections studied by Readman and Evans (1979), that is up to Section 24, and section A of this study (Core sections 28 and 29) showed that all samples above Section 28 have normal inclination, though in some cases this is shallow. Some samples with southerly declination are seen, giving intermediate VGPs. Section 25 is mainly normal (i.e. down to c 20.50m). The Matuyama-Brunhes transition probably lies within sections 26 and 27 but the results for this interval are complicated by the variation in lithology from grey clays to coarse black sands (Figure

Figure 141. Results for Sections 24 to 29 after Demagnetization



141).

The transitions bounding the Reunion Events at 67 to 69m are mainly sharp, however mid-points are seen for the upper reversal of the lower event, occurring off the west coast of South Africa, giving a near-sided path. The lower transition of the Upper Reunion Event occurs about 90° east of the site, passing through eastern Asia. Most of the intermediate poles form a clockwise loop around Asia towards the end of the transition (Figure 142).

MT1

Five sections from MT1 were resampled: the Matuyama at 57m, three possible excursions (71m, 87m, and 100m) and what appears to be the Gauss-Matuyama transition at 75m. NRM results for MT1 are shown in Figure 143. The Matuyama section (at about 57m) has a low average intensity ($0.36(\pm 0.13)\mu\text{G}$) and also low inclination and easterly declination giving VGP latitudes of 0-30° N. The other sections (70-72m, 74-76m, 86-88m, and 99-100m) have mainly normal inclination and northerly declination, however at 87m there is a marked reversal, albeit very narrow, with negative inclination and southeasterly declination. At 100m the inclinations are low (30°) and declinations are centred around 90°, so VGPs are sometimes located in the southern hemisphere.

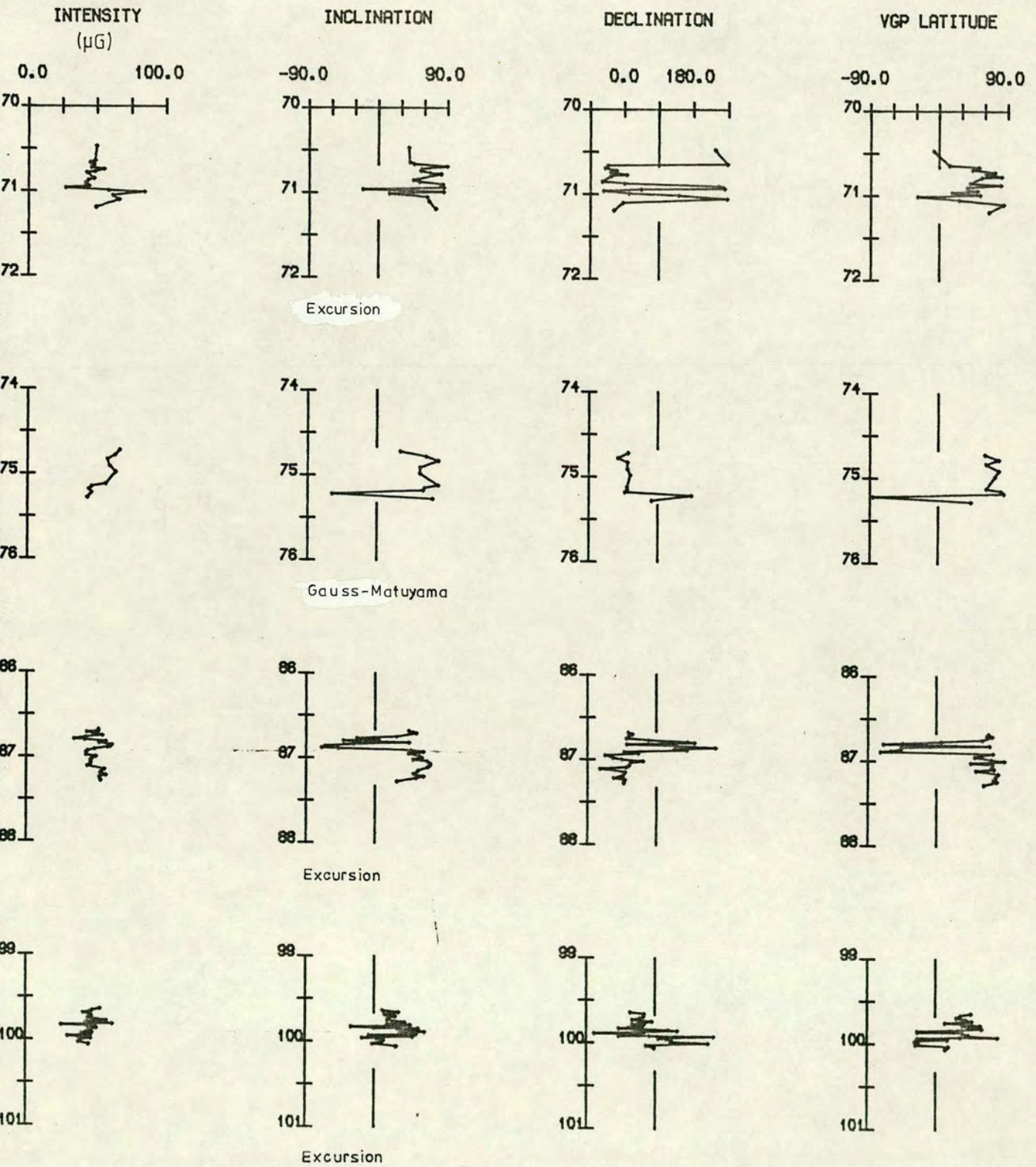
Demagnetization (Figure 144) shows that all of the intervals are stable, however intensity for samples MT1 A2 and MT1 A7 does not decrease at all, suggesting that the Matuyama has a large overprint due to the presence of haematite. Other samples have median destructive fields of 180 to 260 Oe.

After demagnetization the four Gauss intervals are similar to the NRM results (Figure 145). The interval 86 to 88m clearly records an excursion, with about 25cm of reversed sediment separating two



Figure 142. VGP Path for Transition at 68m after 250 Oe

Figure 143. NRM Results for Round samples From MT1



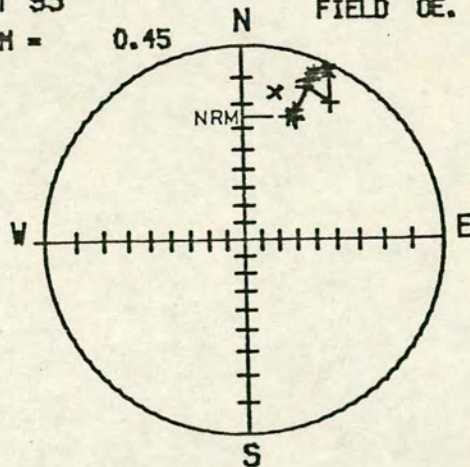
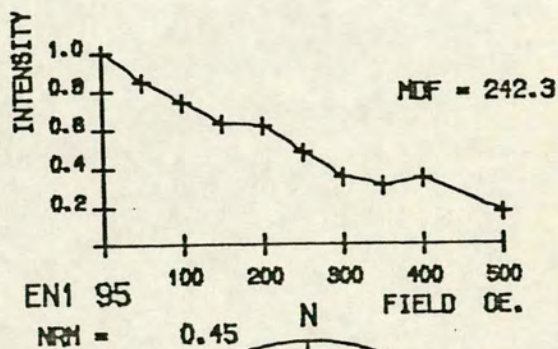
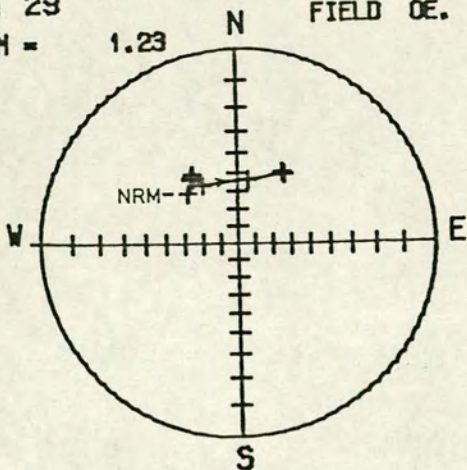
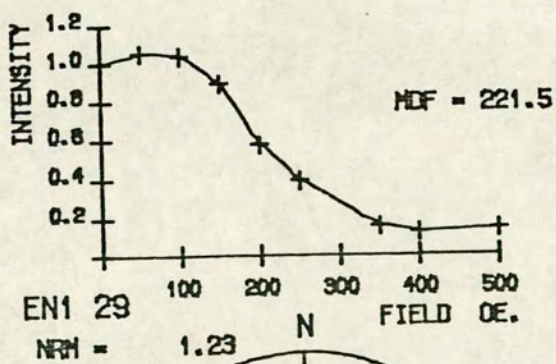
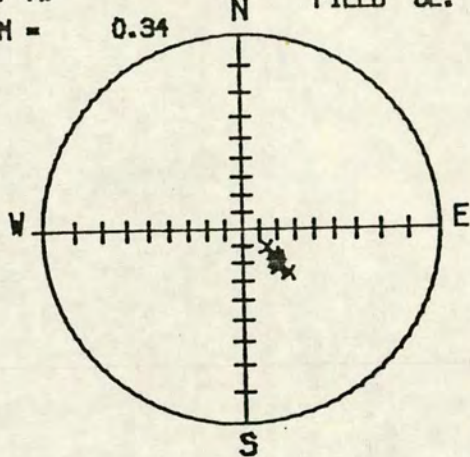
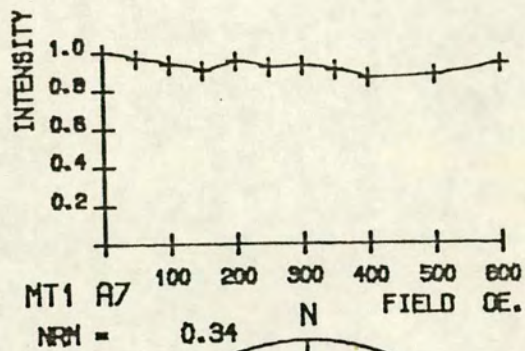
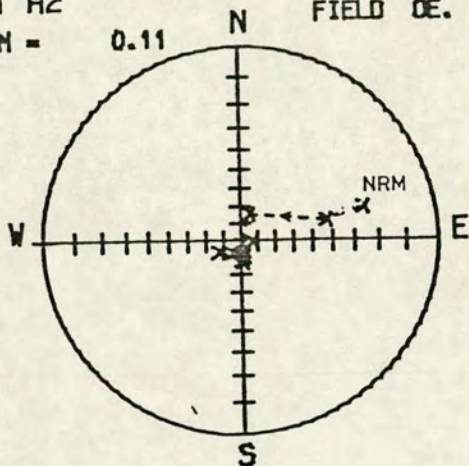
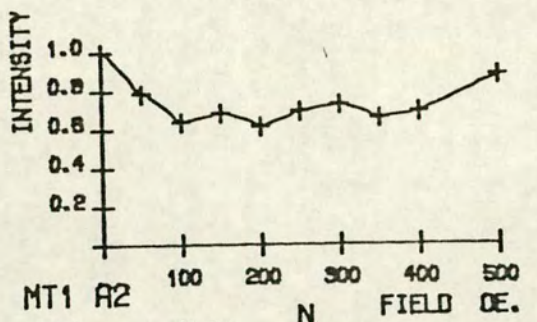


Figure 144. Examples of Pilot Demagnetization from MT1

intervals of normally magnetized sediment, while the interval 74-76m is mainly normal, and 70-72m is normal except for occasional samples. Unless the Matuyama is totally obscured by normal overprints, these sections probably belong to the Gauss. The original investigation (see Figure 3 of Creer et al 1979) showed that either side of the excursion at 100m the directions were consistently normal, so the low VGP latitudes seen here may represent a true excursion, the boundaries of which were not resampled. Figure 146 shows a VGP plot for the excursion at 87m. All the poles are concentrated about 90° east of the site giving transitional paths through east Asia.

MT2

Two sections in MT2 were resampled: 67-68m and 70-71m. The former represents a change from scattered inclination to normal inclination, the latter a change from scattered declination to normal declination, either of which could represent the Gauss-Matuyama transition. On further examination of the interval 74-75m, which may have recorded an excursion, it was decided that the remanence was poorly recorded because the sediments are coarse sands.

NRM directions are shown in Figure 147. The interval between 67 and 68m has scattered declinations similar to those seen in the original survey for the Matuyama. Inclinations are low but positive giving VGPs between 0 and 30°N. Intensity in this interval is low ($0.40(\pm 0.21)\mu\text{G}$). The lower section (70-71m) is slightly stronger: about $4.0\mu\text{G}$, and appears to record an excursion from normal directions to southerly declinations and low inclinations at 70.20 to 70.50m.

Samples from these sections had low median destructive fields (30 to 50 Oe). Samples EN2-36 and EN2-42 (70.35m and 70.66m respectively) change sign at 100 Oe, after which they were more or less

Figure 145 Results for MT1 after Deagnetization

(Square Samples)

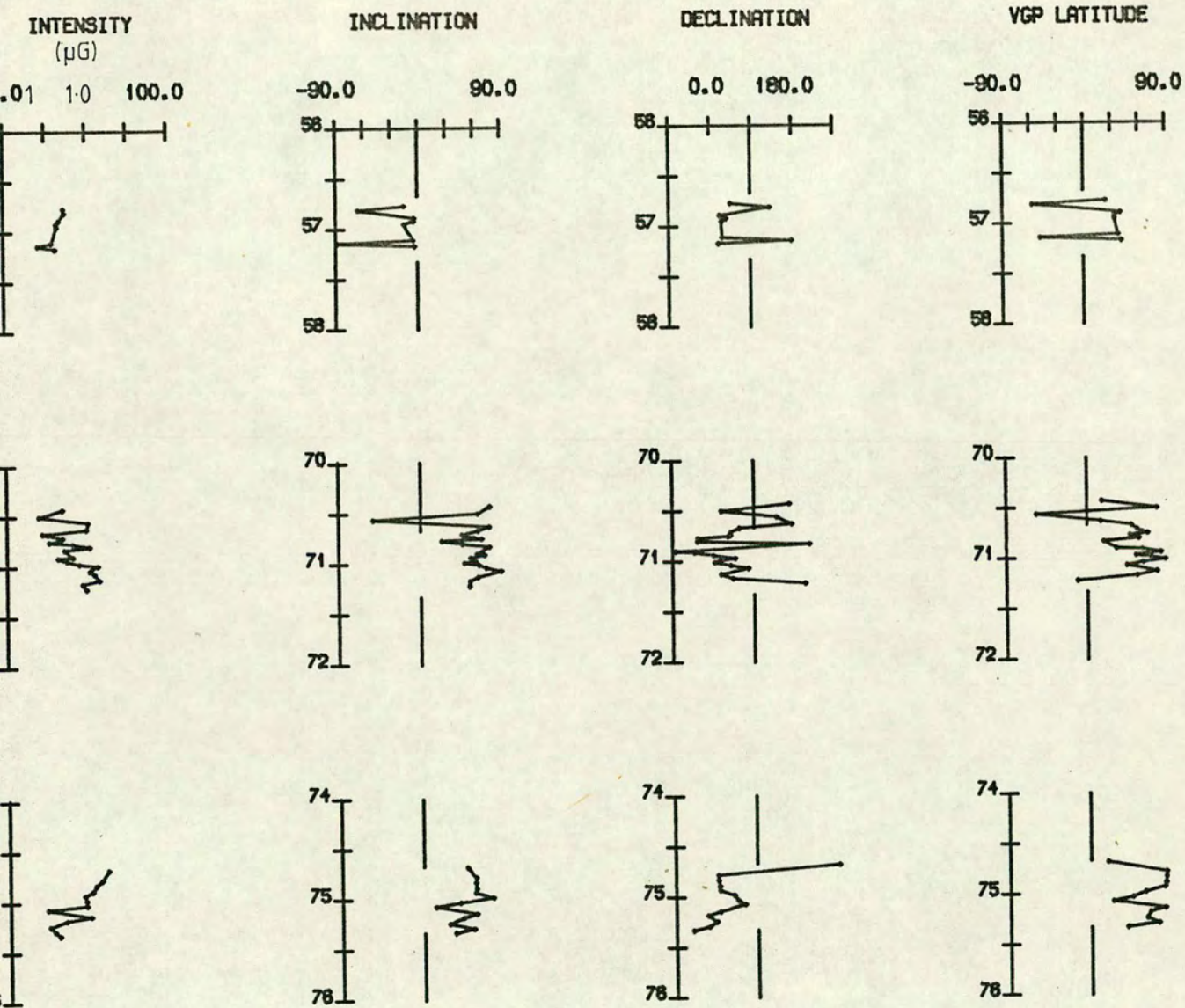


Figure 145. Results for MT1 after Demagnetization, cont.

(Round Samples)

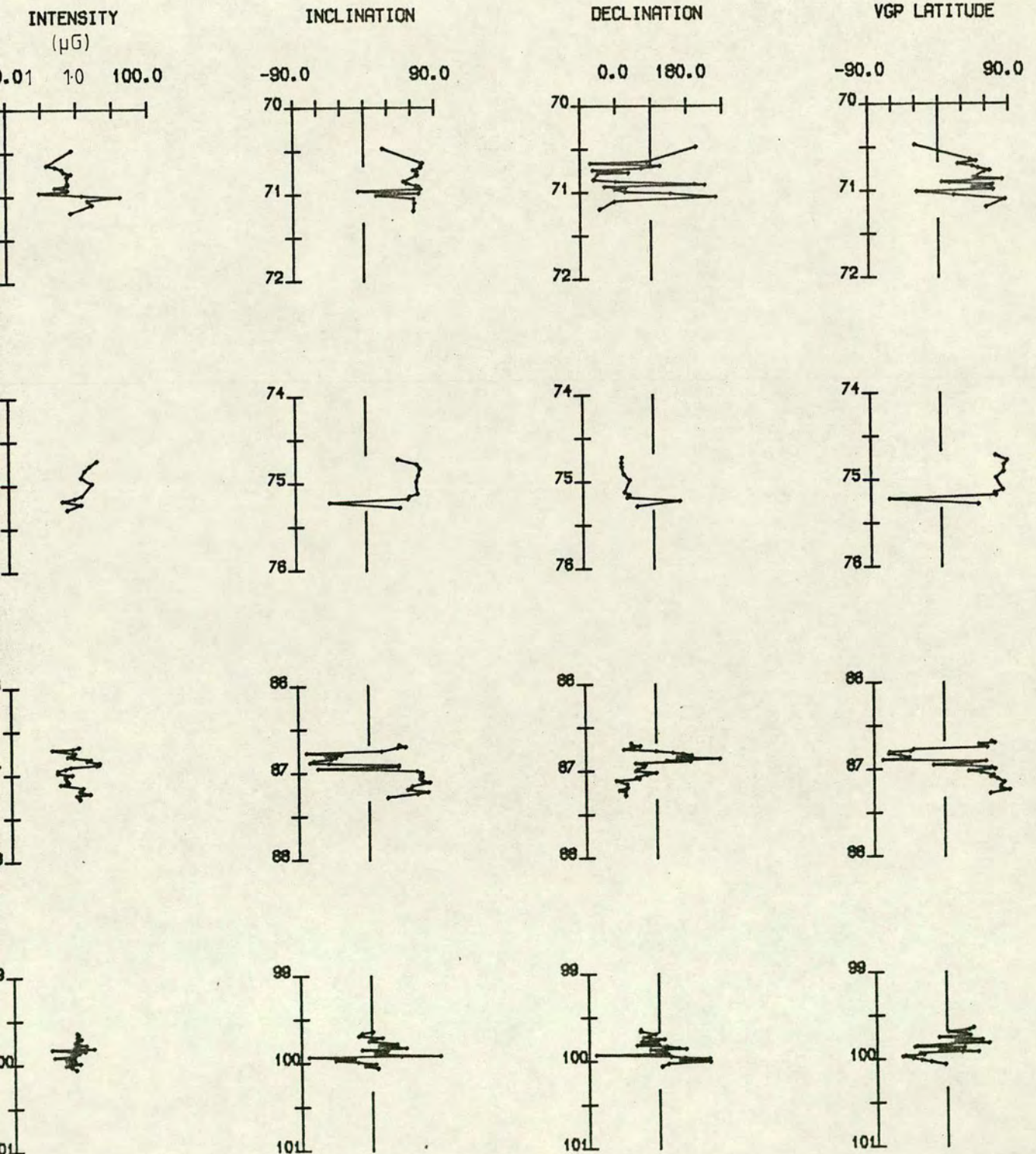
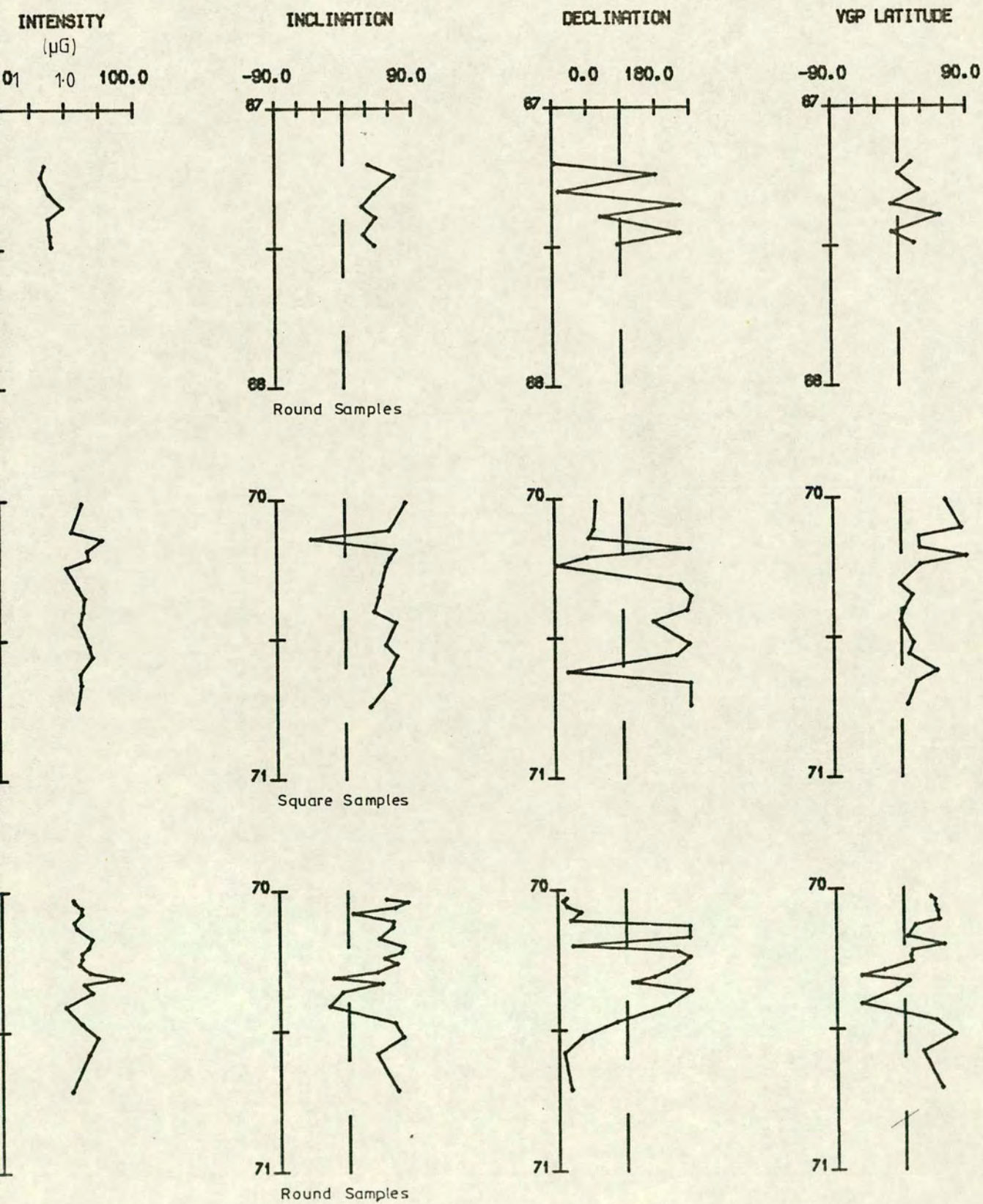




Figure 146. VGP Path for Excursion at 87m

Figure 147. NRM Results for MT2



stable until 300 Oe, Figure 148. After blanket demagnetization the first interval remained scattered, so the results should be rejected as the sediment is a poor recorder of the ambient field. The second interval became almost completely reversed (although the negative inclinations are often shallow). The intensity dropped markedly to about 0.7 μ G. This interval obviously belongs to the Matuyama (Figure 149).

MT3

From Core MT3, samples were taken to study the Gauss-Matuyama transition (81 to 83m) and four possible excursions at 96-97m, 99-101m, 107-109m, and 114-116m. The interval 107-109m was represented by coarse sand, so the magnetic direction is probably inaccurately recorded. NRM results for the four other sections are shown in Figure 150. The interval 81-83m has an average intensity of about 1.0 μ G, the round samples have negative inclination and declination around 135°, while the square samples have normal inclination (c 45°) and easterly declination. Thus the round samples give VGP latitudes of 0 to 60°S, and the square samples 0 to 60°N. The interval 96-97m has fairly scattered results, probably due to the low intensity (0.5 μ G). Inclinations are positive but declinations range from 90 to 180°, giving VGP latitudes from 30°S to 60°N. The other two intervals have higher intensity (about 7 and 13 μ G respectively), and record consistently normal directions.

Examples of pilot demagnetization from MT3 are shown in Figure 151. All samples have low median destructive fields (30 to 60 Oe) and show a large amount of variation even though they are initially strong. Two samples in the topmost section (EN3-8 at 81.70m, and EN3-16 at 82.01m) remain normal, as does one sample from 115.09m (EN3-119). Sample EN3-90 (100.70m), however changes sign at 150 Oe,

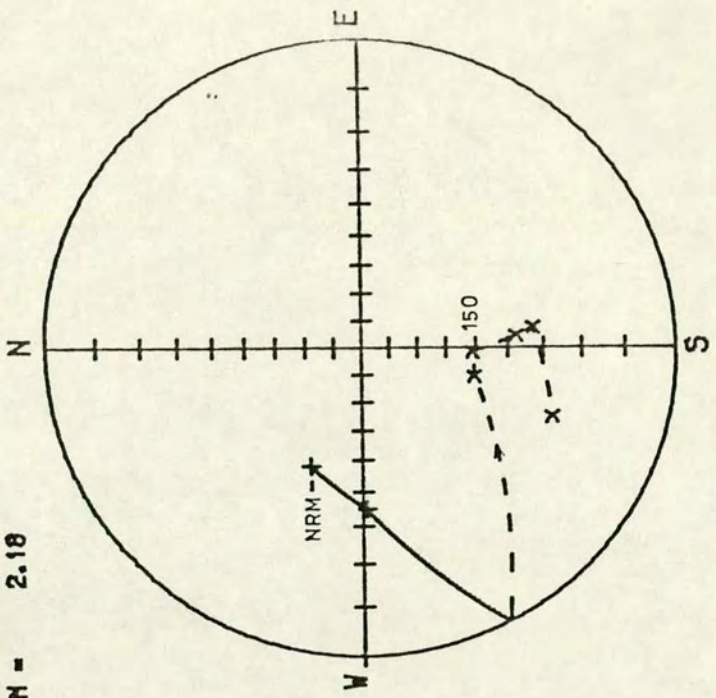
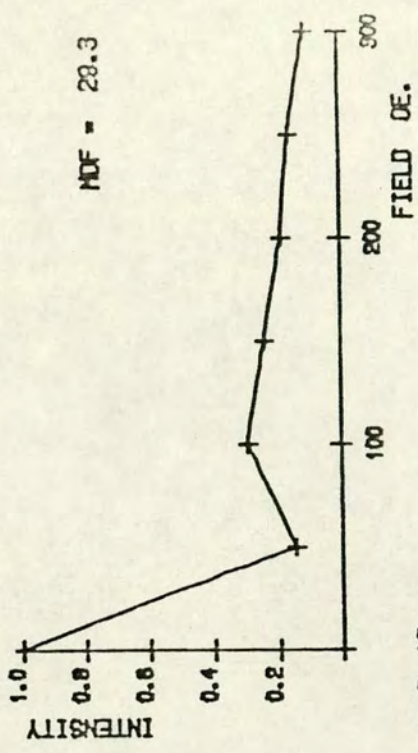
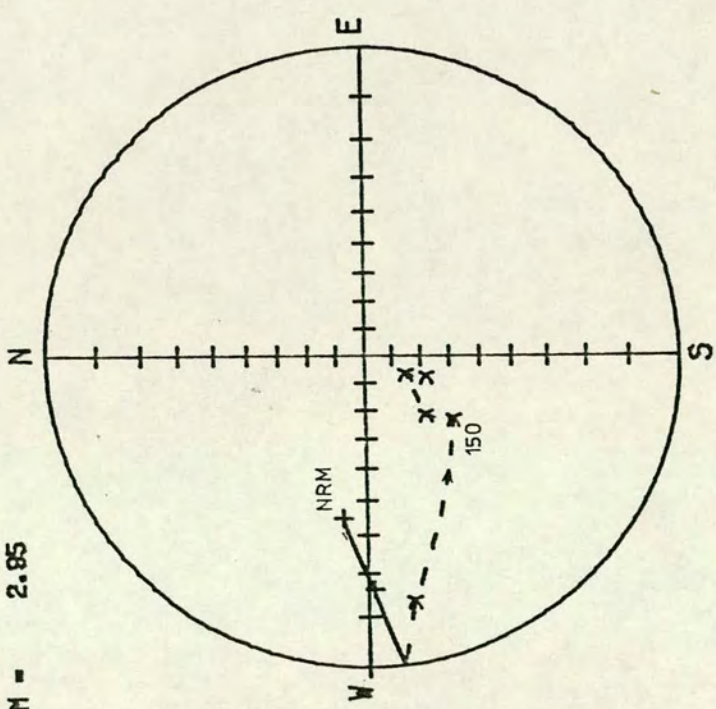
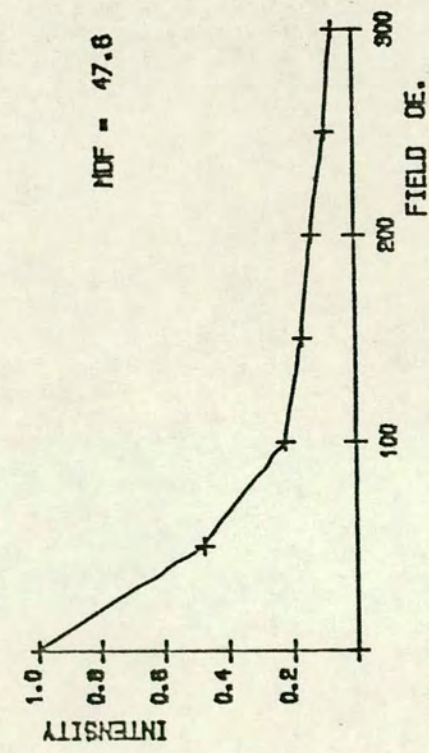


Figure 148. Examples of Pilot Demagnetization from MT2

Figure 149 Results for MT2 after Demagnetization

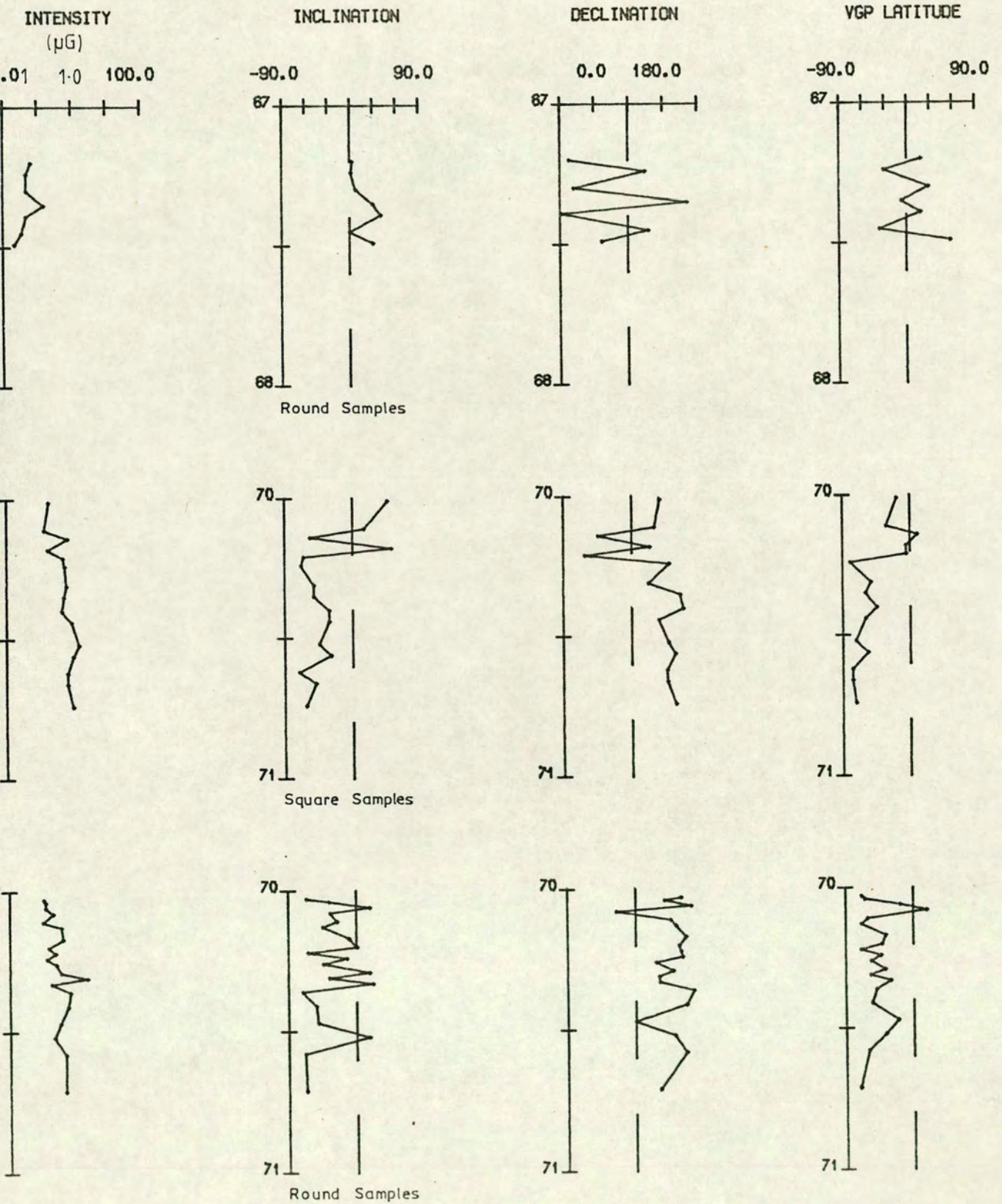


Figure 150 NRM Results For Square samples From MT3

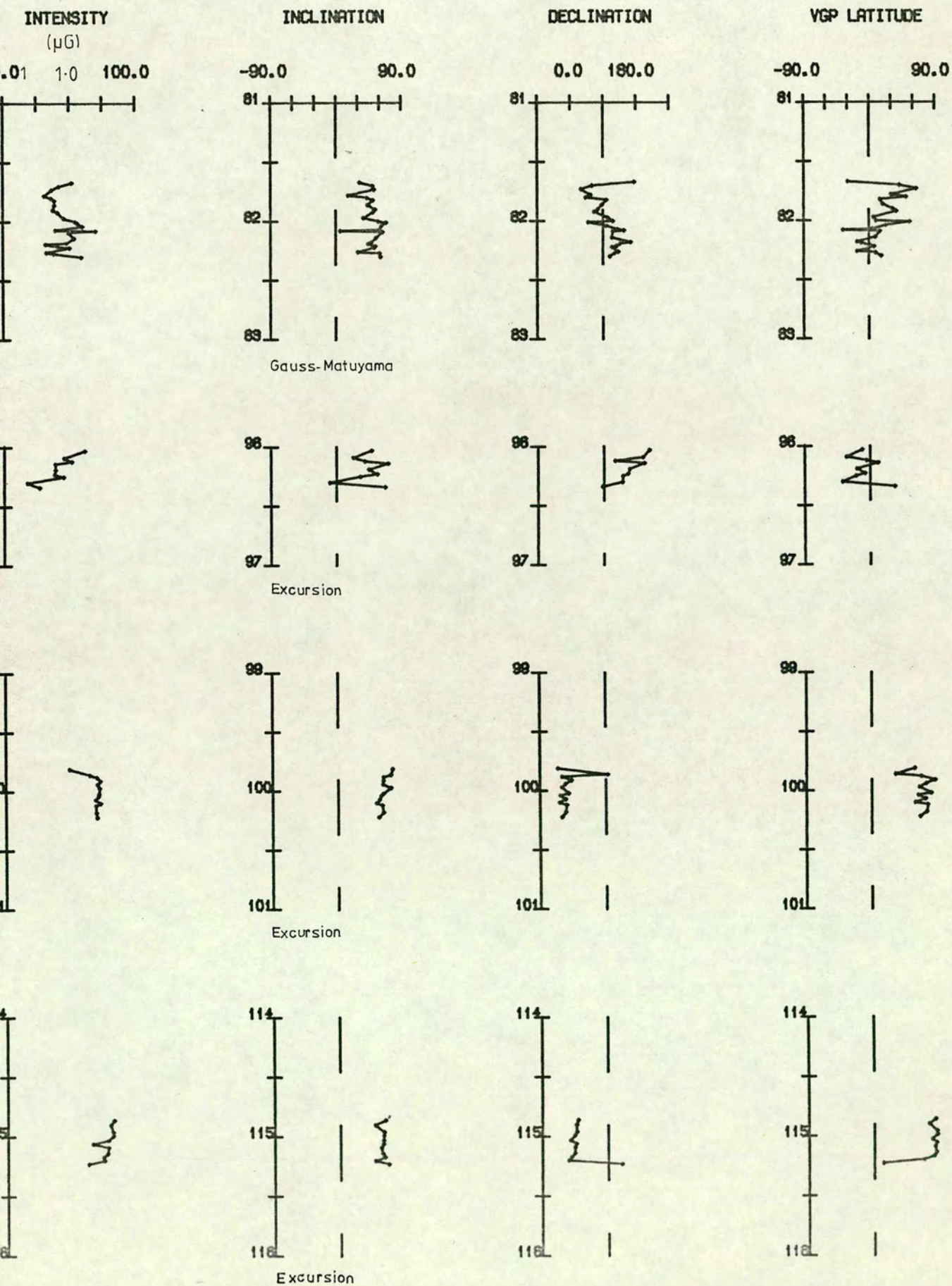
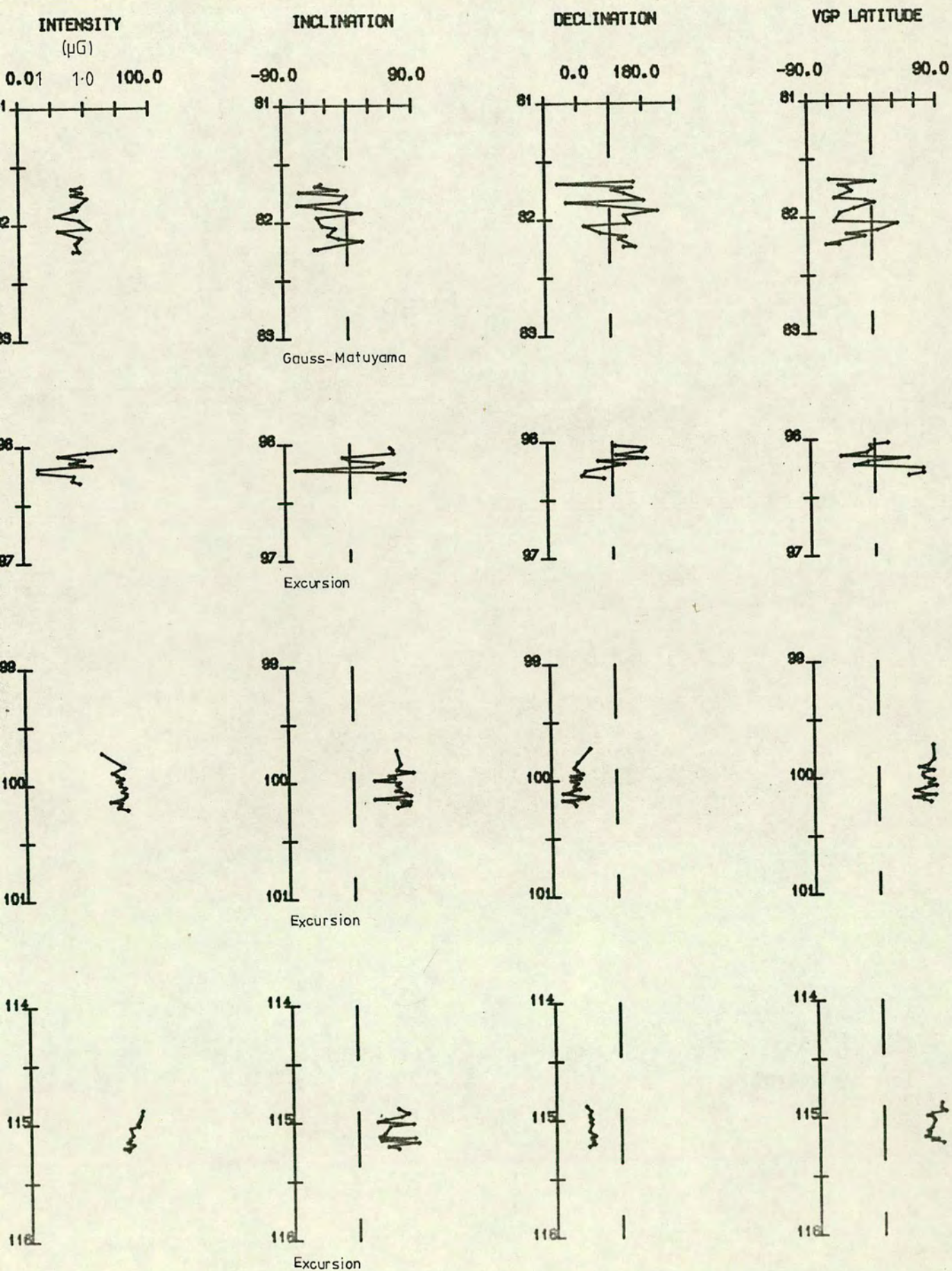


Figure 150 NRM Results for Round samples from MT3



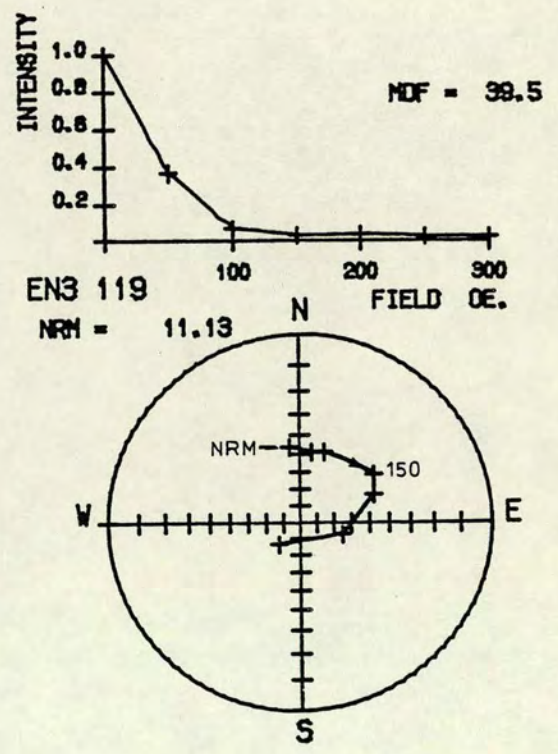
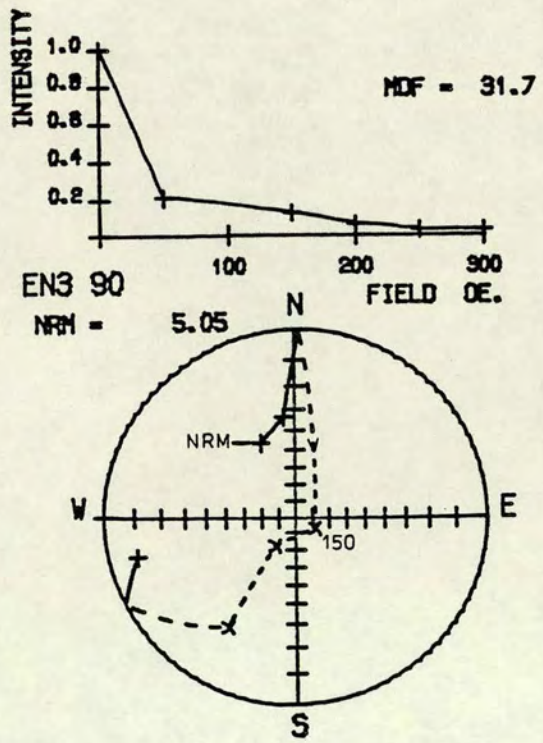
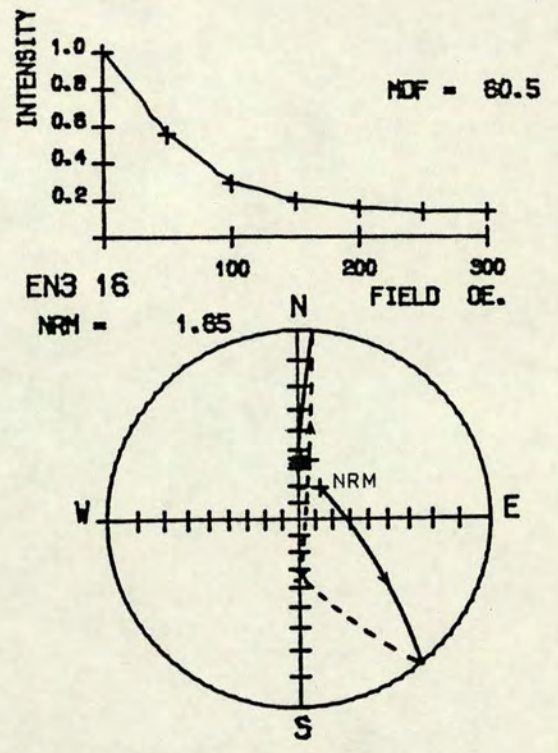
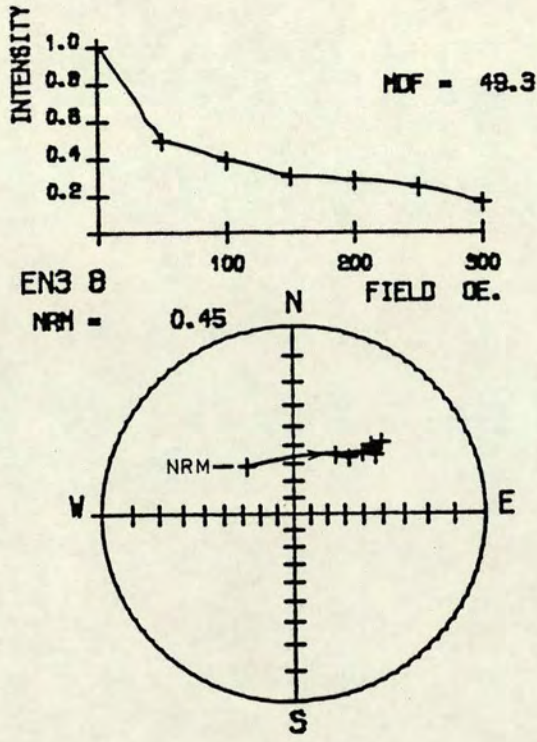


Figure 151. Examples of Pilot Demagnetization from MT3

and remains reversed until it develops an ARM at 250 Oe.

After blanket demagnetization the contradiction between round samples and square samples for the interval 81-83m remains: in both cases declination is easterly yet the round samples have negative inclination and the square samples positive inclination, Figure 152. Intensity is low ($0.25 \mu\text{G}$) for both sample sets. It is possible that the smaller round sample boxes avoided areas of oxidation, and so represent the primary Matuyama magnetization, while the square samples also record a secondary normal overprint due to oxidation.

The interval 96-97m remains intermediate after demagnetization, with a large amount of variation, especially in inclination. The interval 114-116m has shown a large decrease in intensity, and remains normally magnetized, although there may be an excursion at 115m, however this may result from low intensity which dropped by about 95% to $0.5 \mu\text{G}$. The interval 99-101m changes direction completely as indicated by the pilot specimen EN3-90. A short anomalous interval remains at 100m but represented by easterly declinations giving low VGP latitudes, and not by complete reversal. This interval is clearly reversed, and probably represents the Kaena Event.

MT4

The two inclination excursions recorded in the Gauss Epoch of MT4 (91 and 96m) were both recorded in coarse sands, and consequently may not represent a good reflection of the ambient field. The Gauss-Matuyama transition, placed at about 80m was resampled. NRM results are shown in Figure 153. Intensity is relatively high ($30 \mu\text{G}$), but the directions are anomalous: inclination is consistently low (0° to 30°) and declination averages 270° . Pilot demagnetization shows that although median destructive fields are low (58 to 65 Oe), there is little change in direction, Figure 154. After blanket demagnetization

Figure 152 Results for MT3 after Demagnetization

(Square Samples)

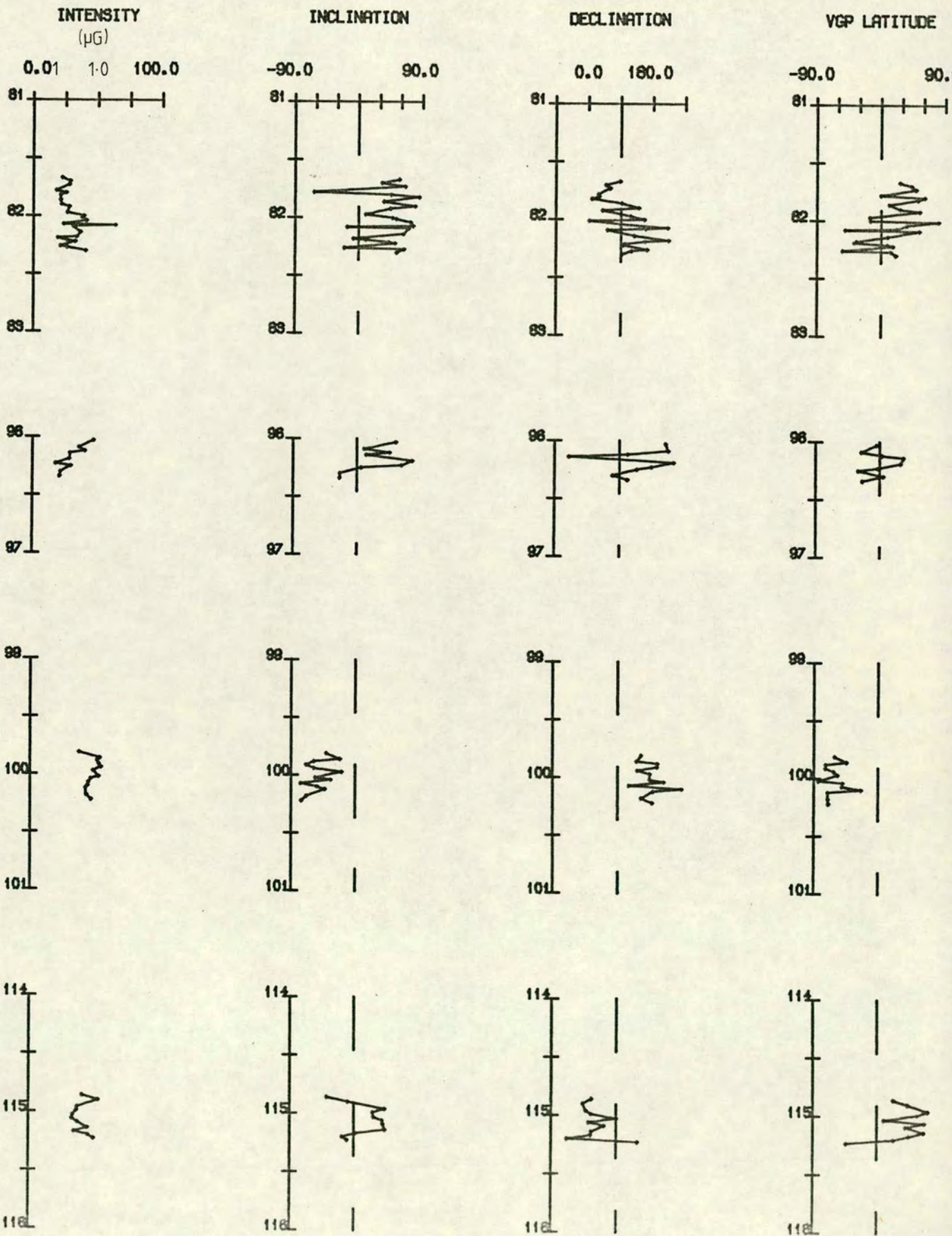


Figure 152 Results for MT3 after Demagnetization, cont.

(Round Samples)

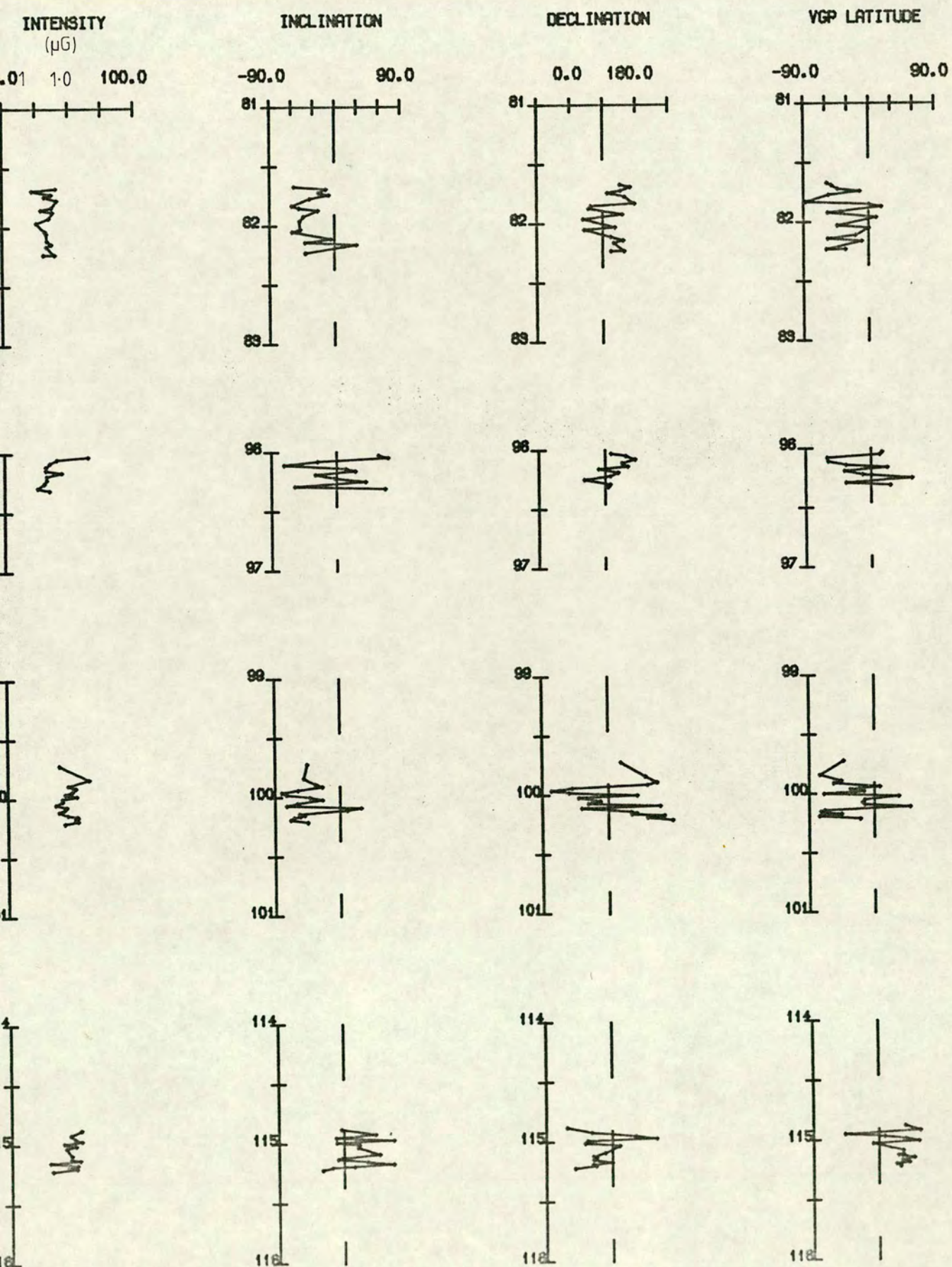
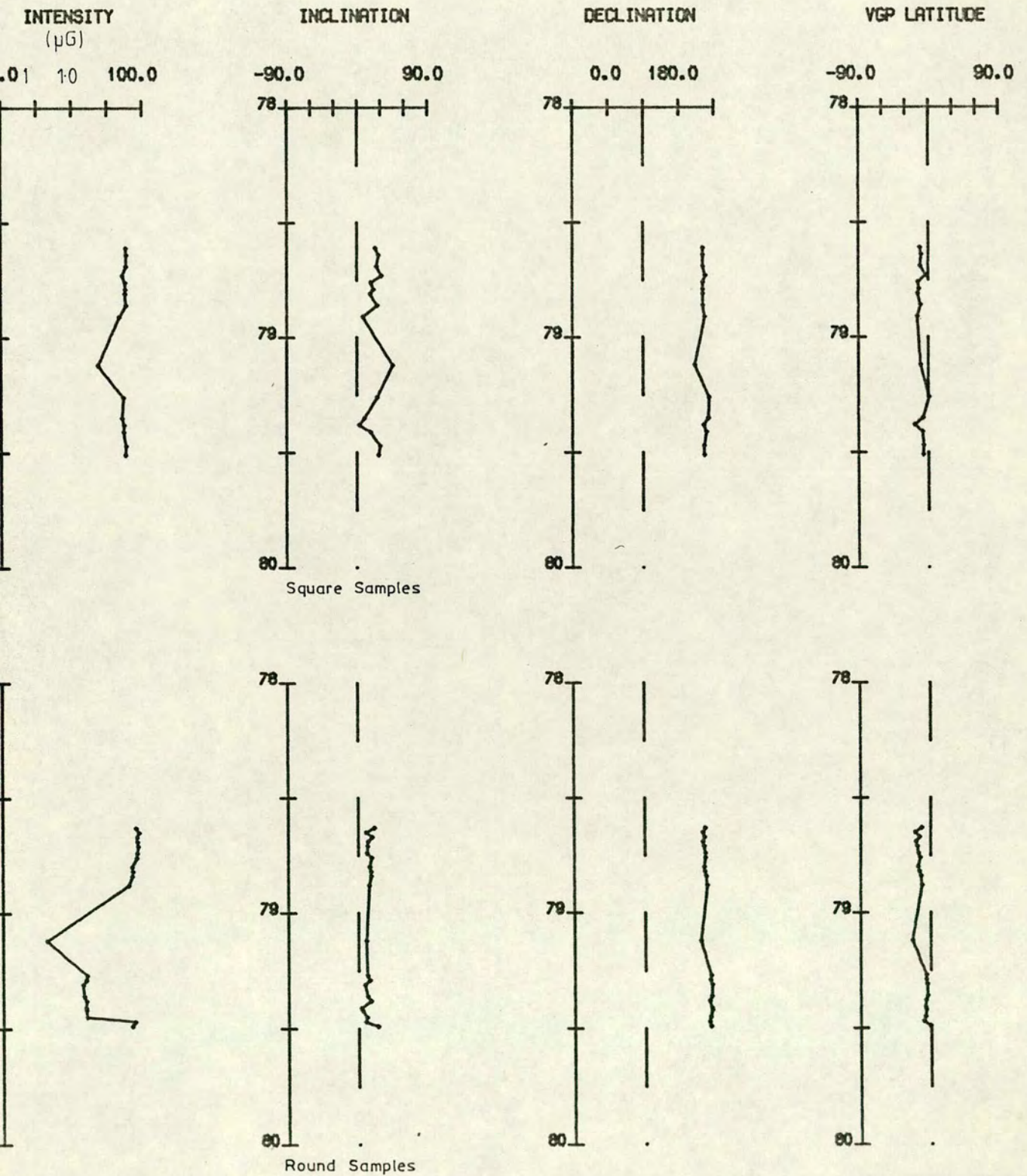


Figure 153. NRM Results for MT4



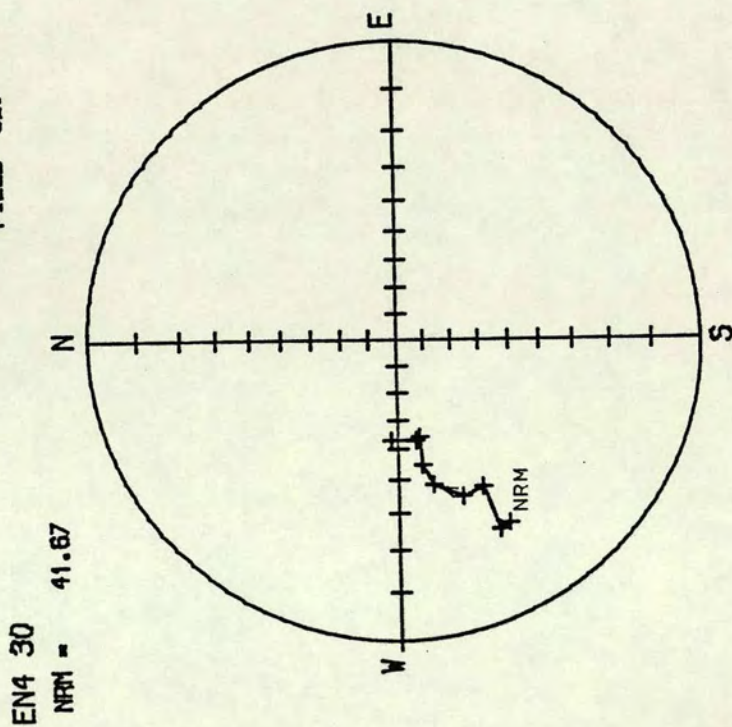
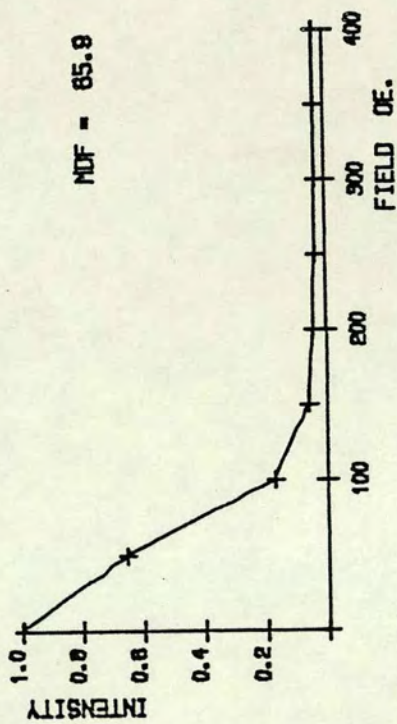
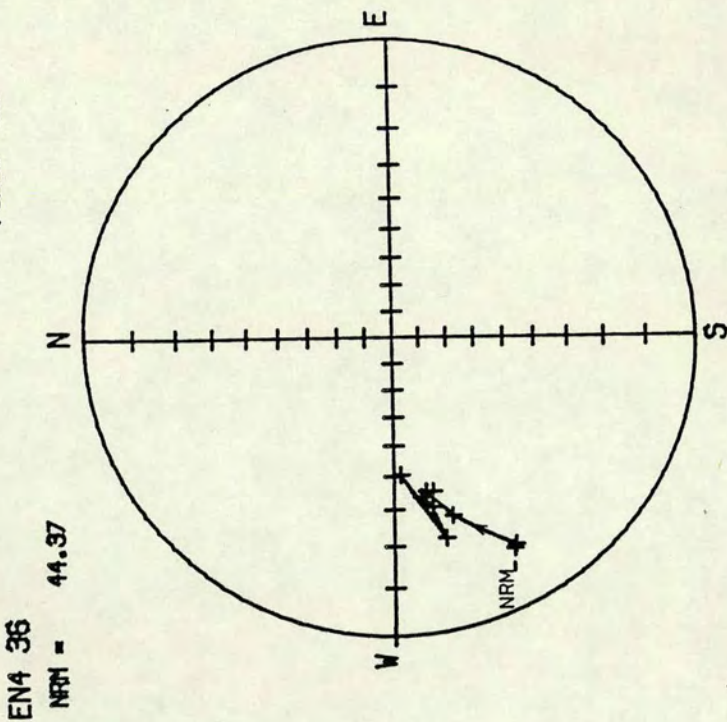
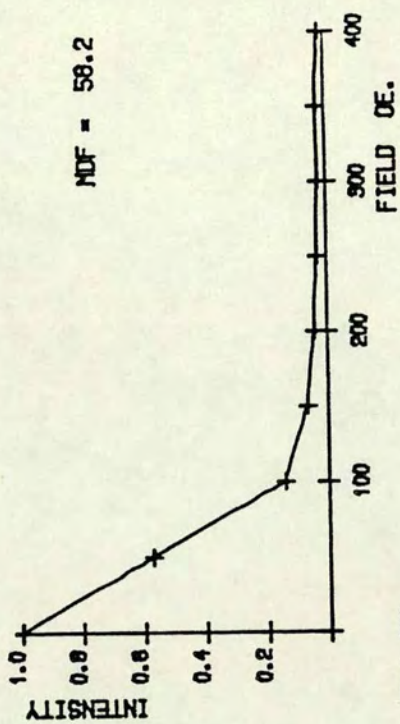


Figure 154. Examples of Pilot Demagnetization from MT4

intensity has dropped to about 4 μ G but there has been no large change in direction. This interval may represent a semi-stable midpoint of the transition, located at the equator at a longitude of 90°W. Given a sedimentation rate of 11cm/1000 years (Creer et al 1979) this interval lasted about 10,000 years, which is much longer than most estimates of the lengths of transitions. Creer et al (1979) note that this interval has much higher Q-ratio than the rest of the core, suggesting a different source for the remanence.

CONCLUSIONS

Although only isolated sections were investigated in this study it is possible to make some remarks about the nature of the magnetization in the Piombino cores. The records of the Gauss are quite often scattered whereas previous work suggested that the Gauss Epoch was represented by consistently normal directions. It may be that the scattered directions result because each of the intervals studied was one in which an excursion was recorded, and an excursion is definitely seen at 87m in MT1. Other excursions in the Gauss may occur at 79m and 83, in MT0, at 100m in MT1, and at 100m in MT3, although this last example is completely reversed, and may be part of the Kaena Event. Further studies must be carried out to prove that the 'quiet' normal Gauss does not show any large variation similar to that seen in MT0.

The removal of large normal overprints from sections of MT0, MT2, and MT3 suggests that more accurate measurement of what is assigned to the Matuyama Epoch will lead to a redefinition of the magnetostratigraphy, particularly as regards the Gauss-Matuyama and Matuyama-Brunhes transitions. The results from MT0 at 22m suggest that the Matuyama-Brunhes boundary occurs higher than noted by Creer et al (1979), probably occurring at about 21m. Further work may

lead to the relocation of the Matuyama-Brunhes transition at the base of the 'quiet' Brunhes seen in all cores at about 20m (as after Creer and Readman, 1978). The doubts that exist over the position of the Gauss-Matuyama transition as a result of these studies make it difficult to date the suggested excursions in the Gauss. The most prominent excursion (at 87m in MT1) was dated by Creer et al (1979) at 2.50 to 2.55 m.y. taking the Gauss-Matuyama transition at 75m. If this transition is relocated at 61m (because the section at 70m was definitely normal) the revised age is only slightly greater (2.65 m.y.), however the age control at the base of the hole is poorly established.

CHAPTER 7

DISCUSSION

PART 1 EXCURSIONS

There has been much speculation about the existence of excursions in the palaeomagnetic record. Before considering the validity of possible excursions recorded at Stirone, Piombino, Pontida, and DSDP Site 514, it is perhaps worthwhile to investigate whether there are any grounds to prove that excursions actually do exist.

Figure 155 shows the Mankinen and Dalrymple (1979) revised timescale for the interval covered by this study (0 to 4 million years b.p.) (Figure 158 shows possible excursions reported during the past 15 years, and also showing the excursions recorded at the sites mentioned above.) Mankinen and Dalrymple state that none of the proposed brief reversals within the Brunhes have been conclusively shown to be reversals of the geomagnetic field, however they admit that the Laschamp Event at 0.02 m.y. b.p. and the Blake Event at 0.18 m.y. b.p. may be of regional significance. Mankinen and Dalrymple suggest that there is little evidence for the existence of a Gilsa Event distinct from the Olduvai Event, however apparent bimodal distribution of dates around 2.00 to 2.14 m.y. b.p. indicates that there may be two Reunion Events. There is also a possible event just above the Gauss-Matuyama transition referred to as the 'X' anomaly in magnetic anomaly profiles.

As Verosub (1982) shows there are sound theoretical reasons for believing in the existence of short excursions. Secular variation due to turbulence in the Earth's core varies in amplitude according to a statistical distribution (e.g. Dodson, 1982). At the extremes of this distribution the largest deviations from an axial field occur,

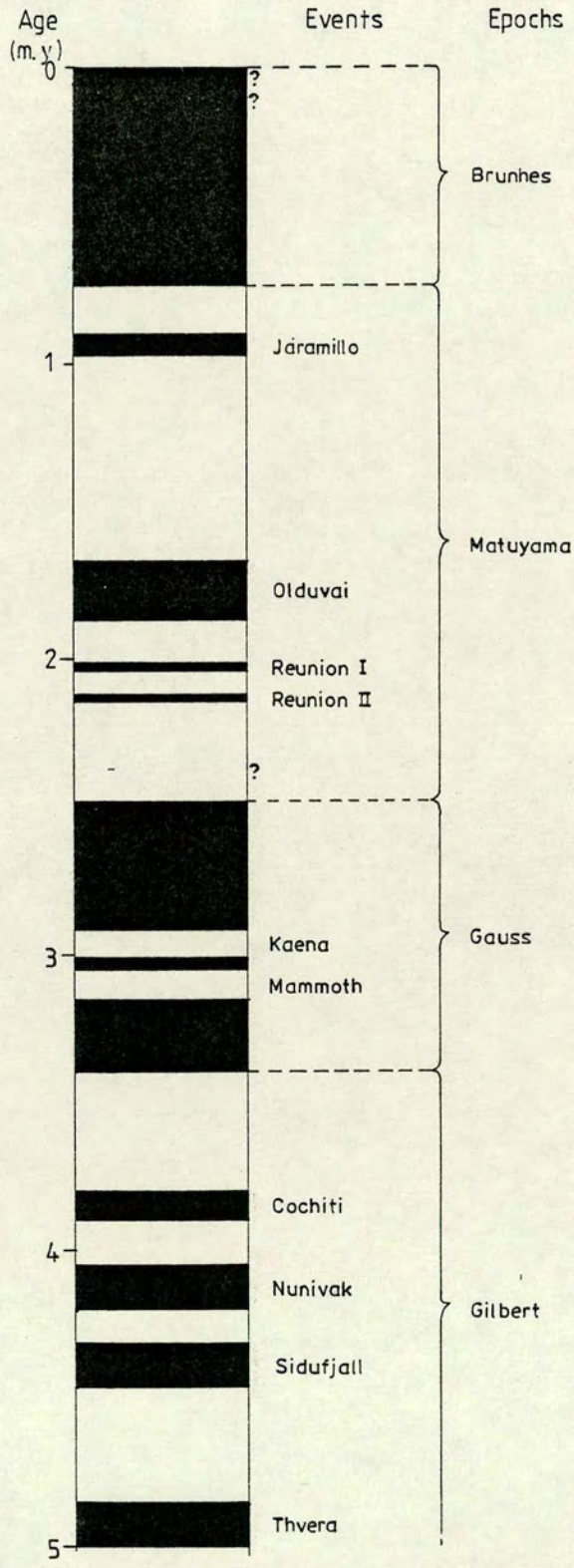


Figure 155. Mankinen and Dalrymple (1979) Timescale

however these will be restricted in geographical extent. It is not known whether these extremes occur for long enough periods, or with large enough amplitudes to be manifested as excursions in the palaeomagnetic record.

Geomagnetic reversals arise from complete reorganization of core motions. Cox (1981) considers stochastic models for geomagnetic reversals: instabilities occur in the core with a statistical distribution with respect to time. Some of these instabilities will be 'fertile' and give rise to transitions. Infertile instabilities may therefore give rise to aborted reversals. If transitional fields are dipolar and instabilities are related to dipole wobble, then the aborted reversals will have the same record at all sites on the Earth's surface, however if the instabilities occur in specific areas of the core as suggested by Hoffman and Fuller (1978) the aborted reversals will be of limited geographical extent. If the instability is of a different nature to normal secular variation then the aborted reversal excursion will have a different structure to a large secular variation excursion - compare for example Dodson (1979) and Hoffman (1981). [A more complete discussion of transitional structure will be found in the following chapter.]

The Cox (1981) model may give rise to very short polarity intervals if two fertile instabilities follow in rapid succession. If the field takes between 5,000 and 10,000 years to reverse completely then the shortest reversed event that will be seen at all sites on the Earth will be 10,000 to 20,000 years long. The shortest event accepted by Mankinen and Dalrymple is the earlier Reunion Event which lasted for about 20,000 years. Complete reversal over a shorter period may occur at some sites during an excursion due to large secular variation or aborted reversal, but these would only

be seen as small deviations from the axial field at other sites.

Verosub and Banerjee (1977) warn about the errors that can arise in the recording of the geomagnetic field by sediments due to slumping, viscous overprinting, inclination error etc (see Chapter 2). Ideally any reported excursion should be confirmed at another site, however excursions will not have the same structure if they are recorded at sites more than about 2000km apart, in fact deviation need not necessarily be seen at all points on the Earth's surface.

REPORTED EXCURSIONS

Reported excursions can be considered in three groups for the sake of convenience, these are:

- (i) the large number of excursions reported during the past 50,000 years,
- (ii) the set of apparently periodic excursions occurring during the Brunhes, and
- (iii) excursions reported in the Matuyama and Gauss Epochs.

Set 1

(a) The Gothenburg Excursion

The Gothenburg Excursion or 'flip' was first reported by Morner et al (1971) at about 12,400 b.p. in a core from Sweden. Morner and Lanser have since claimed that its existence has been confirmed in other Swedish cores (Morner and Lanser, 1974) and in the North Atlantic (Morner and Lanser, 1975). The excursion consists of a swing in declination to about 100° , then back, followed by a temporary decrease in inclination (Morner, 1981). Anomalous directions between 14,000 and at least 7,600 years b.p. were reported by Creer et al (1976) from Lake Erie, Noel and Tarling (1975) report a 'quasi-reversal' at 10,100 B.C. from southern Sweden, both of which may

correlate.

Verosub (1982) points out that much of the data ascribed to the Gothenburg excursion was very poor, for example many of the sightings consisted of just one reversed sample. Opdyke (1976) pointed out that the North Atlantic core was very poorly preserved, and may have undergone rotation between coring and sampling. In addition many European Lake studies have failed to find the excursion in similar aged sediments (Creer et al, 1980). Banerjee et al (1979) failed to observe any abnormal behaviour over the past 16,000 years in two small Lakes in Minnesota, near the original site of the L. Erie excursion. The Gothenburg excursion is probably a result of poor fidelity in glacial sediments, slumping, or weathering due to climatic change (Thompson and Berglund, 1976).

(b) The Imuruk Excursion

Noltimier and Colinvaux (1976) report a change of 50° in inclination at a site in Alaska. The unglaciated lake sediments which record the excursion are dated at 18,000 b.p. on the basis of extrapolation from pollen and radiocarbon dates. This is similar in age to the uppermost Biwa excursion of Yaskawa (1974) which is also dated by extrapolation from radiometric dates. Pierce and Clark (1978) report reversed lavas from Iceland with an age of about 20,000 years. This age is based on the nature of the outcrop which is assumed to be late Wisconsinian and may be inaccurate. Pierce and Clark suggest that the excursion was probably due to a strong dipole feature and may correlate with older excursions such as the Lake Mungo or Laschamp Events.

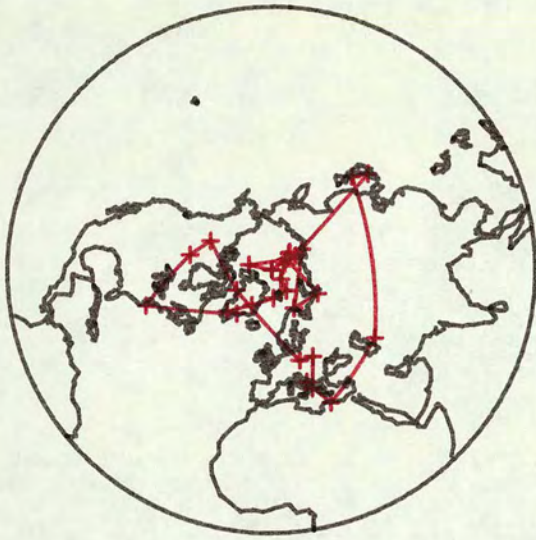
Many excursions have been reported in cores from the Gulf of Mexico (Clark and Kennett, 1973), dated between 5,000 and 20,000

years from the Aegean Sea and from Mono Lake, California. Although there is some evidence for an excursion at Iceland, Japan, and Alaska, the date is at present very uncertain.

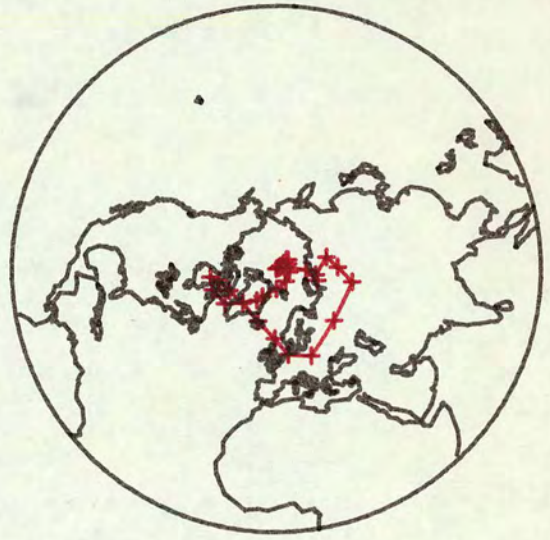
(c) Mono Lake Excursion

The Mono Lake Excursion, first reported by Denham and Cox (1971) has aroused particular interest. Similar records have been reported from four sections on the northern side of the lake, recorded in sediments exposed at the Earth's surface (Liddicoat and Coe, 1979). This would seem to suggest that the excursion dated at 25,000 to 24,000 years b.p. was a real geomagnetic phenomenon, consisting of a westward swing in declination with a shallow inclination, followed by an eastward swing with higher than normal inclination. The resultant VGP path traces first a clockwise loop, then a smaller anticlockwise loop (see Figure 156: No Delay). The excursion lasts for about 1,000 years and would appear to be due to large secular variation.

Nearby sections do not, however, show the excursion, Liddicoat (pers. Comm.) states that on the southern side of Lake Mono only the steepening of inclination is seen. At Clear Lake, 320km away, there is no sign of the excursion (Verosub, 1977). Similarly at Pyramid Lake, Nevada, 230km away, there is no evidence of an excursion between 25,000 and 36,000 b.p. (Verosub et al, 1980). This would suggest that there must be gaps of up to 1,000 years in some lake sediments, or that the dating at Mono Lake is inaccurate, and the excursion covered a much shorter period. Another possibility is that at Clear Lake and Pyramid Lake the signal is averaged out by post-depositional realignment, however the sediment is finer at these sites, and one would expect a greater time delay in coarser sediments (see Chapter 2). Palmer et al (1979) report a feature similar to that



No Delay



Exponential Delay



'S' Delay



Linear Delay

Figure 156. VGP Plot for the Mono Lake Excursion modified by depositional delay

at Lake Mono from Lake Tahoe on the California-Nevada border. The correlation is made by aligning periodic secular variation. The sediments at Lake Tahoe are of a similar grain size to those at Mono Lake, so there may be some sedimentological control on the acquisition of remanence. Figure 156 shows four hypothetical records of the Mono with no non-dipole contributions, interrupted by deviation of the local field to cause the anomalous directions and the intensity pattern noted by Liddicoat and Coe (1979). The first plot is for sediment acquisition with no delay (for discussion, see Chapter 2). The other plots are linear delay, exponential delay, and 'S' delay with half-alignment times of 5, 5, and 2 units. Assuming constant sedimentation at about 35cm/1000 years each time unit represents about 60 years. All delay curves markedly reduce the record of the excursion. The maximum deviation in declination is between 345° and 35° even for the exponential curve. Five samples would have inclinations of less than 30° , with this curve, giving poles in European Russia. These may not be interpreted as anomalous.

There would seem to be a large amount of evidence to support the Mono Lake excursion, however the age is, at present, uncertain. The C^{14} dates at Mono Lake were carried out on material susceptible to contamination (Liddicoat and Coe, 1979) and the age of 24,000 years b.p. is based on extrapolation.

(d) Lake Mungo Excursion

Barbetti and McElhinny (1972) reported anomalous directions dated at 26,000 to 30,000 years from aboriginal fireplaces in Australia. The directions are not completely reversed, however the dating is on the actual material. Soloyanis and Brown (1979) report an excursion which may correlate in New England tills. These are dated at between 22,000 and 28,000 years b.p. by glacial stratigraphy. The Meadow-

cliffe Till near Toronto dated at between 38,000 and 31,500 years b.p. by radiocarbon also records an excursion (Stupavsky et al, 1979). The directions are similar to Lake Mungo in that the VGP passes to equatorial Africa, then to the Mid Pacific. An excursion at Lake Biwa also has a similar path (Yaskawa 1974), but it is dated at 49,000 years on the basis of extrapolation between radiometric dates.

There would appear to be some evidence for an excursion at Lake Mungo, but it is not clear whether this is distinct from the Mono Lake Excursion. Verosub et al (1980) suggest that both the Mono Lake Excursion and the Lake Mungo Excursion are the same geomagnetic phenomenon occurring between 35,000 and 40,000 years b.p. It may be that there are two or three different excursions, including the Imuruk Excursion, with limited extent, occurring at different times, but perhaps all due to the same drifting non-dipole feature.

(e) The Laschamp Event

One further event has been reported to have occurred during the past 50,000 years; the Laschamp Event. This was the first Brunhes event to be reported, but it has been re-dated many times since then, allowing all the 'excursions' listed above to be correlated with it at one time or another. The most recent age: 35,000 to 42,500 b.p. (Gillot et al, 1979) was obtained using the potassium-argon and thermoluminescence methods. Gillot et al confirm the reversed magnetic directions, but note that these do not coincide with those at Lake Mungo. The Event may in fact correspond to the Mungo Excursion the cause being drifting non-dipole sources, Heller and Peterson (1982) show that some samples undergo self-reversal when heated, although Gillot et al state that chemical and mineralogical

analysis and thermal demagnetization suggest this to be unlikely.

Set 2

On a larger scale there have been suggestions that there is long period secular variations in the Brunhes with a period of between 100,000 years and 150,000 years (Wollin et al, 1971; Bucha, 1973). Rampino (1981) suggests that excursions occur at the peaks of each period (Figure 157). This set of excursions have been considered together because they appear to coincide with non-geomagnetic phenomena such as eccentricity of the Earth's orbit and climate (Wollin et al 1977, 1978), suggesting that all three factors are linked by one mechanism. Wollin et al (1978) suggest that increased eccentricity gives increased perturbation in the core due to the difference in torques between the mantle and core. Weaker geomagnetic fields reduce the shielding against corpuscular radiation giving warmer climate. Bucha (1977) first studied climate and intensity over the past 25 years and noted that increased geomagnetic activity at the north pole due to higher corpuscular radiation gives rise to an increase in temperature. This leads to lower pressure areas causing winds to change direction, thus affecting harvests in Central Europe. Bucha suggests that a link between climate and geomagnetism on a larger scale may exist with slight changes in climate such as those mentioned above causing instabilities which lead to the collapse of the present system, possibly resulting in the development of an ice age.

Recently many workers, for example Chave and Denham (1979) and Amerigian (1974) have shown that changes in intensity and direction may be caused by factors such as current strength, rate of erosion on land, and carbonate precipitation, which are governed by climate, Thus magnetic phenomena may be dependent upon climatic phenomena and

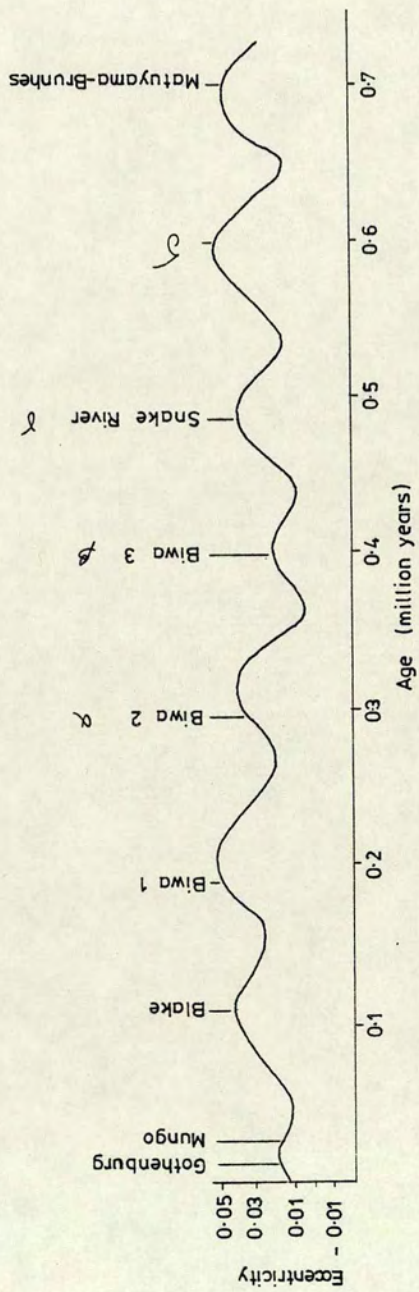


Figure 157. Periodicity of Excursions related to Eccentricity of the Earth's Orbit (Rampino, 1981)

not vice versa.

Rampino (1981) lists three cores in which these periodic excursions are seen. These are Lake Biwa (Yaskawa, 1974), North Pacific Core V20-108 (Wollin et al, 1971) and Gioia Tauro in Calabria, Italy (Creer et al, 1980). Rampino has re-calculated sedimentation rates so that these excursions occur at intervals of about 100,000 years. The lack of age control at these three sites and the doubts raised about the link with eccentricity and climate demonstrate the difficulty in establishing an overall pattern to these excursions. It is perhaps necessary to examine the validity of individual excursions.

The excursions involved are listed in Figure 157. Of these only the Blake and Emperor Events have been identified and dated independently. The other four excursions arise from correlations between the cores of Lake Biwa, Gioia Tauro, the North Pacific, and a Mediterranean core reported by Ryan (1972).

(a) The Blake Event.

The Blake Event was first reported by Smith and Foster (1969) and dated at 114,000 to 108,000 years b.p. This was confirmed from the Greater Antilles Outer Ridge by Denham (1976). The Blake Event seems to be split by a short normal interval, both in the western Atlantic and in Italy (taking the original interpretation of the Gioia Tauro core of Creer et al, 1980). This similarity of records has led even the most sceptical of workers to admit to the existence of this event (Verosub, 1982).

(b) The Emperor Event

The Emperor Event was first reported by Ryan (1972) and has since been confirmed in marine anomalies (Wilson and Hey, 1981) and in lavas from Snake River, Idaho where it is dated at $465,000 \pm$

50,000 years by the potassium-argon method. All the evidence points to the reality of this reversal as a geomagnetic phenomenon, although it is not clear whether it is an excursion or an event.

An excursion dated at around 400,000 years was reported from Core MT1 at Piombino by Readman and Evans (1979). The excursion consists of a clockwise loop of the VGP. Further work on the series of cores suggests that the excursion may be older than noted by Readman and Evans.

(c) Other Events

The other four events are less well represented in the palaeomagnetic record. Ryan (1972) reports results from cores in the Eastern Mediterranean which can be correlated with a core from the Jamaica Ridge of the Caribbean Sea by foraminifera and oxygen isotope climate zones. As well as the Blake Event in faunal zone 'X' there are two events in zone 'V' at about 200,000 and 300,000 termed the Jamaica and Levantine Events respectively. Another small event seen only in the Caribbean core within the 'U' zone was named the Emperor Event by Ryan.

The North Pacific core V2--108 (Wollin et al, 1971) shows three short reversals below the Blake Event, at approximately 0.2, 0.3, and 0.4 m.y. b.p. (the first two were correlated with the Jamaica and Levantine Events). All three have been correlated with short excursions at Biwa (Yaskawa, 1974). In these two cores only inclination is recorded, however the excursions all involve complete reversal, although the Biwa reversals are limited to one or two points. The Biwa I Event at about 100,000 years b.p. has been interrupted by ash layers which correlate with similar layers in Lake Biwa (Hayashida, unpublished).

The four excursions (α , β , γ , δ) seen at Gioia Tauro are

represented by single samples in a section of the core from which few samples were taken. The inclination varies between about 10° and 70° in this part of the section with few definitely positive samples (declination is not recorded).

In all these sections the number of reversed or intermediate samples is high compared with the number of normal samples, which seems to suggest that 20% to 30% of the lower Brunhes was of reversed or intermediate polarity (in the Gioia Tauro core 33% of the samples below the Blake Event record inclinations of less than 35°). This contrasts with the results for lavas in which only 2 out of 73 results dated within the past 730,000 years have proved negative (Champion et al, 1981) and suggests that some of the anomalous sedimentary results are due to errors in the processes of magnetization in depositional rocks. As Champion et al note, this ratio of 2:71 implies that only 20,000 of the past 730,000 years were reversed. Even divided between only two events (Champion et al list the Las-camp and Emperor Events) this gives lengths of 10,000 years for each event, the minimum length of time for a completely reversed event. If more anomalous periods occurred during the Brunhes, which have yet to be located in lava flows, then the average length must be less than 10,000 years, implying that all anomalous directions in the Brunhes are 'excursions'.

Set 3

Less attention has been paid to short events or excursions in the Matuyama and Gauss Epochs. There are four areas of interest in the Matuyama, in addition to the well-established Jaramillo and Olduvai Events. These are the proposed Cobb Mountain, Gilsa, Reunion, and Neuquen Events.

(a) Cobb Mountain Event

Mankinen et al (1978) reported anomalous results dated at about 1.1 m.y. b.p. from volcanic rocks in California. The directions differ by up to 100° from a reversed field suggesting that the rocks record an excursion rather than a completely normal event. Maenaka (1979) proposed a Komyoike Event at 1.1 m.y. b.p. recorded in sediments of southwestern Japan. The sediments are interbedded with ashes which have been dated. The rocks of Cobb Mountain were also dated directly so given the close agreement of dates there seems to be some evidence for an excursion at this time.

(b) Gilsa Event

The suggestion of a Gilsa Event after the Olduvai Event arose from the separate dating of Lower Matuyama events in Iceland and Africa. Watkins et al (1975) studied the type section for the Gilsa Event in Iceland. There was no evidence for more than one event, however the normal lavas gave 'disappointing' potassium-argon results, averaging about 1.6 m.y. b.p. (The results were described as disappointing because of the lack of repeatability and the occasional disagreement with stratigraphy.) Brock and Hay (1976) studying the type section for the Olduvai Event in Africa report a single normal event between 1.86 and 1.71 m.y. b.p. They prefer to think that only one event is represented but admit that an older event may occur, possibly correlating with the Reunion Events. It is probable that the Gilsa and Olduvai Events are one and the same, the confusion having arisen from inaccurate dating. Opdyke (1972) who studied deep sea sediment cores alone reported only one event in this interval.

(c) The Reunion Events and the Neuquen Event.

Mankinen and Dalrymple (1979) accept the existence of two Reunion Events due to bimodality in age determinations for normal rocks at about 2.0 m.y. b.p. McDougall and Watkins (1973) report one event dated at 2.0 m.y. b.p. and lasting between 12,000 and 50,000 years from lava flows on the island of Reunion. The confusion in the number of Reunion Events may, like the Gilsa-Olduvai problem arise from inaccurate dating. It is necessary to study continuous sequences in order to resolve this. One such section is the Searles Valley core (Liddicoat et al, 1980). Two Reunion Events are seen, together with three unidentified events. Two of these unidentified events occur between the Jaramillo and Olduvai Events and may correlate with the Cobb Mountain Event and suggested Gilsa Event, however Liddicoat et al have reservations about the reliability of the section of the core recording this latter event. Rea and Blakely (1975) report a number of short wavelength anomalies including one at 1.1 m.y. b.p. They point out that there need only be one event at 2.03 to 2.06 m.y. b.p., but add another at 2.24 to 2.26 m.y. b.p. This latter may represent what is known as the lower Reunion Event, or it may correlate with N1 from Liddicoat et al (1980). Liddicoat (1982) includes this short reversal in his study of the Gauss-Matuyama transition (he in fact refers to the short reversed interval as a pre-transition excursion in the Gauss). This lowest normal excursion in the Matuyama is probably the Neuquen Event of Valencio (1981) which is seen at Buenos Aires. It may be advisable to refer to this as a Gauss excursion if the Neuquen Event can be correlated with Liddicoat's results. The reversed directions in the Gauss do not necessarily involve complete reversal as it is not certain that declinations were southerly. Liddicoat (1982) points out that the two short intervals lasted for 2,000 years as did the final normal to reversed transition.

The Neuquen Event may be referred to as a separate entity or as part of the compound Gauss-Matuyama' transition. Apart from this only two events are necessary to explain palaeomagnetic results below the Olduvai Event.

(d) Gauss Excursions

The Searles Valley core (Liddicoat et al, 1980) also includes two reversed intervals above the Kaena Event in the Gauss Epoch. These are dated at 2.81 to 2.79 m.y. b.p. and 2.71 to 2.67 m.y. b.p. on the basis of extrapolation of sedimentation rates which appear to be constant in the Matuyama and Brunhes Epochs. Liddicoat et al. state that some reversely magnetized basalt flows of this age have been reported from Hawaii, Iceland, and St. Vincent.

EXCURSIONS REPORTED IN THIS STUDY

A number of excursions were seen at Stirone and Piombino, with other possible excursions at Pontida and DSDP Site 514. The Pontida excursion seems to be a large secular variation loop and is dated by the radiocarbon method at about 18,000 b.p. The sediments are fine-grained, however at other levels they record an anomalous field, that is inclination of about 30° compared with the axial field inclination of 60 to 65° . This excursion may correlate with the short Imuruk Lake excursion reported by Noltimier and Colinvaux (1976), but it is probably distinct from the Mono Lake Excursion.

The continental deposits of Stirone record perhaps three excursions at 450,000; 520,000; and 680,000 years b.p. on the assumption of constant sedimentation rates, however there is a great deal of error involved in this calculation because of the probable intermittent deposition. Of these the youngest and oldest are the ones

which are most likely to have occurred, the other may perhaps be due to slumping. The simplest explanation of the Stirone results is to accept only the oldest excursion but correlate it with the Emperor Event at 465,000 years b.p., implying that an even longer hiatus than was originally imagined is represented by the unconformity at the top of the marine series (500,000 years compared with 200,000 years). A more likely explanation is that the excursion at 450,000 yr. b.p. correlates with the Emperor Event and the excursion at 680,000 yr. b.p. is a newly discovered phenomenon and should be named the Laurano Excursion after the nearby hamlet.

If the Cobb Mountain Excursion at 1.1 m.y. b.p. is accepted as real the upper Matuyama event at DSDP Site 514 could be correlated with this and not the Jaramillo Event, thus explaining the absence of completely normal directions. The Stirone excursion toward the top of the marine series was probably due to inaccurate recording of the field, however if the directions are real, this interval may also represent the Cobb Mountain Event.

At 67 to 69m in MTO at Piombino two normal intervals are seen interpreted as Reunion Events. Similarly complex behaviour occurs above the Plio-Pleistocene boundary at Stirone, where the lowermost normal interval is split by reversed samples and at least one further normal interval occurs between this event and the Olduvai Event. The Reunion Events have been correlated with the Plio-Pleistocene elsewhere in Italy (Kukla et al, 1979; Arias et al, 1982). In both cases there are good reasons to accept the results as accurate reflections of geomagnetic behaviour, so there may in fact be more than one Reunion Event.

Many excursions were seen in the Gauss of the Piombino cores, however only one of these consists of a clear change from the stable

normal field, consisting of 25cm of clearly reversed sediment. This is dated at about 2.65 m.y. b.p. which correlates with one of the excursions of Liddicoat et al (1980). Other excursions may occur in the Piombino cores, correlating with this R2 excursion, or the older R1 excursion of Liddicoat et al. The existence of at least one excursion above the Kaena Event is confirmed, this should be referred to as the Searles Valley Excursion.

The short excursion at about 3.95 m.y. b.p. recorded at DSDP Site 514 is represented by at least two stable samples, although adjacent samples showed erratic behaviour when demagnetized. Apart from reported sightings in other South Atlantic cores this short excursion has not been previously reported, and should be referred to as the Argentine Basin Excursion.

CONCLUSION

Figure 158 shows the polarity time scale of Figure 1 amended as a result of this study. Three late Brunhes excursions are included, each recorded over limited areas at slightly differing times, namely the Imuruk, Mono, and Mungo Excursions. Two other reversals are seen in the Brunhes, the Blake Event at 0.11 m.y. b.p. and the Emperor Event at 0.465 m.y. b.p. The results from Stirone suggest that another excursion may have occurred at about 0.68 m.y. b.p. In the Matuyama the Cobb Mountain and Neuquen Excursions are added to the Mankinen and Dalrymple (1979) timescale, while in the Gauss and Gilbert Epochs the Searles Valley and Argentine Basin Excursions are also included.

These additional events and excursions may not represent a complete record of geomagnetic phenomena for the past 4 million years; however it would appear that at least 27 reversals have occurred in the past 4 million years, 21 (78%) of them successful (if the Blake and Emperor are classified as Events, and the other 6 as excursions).

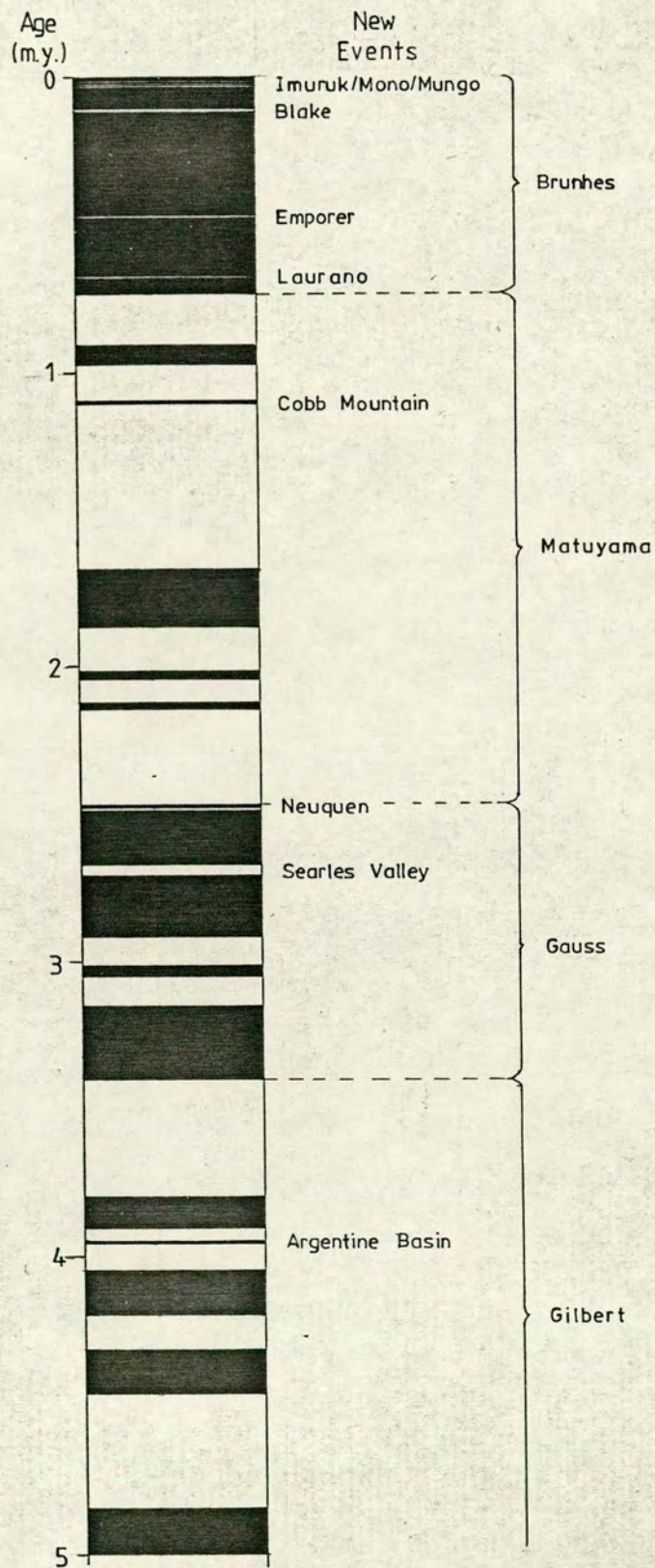


Figure 158. Revised Late Cainozoic Magnetostratigraphy

Nine of these reversals have been reported during the past 1 m.y., this slightly greater concentration is probably due to the larger amount of research concentrated on this interval.

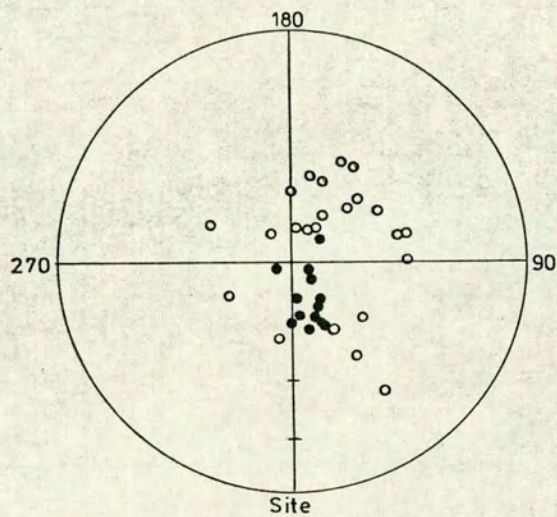
PART II TRANSITIONS

THE STRUCTURE OF STABLE FIELDS

The geomagnetic field is seen, in the palaeomagnetic record, to have two equally stable states each of which can be modelled in the simplest form by a dipole at the Earth's centre, aligned along the rotation axis. These states are normal polarity, as at present, when all magnetic compasses point towards the north geographic pole, and reversed polarity, during which compasses point towards the south magnetic pole. The magnetic field remains stable in one polarity for periods of between 50,000 and 10,000,000 years (Cox, 1981), compared with which the periods of transition between two states are relatively quick, occurring in less than 10,000 years.

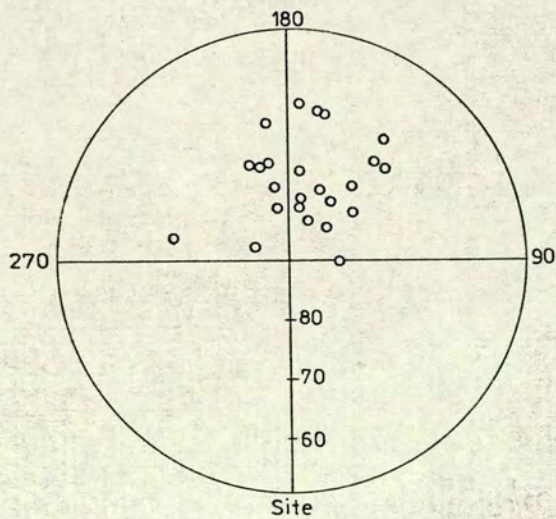
Superimposed on the simple dipole model are such factors as dipole wobble and dipole offset in addition to non-dipole effects. The offset dipole was used by Wilson (1972) to explain the apparent 'far-sidedness' of poles for the past 25 million years (Figure 159). The axial dipole should be offset to the north by about 1,050 km during reversed polarity and 175km during normal polarity. An alternative solution is that a quadrupole source exists which is stronger during reversed polarity. The offset dipole theory has recently been checked by Harrison and Watkins (1979) who found it a more likely cause for far-sidedness than any non-dipole configuration. The axis of the main dipole deviates slightly away from the spin axis, the change in deviation known as dipole wobble has been shown by Thompson (1982) to vary between 2° and 9° over the past 300 years.

The non-dipole field contributes about 10% of the total intensity of the geomagnetic field. It is due to turbulence in the core, however there does seem to be some pattern. Alldredge and Hurwitz (1964) pointed out that the present Earth's field could be modelled



North Poles for Normal Results

(● Brunhes Poles)



South Poles for Reversed Results

Figure 159. Far-sidedness of Upper Tertiary Poles from Wilson (1972)

by a main dipole and a number of radial dipoles representing current loops at the surface of the core. These radial dipoles are a very popular method for modelling non-dipole field changes. Harrison and Carle (1982) point out that radial dipoles are preferable to spherical harmonic analysis in that they do not lead to long wavelength features contained in higher harmonics being cut off. Another advantage is that they can be related directly to physical processes in the core. Figure 160 shows the variation in potential due to a radial dipole at a depth R_d compared with a loop of radius r . Harrison and Carle obtained the following expression linking depth of a radial dipole to width of a current loop

$$r \text{ (km)} = 3701 - 4915R_d/R_e$$

where R_e is the Earth's radius.

Cox (1975) suggested that these radial dipoles were preferentially arranged to account for a bias in secular variation in Hawaii. Most periods of large deviation from the normal field involved deflection to lower inclinations. Cox explained this as due to passing cyclones in the core, these cyclones (represented by radial dipoles) are negative, that is the dipoles point outward, near the equator, and positive at high latitudes. This suggestion would give higher than normal inclination at Iceland which, as Harrison and Watkins (1979) show, is not the case. Dodson (1980) suggests that the distribution of radial dipoles is more or less random, there is, however, greater variation in the non-dipole field in Iceland than at lower latitudes, so Dodson considers non-dipole sources to be stronger or more numerous at higher latitudes.

Given that a distribution of radial dipoles can account for the non-dipole field at specific times during the past, the next point

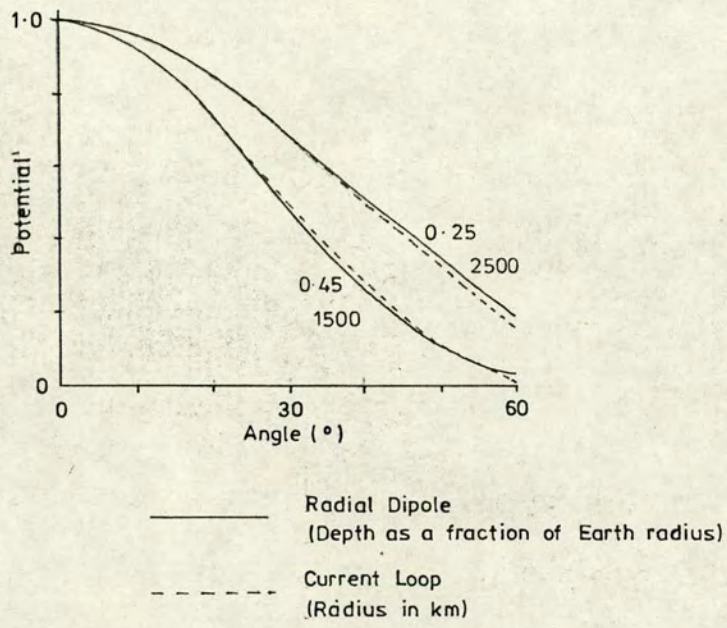
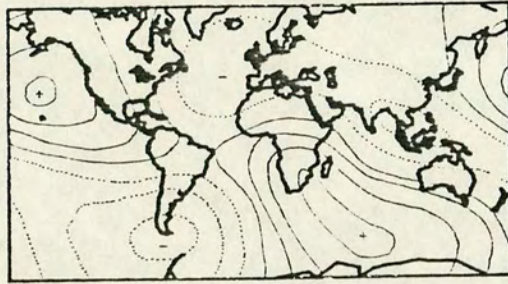


Figure 160. Variation of Potential for Current Loops and Radial Dipoles from Harrison & Carle (1982)

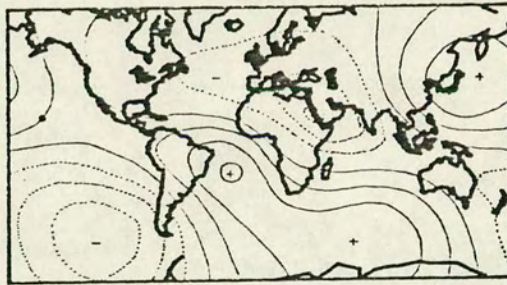
is the question of how variation in these sources contributes to the variation of the geomagnetic field with time. Recent secular variation recorded directly in observatories extends back only as far as the 16th century, so these records must be supplemented by palaeomagnetic studies on lakes in which deposition rates are high.

Creer (1981) shows maps of the vertical component of the non-dipole field for the past 400 years which is essentially quadrupolar, that is one negative and one positive anomaly occur in each hemisphere. These have drifted westwards at $0.25^\circ/\text{year}$ for at least the period of 400 years studied (Figure 161). Thompson (1982) suggests that the average lifetime of a vertical anomaly is only 500 years (Figure 162), however the period of time available for direct study through observatory records is not long enough to show whether anomalies disappear, or continue drifting and merely oscillate in intensity.

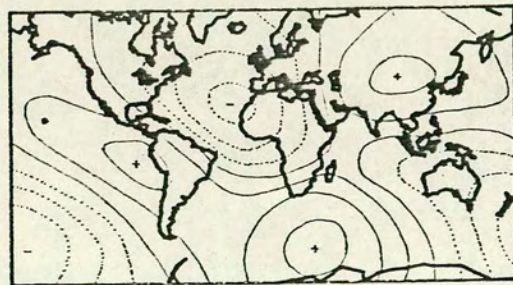
The lake sediment records show periodic variations in both inclination and declination. These produce VGP paths which loop around the geographic pole (see Figure 163, from Creer and Tucholka, 1982; which shows paths for North America and the U.K. between 5500 and 2000 b.p.). Since 1972 much work has been carried out redefining the record from lakes in North America and Europe. If the variation was solely due to westward drift of anomalies, the North American record should be similar to that of Europe, but delayed by a time approximately equal to one quarter of the period. While there are some similarities for the past 4,500 years, the records differ before this. An alternative to the drifting non-dipole field is the oscillation of two out of phase anomalies. Creer and Tucholka (1982) show that this can also produce looping of the virtual geomagnetic pole about the geographic pole, and that this may be either



1600 A.D.



1800 A.D.



2000 A.D.

Figure 161. Westward drift of Non-dipole foci from Creer (1981)
(contour interval: 4,000 nT)

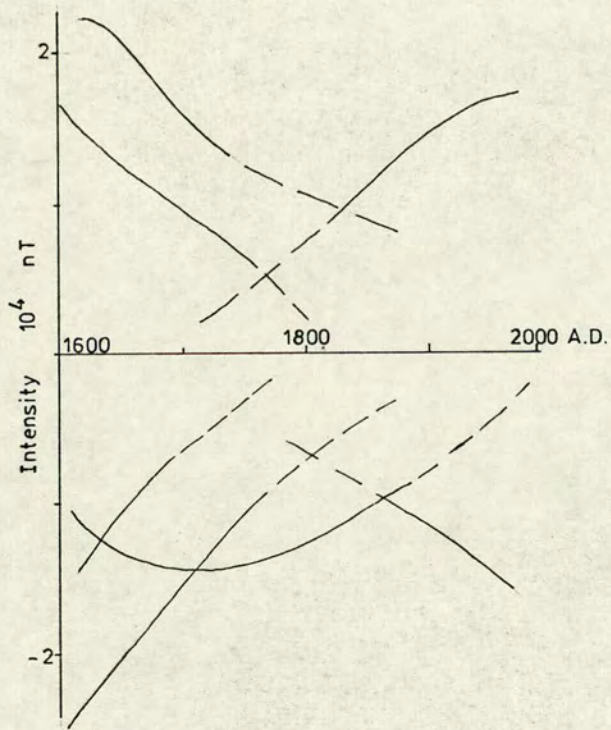


Figure 162. Variation in strength of the Vertical Component of selected Non-dipole foci (after G. Smith)

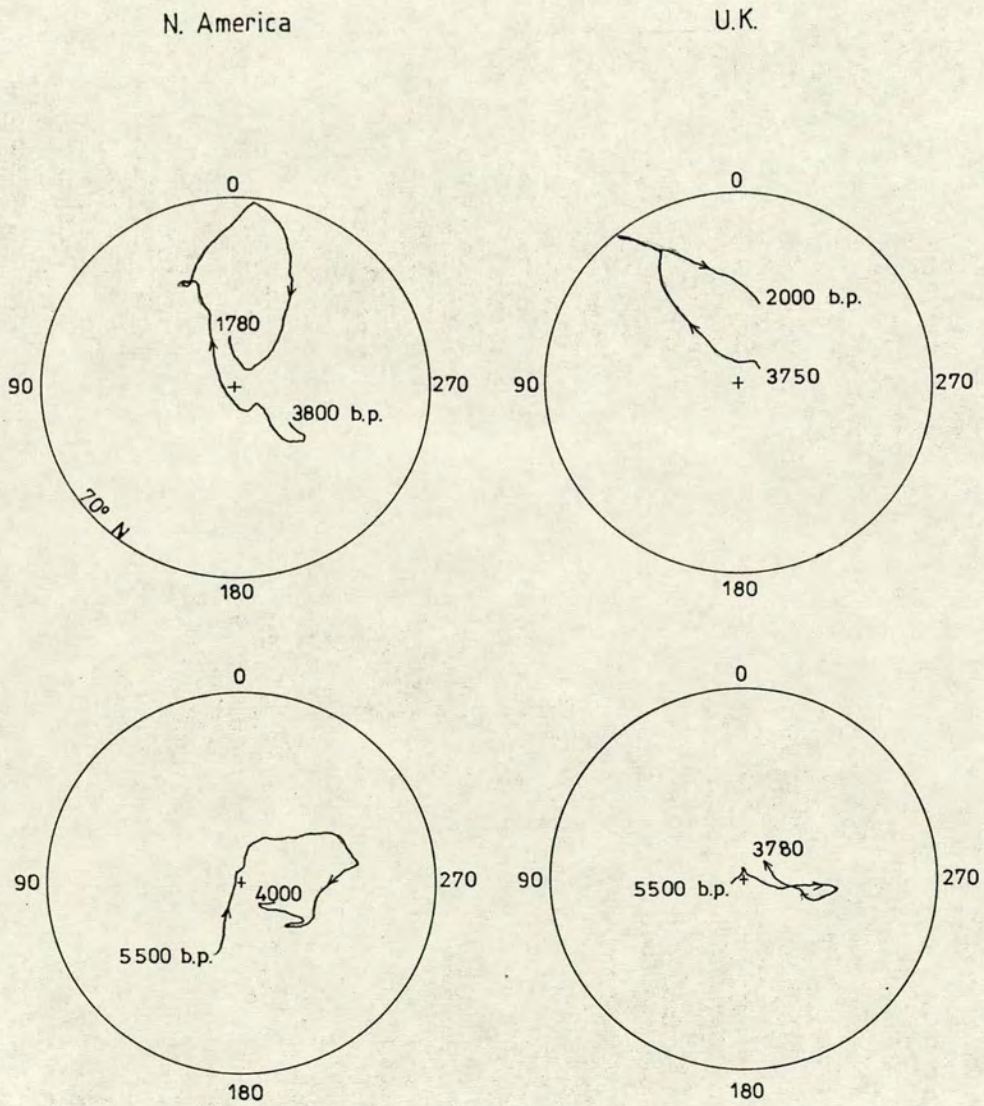


Figure 163. Secular Variation from Lake sediments (Creer & Tucholka, 1982)

clockwise or anticlockwise depending on the phase. As a possible explanation for the change in the nature of the secular variation curves at 4,500 years b.p. Creer and Tucholka suggest a drifting radial dipole which oscillates in strength. The sense of the variations will be similar for both Europe and North America, unless the radial dipole is between the two sites, in which case the variations will be opposite. The change at 4,500 y. b.p. may be due to the radial dipole passing beneath one of the sites.

TRANSITIONS

The dipole field reverses on average once every 330,000 years (Cox, 1975 estimates reversal frequency for the past 50 m.y. to have been about 3 per million years). Based on our knowledge of the structure of the stable field we can envisage three types of reversal, each started by some sort of instability in the core which may or may not develop to cause full scale reversal.

(a) Dipolar Transitions

The simplest type of reversal is a change of the whole field with the main dipole (and possibly the non-dipole field) reversing, but maintaining the characteristics of stable polarity during the reversal. Thus part way through the transition the field would still be dominated by the dipole, and palaeomagnetic results from all sites on the Earth for the mid-point of the reversal in time should give the same pole. If transitions are caused by instabilities as suggested by Cox (1981) one can imagine dipole wobble reaching a point at which the field becomes over-balanced and reverses, eventually settling at its other stable state.

Initially it appeared that many transition paths passed through the Indian Ocean (Creer and Ispir, 1970) however once two paths had been

obtained for the same transition this was shown not to be the case. Niitsuma (1971) reported a record of the Matuyama-Brunhes transition from Japan in which the virtual geomagnetic pole passed through the West Pacific. Hillhouse and Cox (1976) studied the same transition in sediments of California which gave a path passing through the Atlantic.

(b) Transitions Dominated by the Normal Non-Dipole Field

If the dipole does not simply rotate from one stable polarity state to the other it must undergo some sort of breakdown. If both dipole and non-dipole field decrease to zero there would at some stage during the transition be no geomagnetic field. With no field at all the alignment of magnetic grains would be governed by currents, or by shape, or if anisotropy was absent, they would be randomly oriented. Many transitions, however, seem to be repeatable at different sites within a region suggesting that there are magnetic fields during transitions. The Gauss-Matuyama transition, for example, is seen to be similar at sites in Turkmenia up to 300km apart (Burakov et al, 1976).

If the dipole disappears without similar disappearance of the non-dipole field, the non-dipole field would dominate transitional fields. The type of transitional field produced by a non-dipole field depends on the structure and variation of this non-dipole field. The lengths of transitions are of the order of the length of the lake sediment secular variation record, so it should be possible to compare models to investigate whether the non-dipole field drifts, oscillates, or does both during a reversal. Larson et al (1971) modelled a transition with non-dipole drift of 0.2° yr⁻¹ during a reversal of the dipole which lasted 3000 years, and involved rapid reduction in dipole field strength. The VGP path

completed at least one complete loop of the globe (Figure 164 shows a similar path created by allowing a radial dipole to drift during a simple dipole reversal). The linear path at Lake Tecopa (Hillhouse and Cox, 1976) among others suggests that this drift pattern did not occur during the Matuyama-Brunhes transition. Dodson et al (1978) show that drift of the non-dipole field during a reversal of the dipole field would produce effects similar to those which they observed in the Tatoosh Intrusion record. Hillhouse and Cox point out that reduction in dipole strength would reduce core-mantle coupling, and thus reduce drift. They propose that transitional fields are governed by stationary non-dipole features. The non-dipole field may increase in strength as the dipole field weakens, leading to increased stability of the non-dipole features. This may give rise to phenomena such as that reported by Shaw (1975). Directions part way through a reversed to normal transition in Iceland became stable while palaeointensity which had decreased during the beginning of the reversal temporarily regained its initial value (Figure 165).

The cause of the instability for reversals dominated by the ordinary non-dipole field would be the non-dipole anomalies themselves. Either the configuration of sources is such as to over-balance the dipole field, or the magnitude of one or more of the anomalies have reached the limits of their range. If growth of the non-dipole feature caused the reversal one would expect growth to continue until the main dipole began to reassert itself. In this case 'normal' non-dipole field reversals are unlikely.

(c) Hybrid Transitions

A third possible form for a transition is one in which the dipole field breaks down into a form which is unique to transitions.

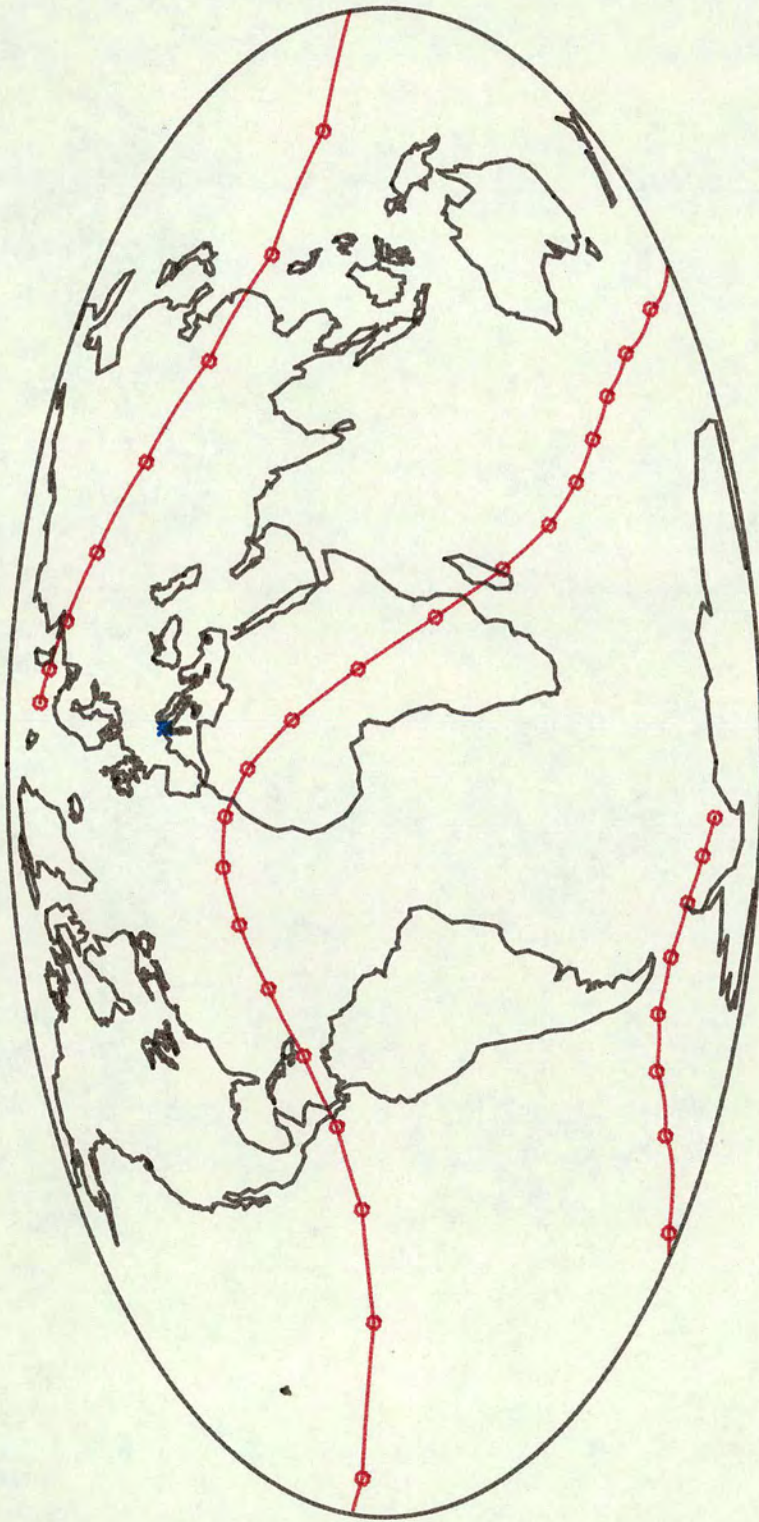


Figure 164. Transition modelled with drifting Radial Dipole

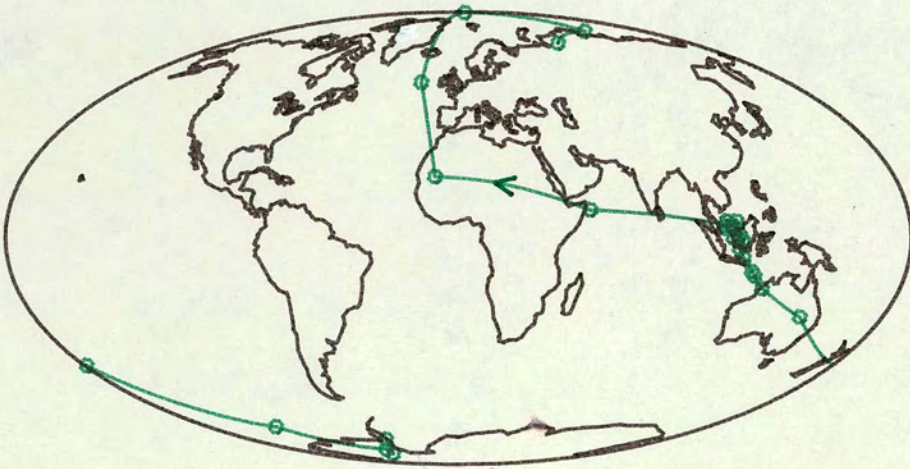
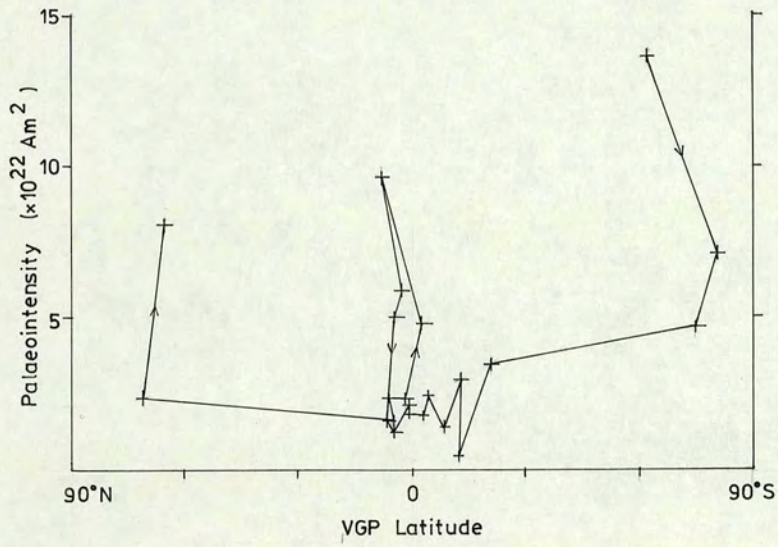


Figure 5. Strong Fields during a Transition
(Shaw, 1975)

The non-dipole field may or may not contribute to this creation. The instability causing breakdown occurring in the actual dipole dynamo as distinct from the non-dipole current loops. Hoffman and Fuller (1978) noted that many transitional fields were constrained in longitude and considered axisymmetric non-dipole fields. A quadrupole field (Figure 166) may arise through the core reversing in one hemisphere before the other. An octupolar field would result from the core reversing first at the equator, or, simultaneously at both poles. These types of transitions would give paths which either passed through the site (that is the magnetic vector would at some stage be vertically downward) or at 180° from the site (with the vector vertically upward). Study of reversals of both senses (normal to reversed and reversed to normal) from both hemispheres would determine which, if any, of these configurations occurred for all transitions.

Initially (Hoffman and Fuller, 1978; Fuller et al, 1979) it seemed that most reversed to normal data from the northern hemisphere was near-sided suggesting either a quadrupolar field reversing first in the southern hemisphere or an octupolar field reversing first at the equator. Data from excursions, which may be aborted transitions, from the southern hemisphere appeared to indicate that fields are quadrupolar (Hoffman, 1981). Recent results from the Phillipines, however show a far-sided reversed to normal path (Williams and Fuller, 1982) indicating that a general site dependence for all transitions does not exist.

While there is no indication that each reversal has the same harmonic content, it seems that the most recent generally accepted reversal (i.e. the Matuyama-Brunhes) can be modelled in this way. Hoffman (1979) reports five paths for this transition all of which are

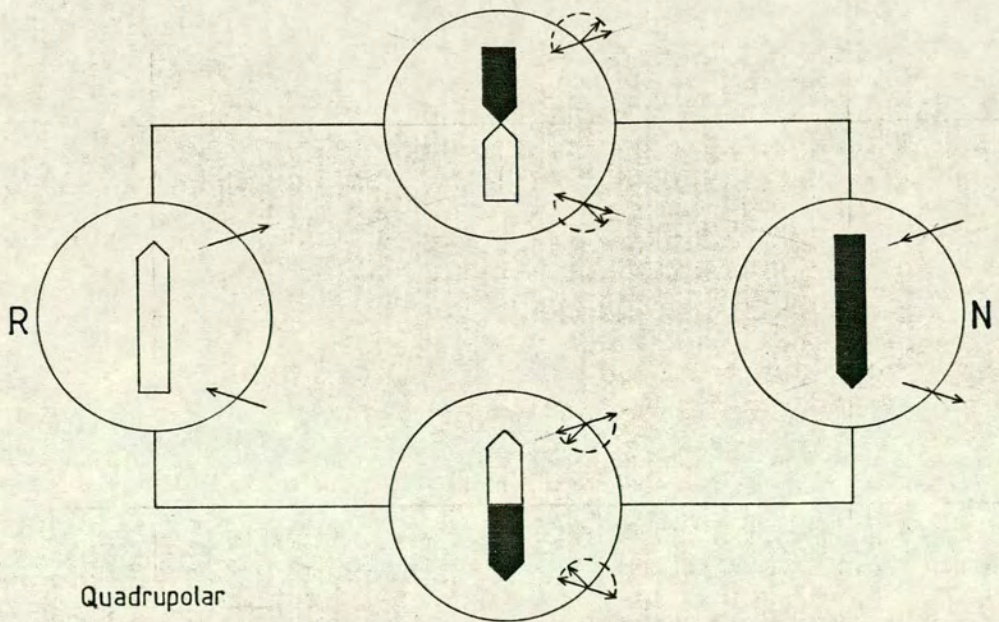
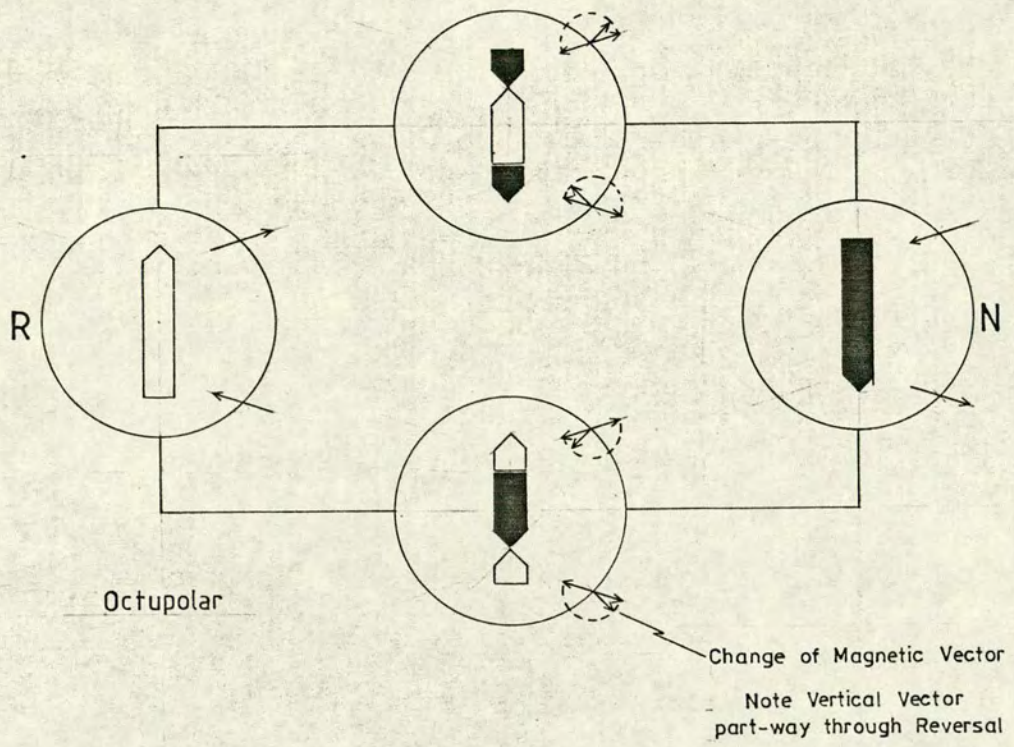


Figure 166. Axisymmetric Reversals from Hoffman and Fuller (1978)

near-sided. By imagining the transition to commence at a point in the core with a latitude of 0° and a longitude of 338° E and spread like a cancer, Hoffman is able to model the VGP paths for these five transition records (Figure 167 shows four of these records together with Hoffman's predicted path). Williams and Fuller (1981) also modelled the Matuyama-Brunhes transition, they distributed the energy from the dipole (i.e. the g_1^0 field) between the three terms g_2^0 , g_3^0 and g_4^0 in the ratio 2:3:5. The modelled and observed inclination records can all be stretched so as to coincide, except the Lake Tecopa record which may contain non-zonal terms. The Williams-Fuller model assumes these to be absent, and therefore does not take declination into consideration.

Testing the Models

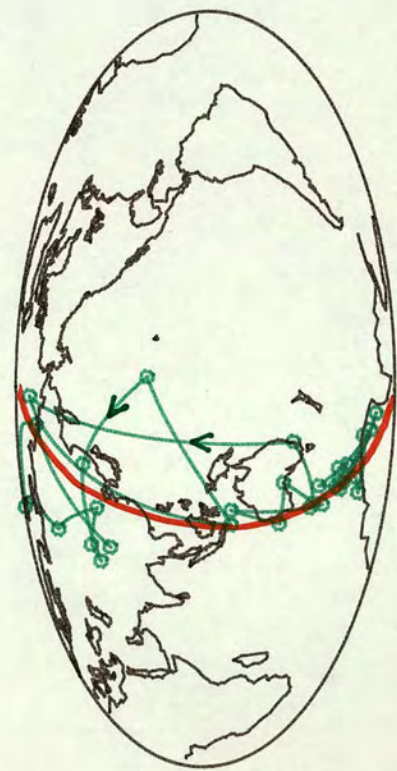
As yet the structure of reversals is not known. It is, however, possible to test whether any of the proposed models actually stand up to the observed data. The Hoffman model predicts that all reversals for the same transition should have similar paths when compared with the site longitude. He has shown that this holds for the Matuyama-Brunhes transition, and this can be further tested using the Italian data. Both the possible axisymmetric structures for the Matuyama-Brunhes transition (a quadrupolar field resulting from initiation in the southern hemisphere and an octupolar field resulting from initiation at the equator) should, if they apply to consecutive reversals, give paths 180° apart, while the standing field model of Hillhouse and Cox (1976) should give identical paths if the non-dipole field persists for periods longer than epoch lengths. Valet and Laj (1981) report two consecutive reversals from Crete which have paths 180° apart (Figure 168). There are additional reversals both above and below those shown which conform to the



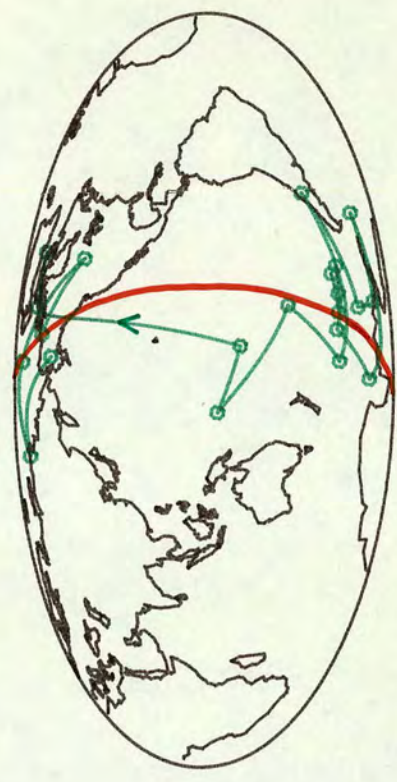
Tecopa



Bruggen



Boso



Pacific Ocean

Figure 167. A Phenomenological Model for the Matuyama-Brunhes Transition from Hoffman (1979)

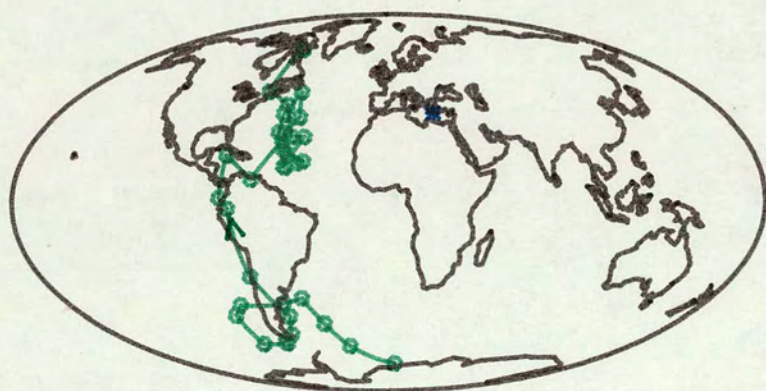
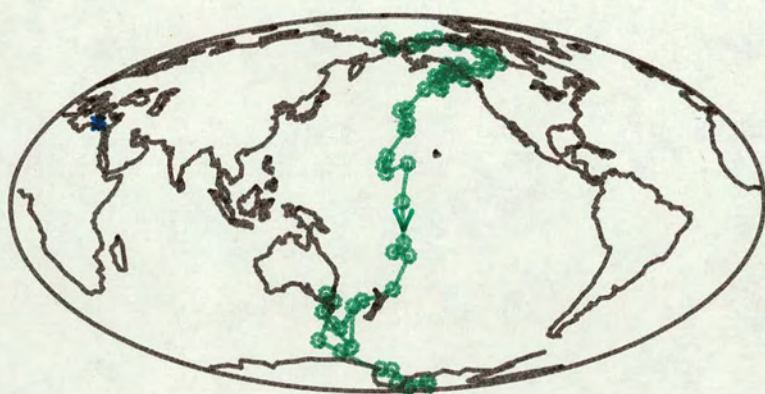


Figure 168. Transitions from Valet and Laj (1981)

pattern (Laj, pers. comm.), alternating between about 90° W (Reversed to Normal) and 135° E (Normal to Reversed). On the other hand Bogue and Coe (1982) report similar paths for two successive reversals in Hawaii, so neither system can be proved conclusively.

Although many reversals are linear, there exist transitions in which looping, drift, or oscillation of the virtual geomagnetic pole occur. Oscillation of the field (for example the Upper Jaramillo transition recorded by Kawai et al, 1973: see Figure 169) may be due to poor recording of the field or acquisition of the remanence at different times. The Searles valley core clearly shows three reversals comprising the transition, recorded over 2m, which is probably beyond the limit of post-depositional realignment.

The Steens Mountain transition (Watkins, 1969: Figure 170) shows a loop across the Pacific superimposed on a path through America. At the extremity of the loop there is an apparently semi-stable point at which a number of poles occur. Other transitions such as the Santa Rosa transition (Larson et al, 1971: Figure 171) show large amounts of drift during the transition. Both of these features resemble non-dipole field variations suggesting that in some cases the 'ordinary' non-dipole field is important during a reversal. Many of the transitions from Iceland display anomalous behaviour - Hoffman and Fuller (1978) noted that reversed to normal transitions from Iceland did not conform to the near-sided pattern shown by all other data. This may be due to the greater variation in the non-dipole field seen at higher latitudes.

Even those transitional paths which do conform to the Hoffman model show a larger amount of variation in the later stages. Hide (1982) suggests that this is because decaying fields have an axis of symmetry but stable fields cannot have axial symmetry, in which case

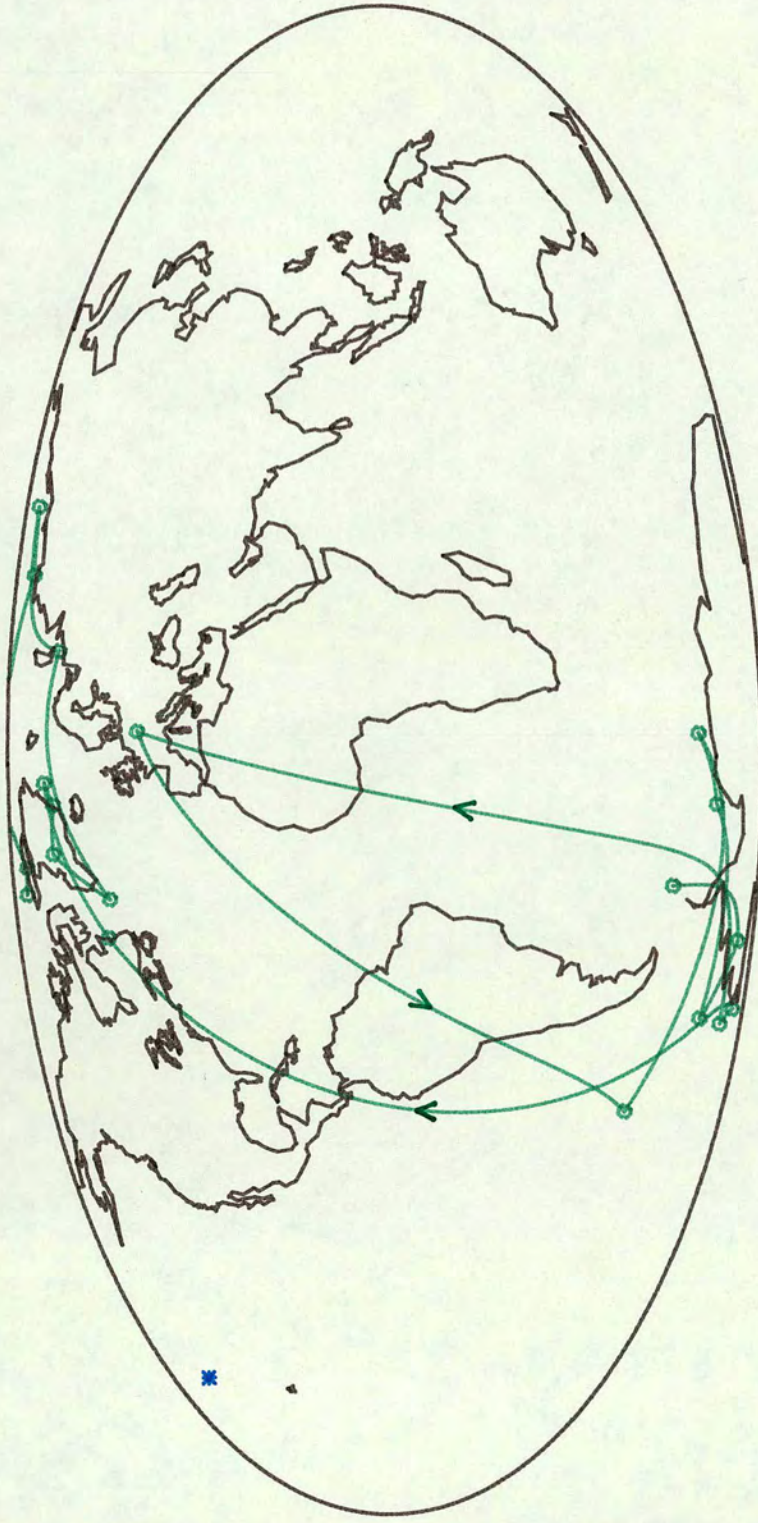


Figure 169. Upper Jaramillo Transition from Kawai et al (1973)

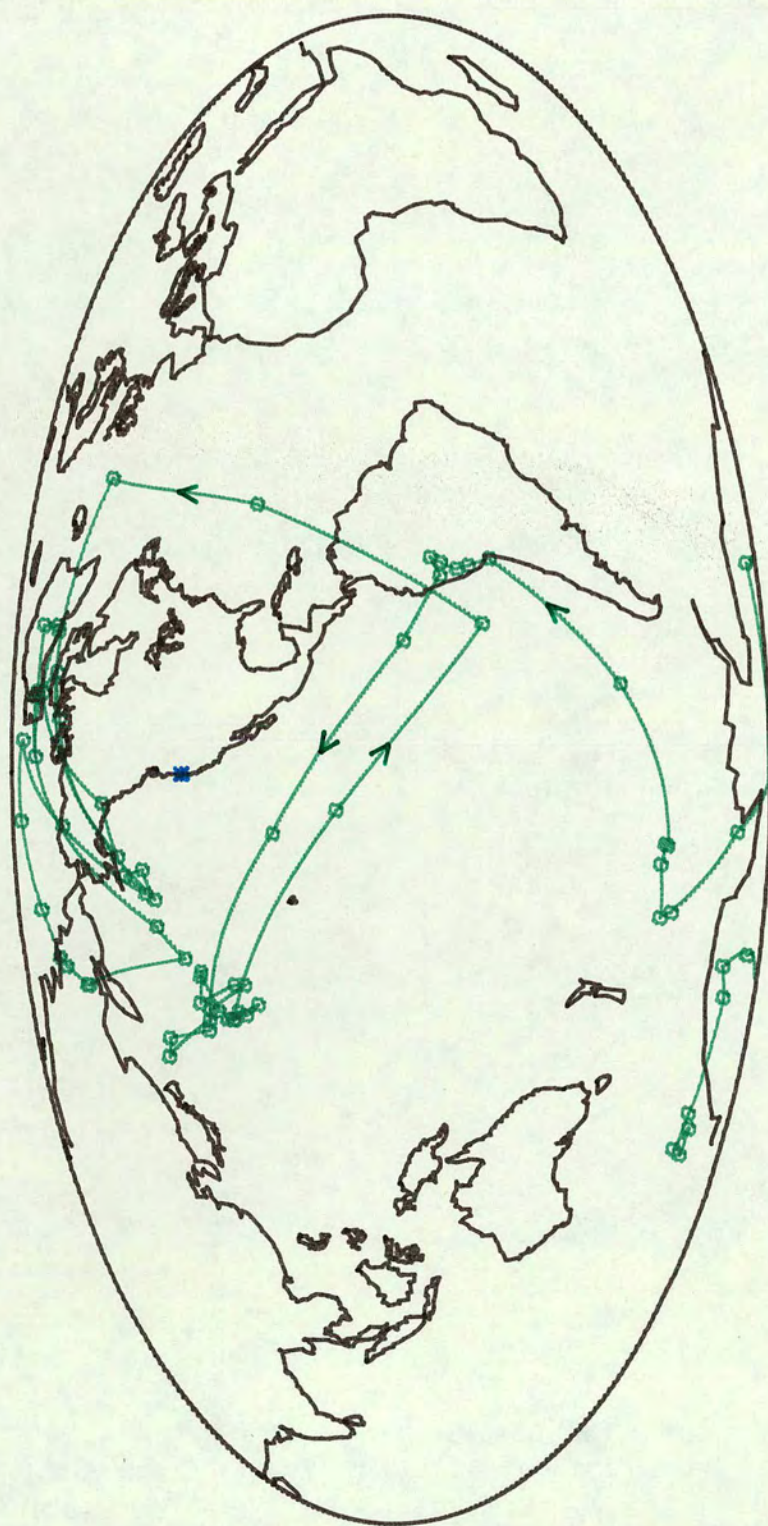


Figure 170. Steens Mountain Transition (Watkins, 1969)

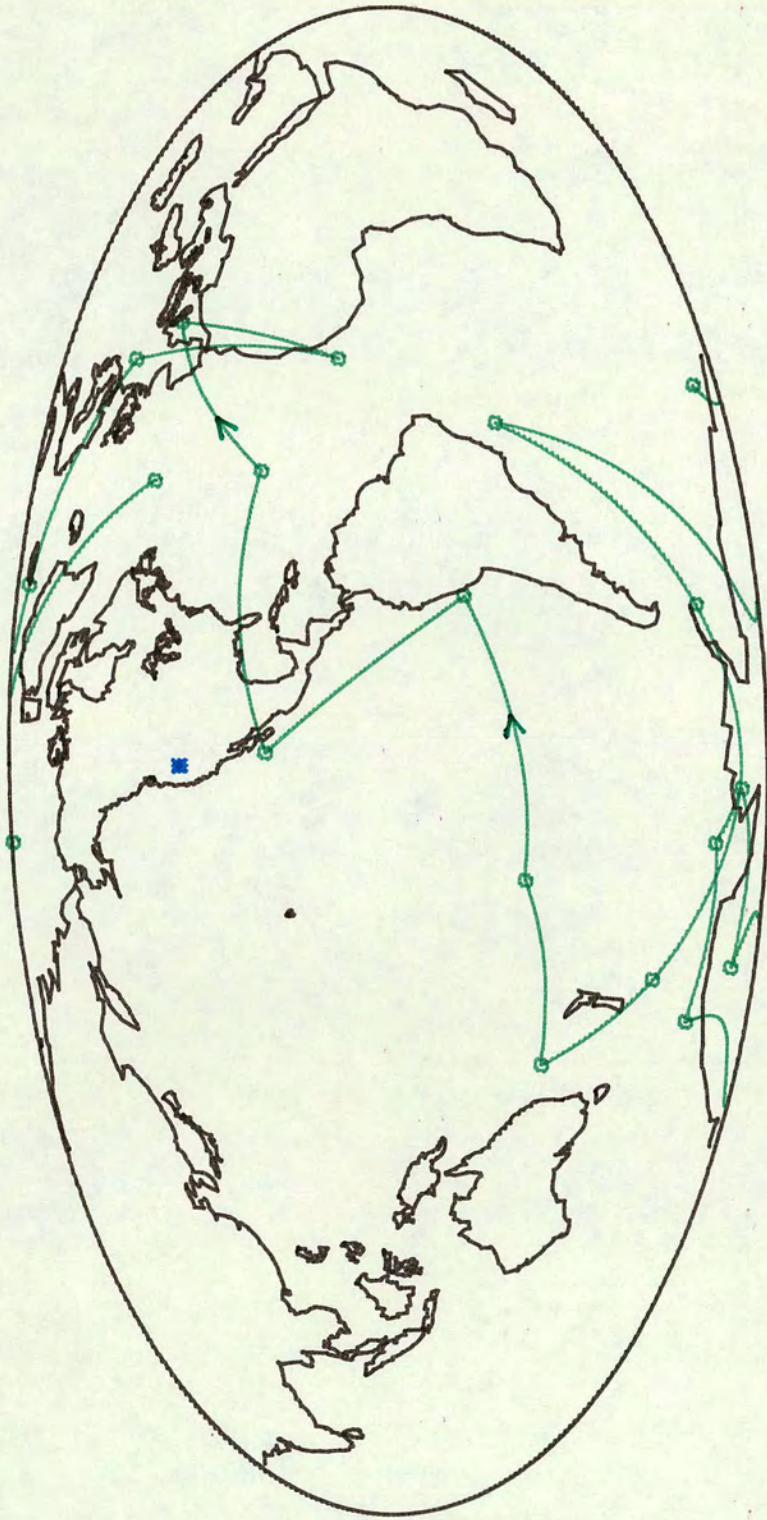


Figure 171. Transition at Santa Rosa from Larson et al, 1971

studies relating to quadrupolar or octupolar fields should be carried out on the first part of the transition.

OBSERVED TRANSITIONAL PATHS

(1) The Matuyama-Brunhes Transition in Europe

Hoffman (1979) uses the Bruggen path from Koci and Sibrava (1976) as his type section for the Matuyama-Brunhes transition in Europe. Other European records of the Matuyama-Brunhes transition from Koci and Sibrava (1976) and Bucha et al (1975) are shown in Figure 172, together with the Bruggen transition and the Tiepido record for the Matuyama-Brunhes. The geographical location of each site is shown in Figure 173.

The Tiepido transition, recorded in continental fluviatile silts and clays was described in Chapter 4 Part III. It consists of a far-sided path through the Pacific possibly including an anti-clockwise loop about Australia. The Krems transition from Austria is found in loess underlying a soil attributed to the Cromer interglacial. The path involves much oscillation, but is mainly confined to the far east, the path including a clockwise loop about Australia.

At Stranska Skala, near Brno, in Czechoslovakia, the Matuyama-Brunhes transition is recorded in loess. The interglacial layer overlying the loess is correlated with the soil at Krems. The transition consists of an anticlockwise loop about eastern Australia, then a far-sided reversal through Japan. The Cerveny Kopec transition, from a site near Stranska Skala, is also far-sided, passing through Indonesia and oscillating across eastern Asia. The Suchdol transition also in Czechoslovakia, is recorded in aeolian, fluvial, and colluvial deposits. The path includes a clockwise loop about India, and a reversal through Asia. A reversal at Bad Soden (West Germany)



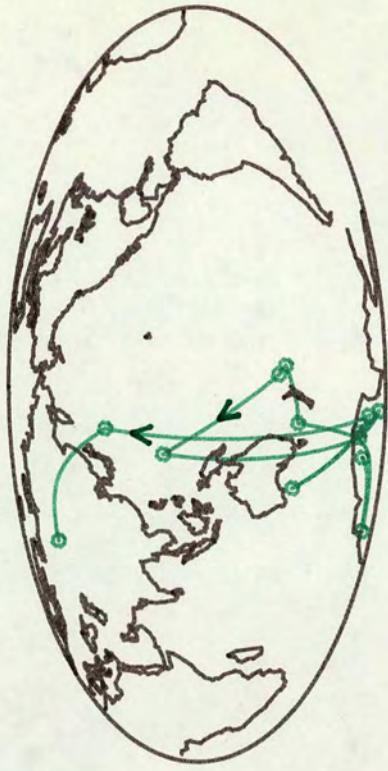
Krems



Cerveny Kopec



Tjepido



Stranska Skala

Figure 172. European records of the Matuyama-Brunhes Transition from Bucha et al (1975) and Koči & Sibrava (1976)



Bad Soden



Bruggen



Suchdol



Regensburg

Figure 172, continued



Figure 173. European sites recording the Matuyama-Brunhes Transition

contains one intermediate pole which lies north of Australia giving a far-sided path (Bucha et al, 1975).

At Regensburg in West Germany the transition is recorded in terrestrial loess. Few intermediate poles are seen, but these lie in the Atlantic region. An excursion preceding the reversal involves a loop about South Africa. The Bruggen transition is recorded in clays at a site in West Germany near the border with Holland. This was considered by Hoffman to be the most complete record. There is an initial excursion to China represented by one sample followed by reversal across the western Atlantic. The main path is similar to that at Regensburg but different to the other paths. Hoffman (1979) suggests that these other records show only the initial excursion at Bruggen, and not the main transition. Hoffman had no direct contact with Koci concerning these records. The bases for the correlations mentioned by Koci and Sibrava are not fully explained, although most correlations are based on glacial stratigraphy. Koci (pers. comm.) suggests that the Bruggen transition may be as old as the Lower Olduvai, and also expresses doubt about the age of the Regensburg transition. Thus it would appear that the Matuyama-Brunhes transition in Central Europe was far-sided, crossing the equator at a longitude of about 150° E.

This is incompatible with Hoffman's (1979) model (and if Bruggen did represent the Matuyama-Brunhes transition, the excursion to India should be taken as the important part of the transition). The Matuyama-Brunhes transition as recorded at Boso in Japan (140° E; Niitsuma, 1971) passes more or less through the site, however most other paths occur to the east of the site longitude. The difference is smaller for the Pacific sites: KH 70.2.5 (190° E) has a path 25° E of the site (Kawai et al, 1973) and the Freed results from the east

Pacific (269 to 273°E) pass between 30° and 79° east of the site (see Hoffman, 1979). At Tecopa (244°E; Hillhouse and Cox, 1976) the difference is 85°, while in Europe (10 to 20°E) the difference between site and path ranges between 55° and 135° (see Figure 174). This would seem to suggest some sort of non-dipole field having a stronger effect on European sites than on sites elsewhere. There are three records of the Matuyama-Brunhes transition from southern Siberia. The sections are all near the town of Novosibirsk (84°E), and were studied by G. A. Pospelova. The deposits are loessic soils, with some fluvial and lacustrine sediments interbedded. Each of the transitions involves much oscillation between the northern and southern hemispheres, most intermediate poles being located on the near side. The final reversed to normal transition after smoothing by a running mean of two is shown for all three sites in Figure 175. At Gonba the path passes more or less through the site but involves a westerly loop at the end. At Elunino the path begins via Australia but crosses the equator at more or less the same longitude as the site. This path also shows a westerly loop in the northern hemisphere. At Shelabolikha the path crosses the equator 70° west of the site. Taken overall these paths show a slight westerly bias superimposed on a near sided path, suggesting an extra source region between Central Europe and Siberia. These sites have mid-northern latitudes, similar to all the others listed except the east Pacific results of Freed.

The two mid-northern latitude sites studied by Clement et al (1982) give eastward components, producing paths 30 to 75° east of the site which is near that studied by Kawai et al (1973). They also report an equatorial site near that studied by Freed giving a main reversal 40° west of the site, but including a loop around the

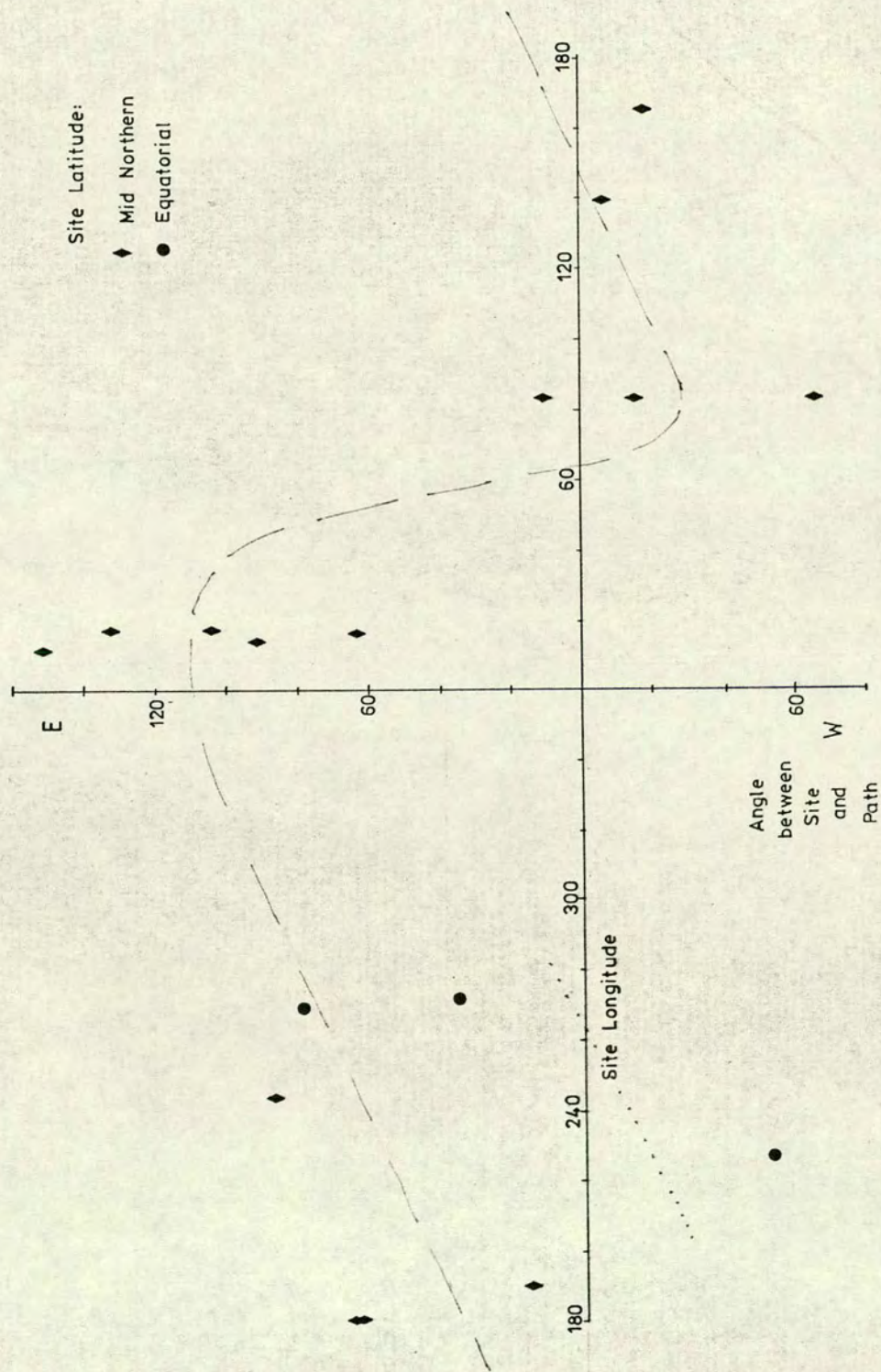
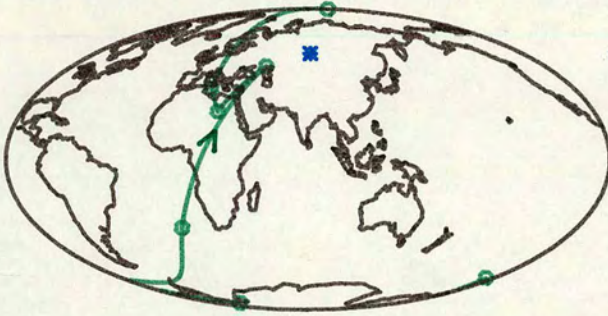
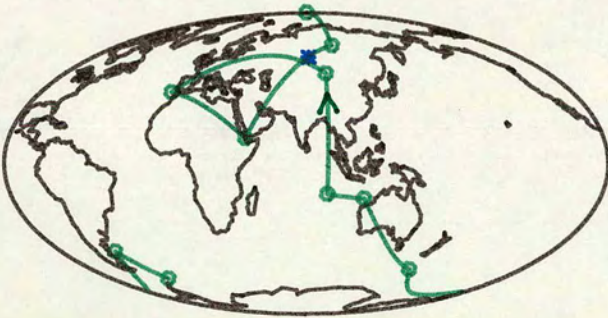


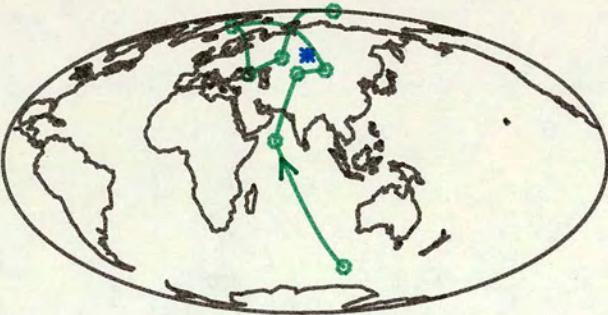
Figure 174. Angular Distance between Site Longitude and Transition Crossover as a function of Site Longitude for the Matuyama-Brunhes Transition



Shelabolikha



Elunino



Gonba

Figure 175. Siberian records of the Matuyama-Brunhes Transition

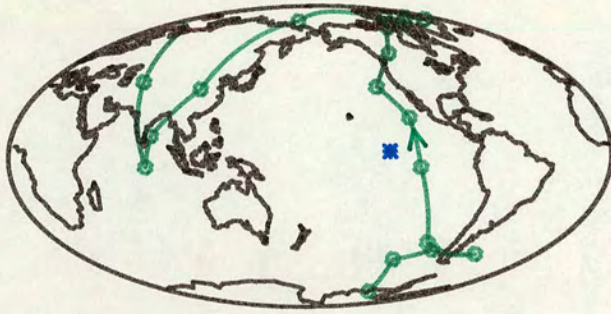
site (Figure 176). Kawai et al (1976) report a further equatorial Pacific record for the Matuyama-Brunhes transition. This involves three reversals, all of which are near-sided, crossing the equator between 75°W and 36°E (average of the 3 paths is 20°W , see Figure 177). The localised source between Europe and Siberia may also influence the equatorial results, however there seems to be an additional easterly bias on all mid-northern latitude data which may be related to the right-handedness noted by Wilson (1972).

All the five far-sided paths for Europe show short returns during the transition. At Tjepido, Stranska Skala, and Suchdol these take the form of anticlockwise loops. The Tjepido path is very scattered, but the close agreement of the three smoothed paths may indicate that the loop is a real feature.

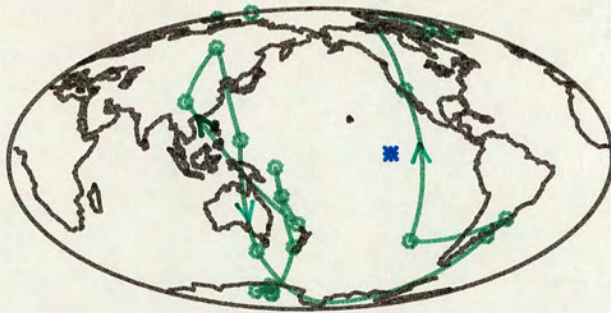
The Matuyama-Brunhes transition may thus be dominantly axisymmetric but, if so, then there are additional fields acting, including a localised source situated beneath Eastern Europe affecting most sites in America, Europe, and Asia; secondly some form of field may give rise to a right-handedness in the Northern hemisphere (either the dipole retains an influence, or the effect is caused by current phenomena); and thirdly, minor perturbations have caused looping of the field in Central Europe.

(2) Other Transitions in Europe

There are few transitional paths for other reversals recorded in European rocks. Bucha (1970) reports a path through Australia and the far east which he thought could have been the Lower Jaramillo, although no reversed sediments were seen above it (Figure 178). However like the Matuyama-Brunhes paths it shows a very narrow clockwise loop. The paths for the reversals at Stirone (Section A)



V20.108



V20.107



RC15.21

Figure 176. Records of the Matuyama-Brunhes Transition from Clement et al (1982)

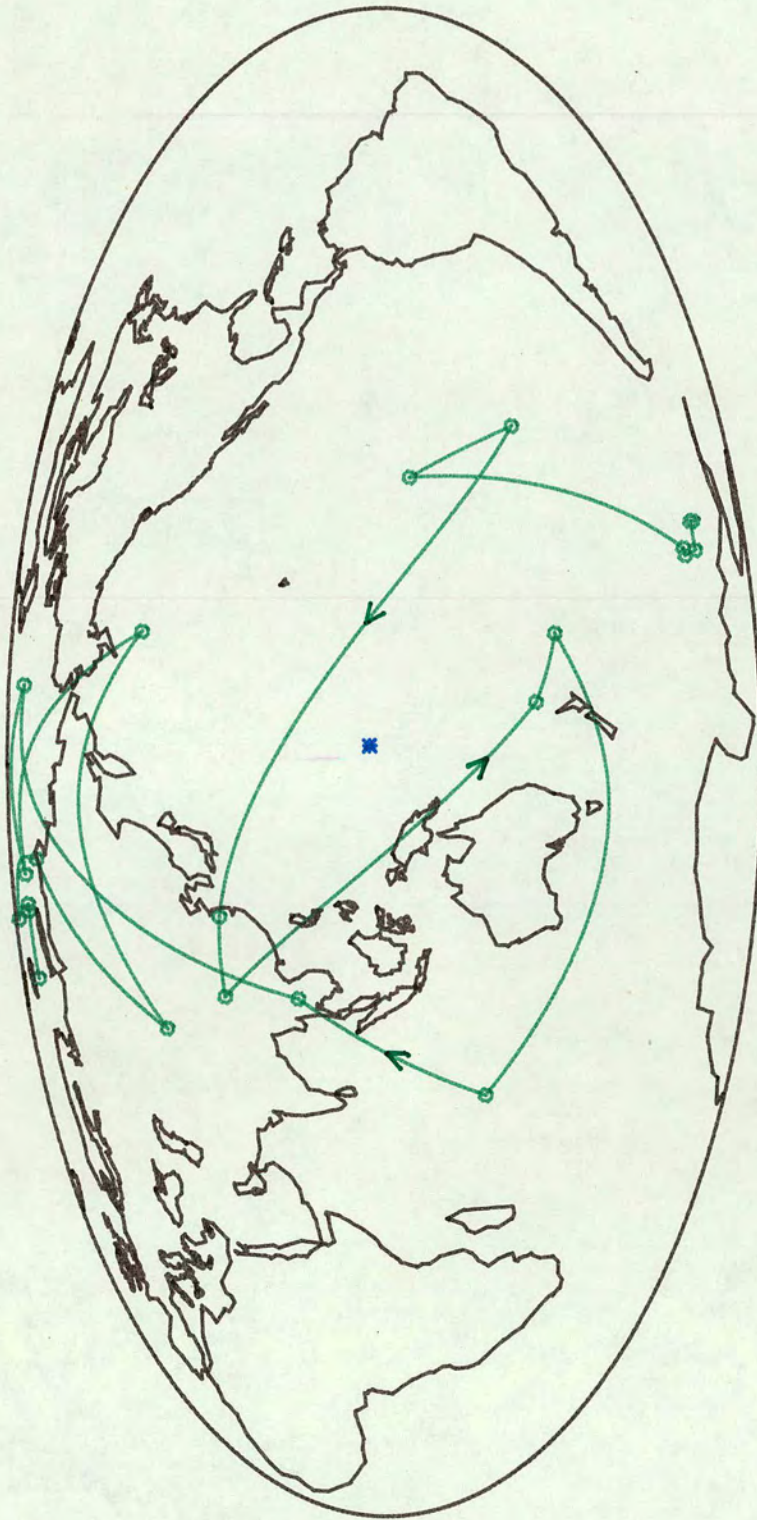


Figure 177. Matuyama-Brunhes Transition from Kawai et al (1976)

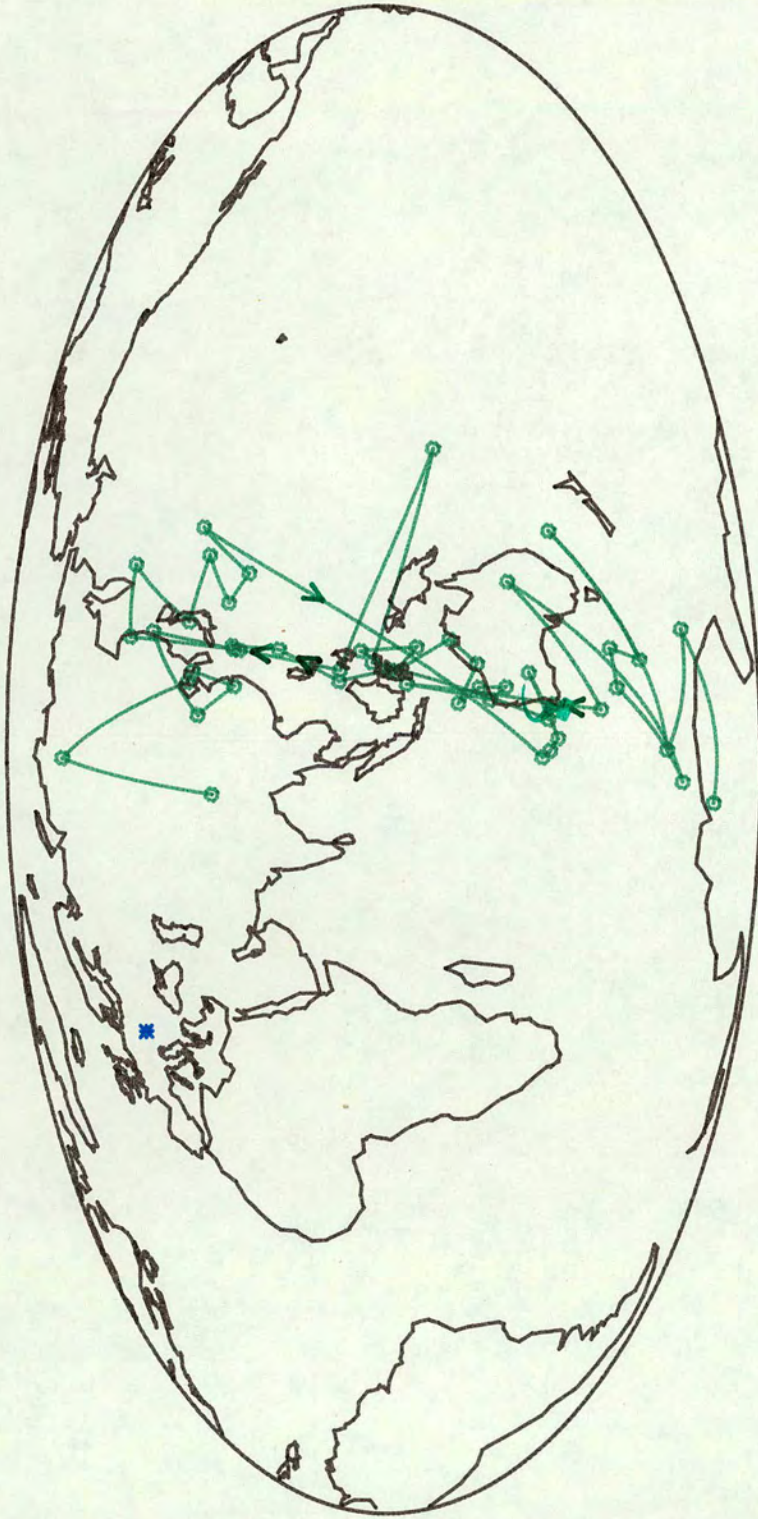


Figure 178. Reversed to Normal Transition from Bucha (1970)

and Bagaggera are both near-sided, as are those of Bruggen and Regensburg. The Stirone and Bagaggera transitions are probably the Lower Jaramillo, although at neither site are reversed directions seen above the sediments recording the transition. If this is correct then the Cerveny Kopec reversal is probably the Matuyama-Brunhes.

A transition recorded in Core MTO from Piombino (Readman and Evans, 1979) is also most probably the Lower Jaramillo (see Chapter 6). The transition consists of at least five reversals which may be due to delayed acquisition, however all paths pass through the Americas, so it would seem that this is the typical path for the Lower Jaramillo in Europe, crossing the equator about 90° west of the site. If the Bruggen transition is the Lower Olduvai, then this Atlantic/Americas path seems to have been favoured more than once.

The Stirone paths (both 1980 and 1981 sections) show loops around the east Atlantic and Africa part way through the transition, however the 1980 section has an anticlockwise loop, and the 1981 section a clockwise loop. The Bagaggera transition has one intermediate pole in Africa, so this may reflect rapid east-west drift at the centre of the transition, however other results for Bagaggera (in Billard et al, in press) do not show this anomalous direction.

Two reversed to normal transitions at Stirone just above the Plio-Pleistocene boundary may represent the start of the two Reunion Events, although the lower path is more likely to be part of an excursion within the Lower Reunion Event. Both paths pass through the eastern Pacific, although they are represented by just two intermediate poles in each case. These paths are different from the reversed to normal transition at 68m in Core MTO at Piombino which crosses the equator about 90° east of the site. The transition consists of a rapid reversal with no intermediate poles, then a loop

about Asia, so the actual reversal may have been via the east Pacific.

The only normal to reversed transition recorded in the Italian sediments is the Upper Olduvai reversal at Stirone, although many of the results are scattered. Most of the poles are far-sided giving a path through the east Pacific similar in some ways to that for the Matuyama-Brunhes transition, but about 90° further east. This Upper Olduvai path is less than 90° from the following transition the Lower Jaramillo, and about 90° from Bruggen which may record the preceding transition. However the earlier part of the transition which involves a loop across Asia is approximately 180° away from both the preceding and succeeding transitions.

Valet and Laj (1981) report two back to back transitions from Potamida, Crete, approximately 1600km southeast of the Po area. The reversed to normal transition is near-sided, passing through the equator 70° west of the site, that is through America. The following normal to reversed transition passes through the central and western Pacific (130° E of the site). Successive and preceding transitions at Potamida and nearby Skailadhiana repeat the alternating pattern (Laj, pers. comm.). These paths are similar to the Lower Jaramillo and Matuyama-Brunhes transitions respectively, although the Matuyama-Brunhes is of a different sense to the Cretan transition. Figure 179 shows that other European transitional paths cross the equator near one or other of these regions. It would seem that no simple axisymmetric pattern exists in Europe. If this pattern exists globally, then in Europe it has been repeatedly disturbed by other non-dipole sources. One possible explanation is that there are two favoured paths, perhaps due to recurring standing fields which occupy one of two 'easy' positions. Alternatively drifting non-dipole sources reach these areas, which may result from the topography of

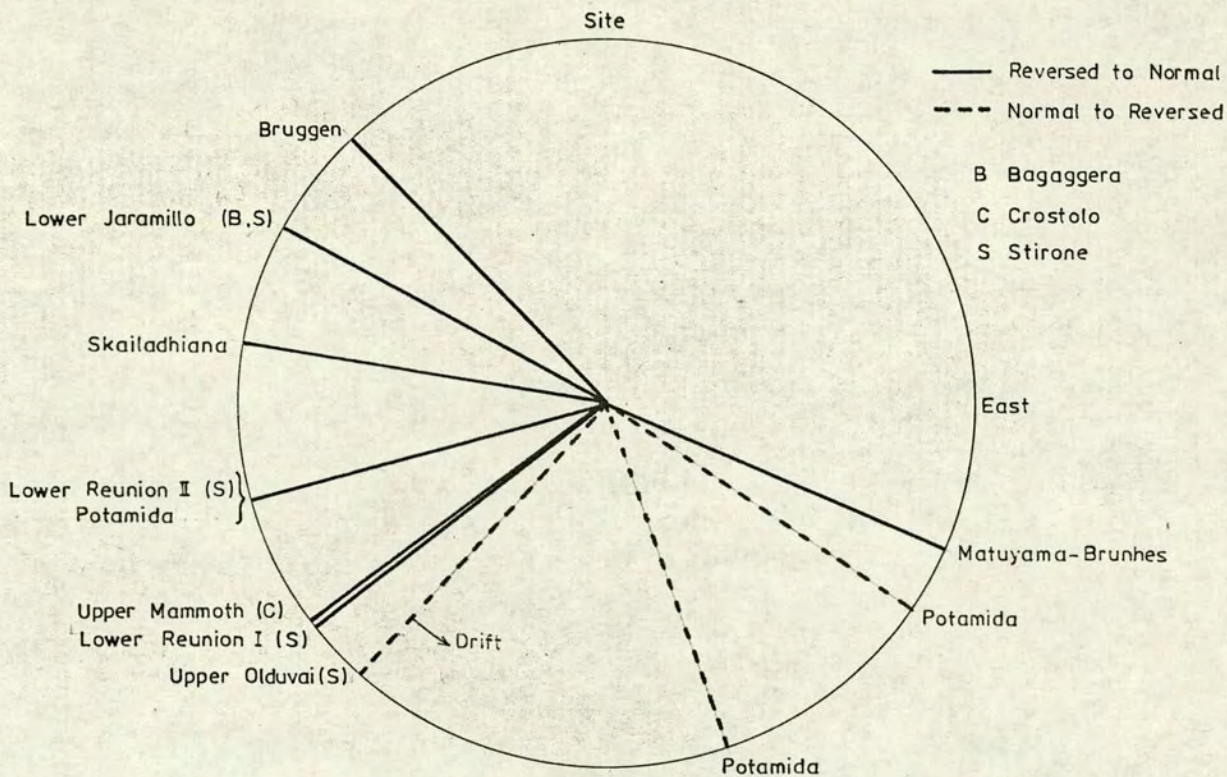


Figure 179. Equatorial Crossover Points for European Sites

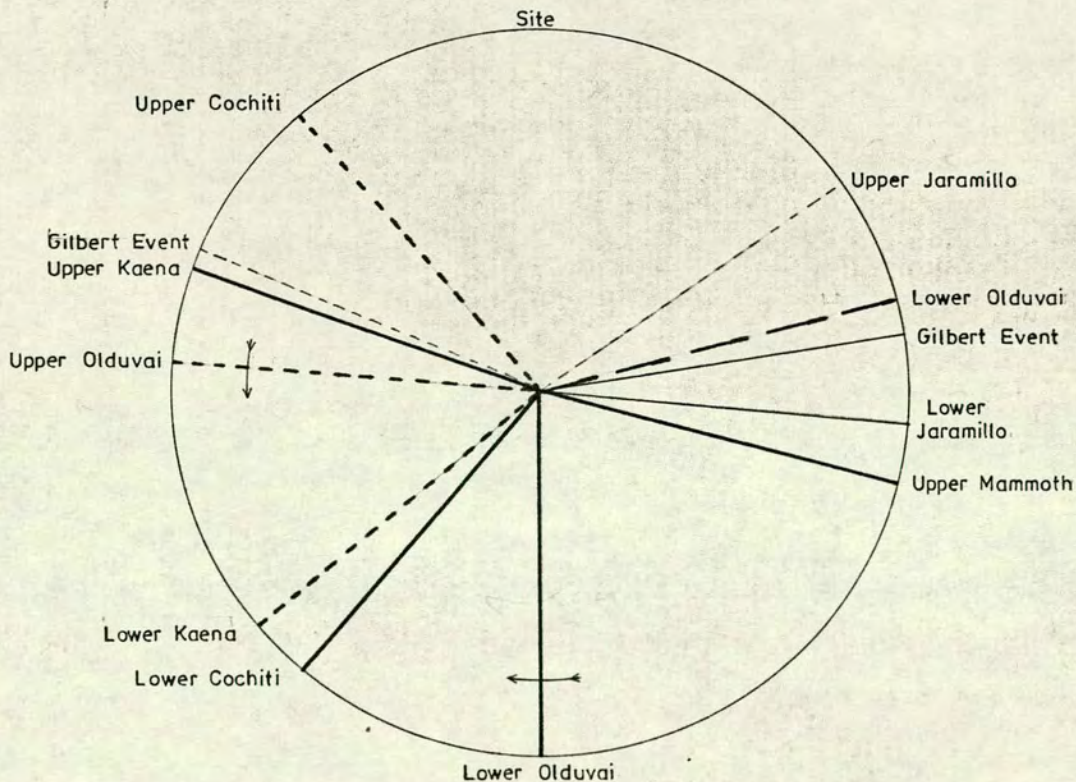


Figure 180. Equatorial Crossover Points for Site 514

the core-mantle interface, and are induced to stop and grow for some reason, leading to downfall of the dipole system. The Matuyama-Brunhes reversal is the only reversal that breaks the alternating pattern, so this transition may be affected by fields not normally present during a transition.

(3) Reversals in the Argentine Basin.

Successive reversals are seen at DSDP Site 514, however there does not seem to be any alternating pattern to the transitions. The Olduvai transitions differ by about 180° , with two of the lower set of three 90° east of the site and the upper normal to reversed transition about 90° west of the site. The third reversal forming the Lower Olduvai transition drifts across the far-side from 115°E to 135°W . The Upper and Lower Kaena transitions take paths 60° apart in the eastern Pacific, although the upper reversal is interrupted by a short return to southerly latitudes. The upper Mammoth reversed to normal transition is about 180° from the Upper Kaena path. The Cochiti paths are about 90° apart, with the lower reversed to normal transition lying near the lower Kaena normal to reversed transition, and the Upper Cochiti path similar to the Upper Kaena path. Considering the seven transitions mentioned there are two groups of paths one passing through the Indian Ocean, the other through the eastern Pacific (Figure 180). This includes the drifting Upper Olduvai path within the Pacific group and the drifting lower Olduvai path within the Indian Ocean group as these parts of the paths represent the initial stages of each reversal. The Upper Matuyama excursion which only reaches 20°N is centred on the Indian Ocean.

There are few intermediate poles in the DSDP data, so many of the transitional paths are defined by only one or two VGPs. Again

there is no clear-cut near-sided or far-sided pattern, in fact the two favoured areas are almost 90° E and 90° W of the site. This may also be due to recurring non-dipole fields.

(4) Western U.S.A. and Iceland.

There are two other areas where a number of transitions have been studied (the western states of the U.S.A. and Iceland) which can be compared with the results discussed above to see whether favoured paths exist elsewhere. Figure 181 shows the equatorial crossover point for six transitions from the western U.S.A. These are the Tecopa and Searles records (Hillhouse and Cox, 1976; and Liddicoat, 1982) which are from sediments and studies on igneous rocks from Steens Mountain (Watkins, 1969), Santo Rosa (Larson et al, 1971), Laurel Hill (Mount Hood) and the Tatoosh Intrusion (Mount Rainier: Dodson et al, 1978). The Steens and Santa Rosa records involve large amounts of drift or looping, but pass through the equator near the site longitude. The Tecopa and Searles records are similar although they represent transitions of opposite senses. These paths cross the equator about 90° east of the site, almost 180° from the Mount Hood and Mount Rainier paths which cross at almost the same point, 60° west of the site. There is a bimodal distribution of transitional paths if the complex reversals are discounted (the Santa Rosa transition starts along a path 60° west of the site before drifting to the east). The looping and drifting at these two sites may be due to additional non-dipole fields which do not usually oscillate or drift during a reversal.

The records from Eastern Iceland (Dagley and Lawley, 1974) and Western Iceland (Shaw, 1975) show much more complexity in the paths. The equatorial crossover points seem to be randomly distributed, although reversed to normal transitions are biased to the near-side

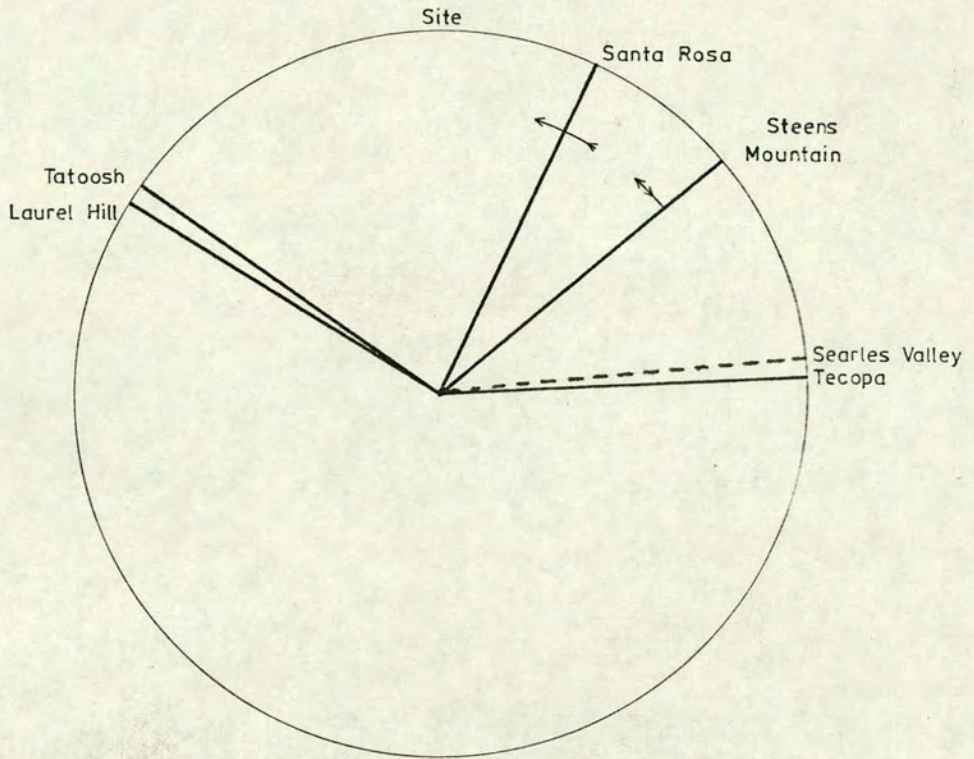


Figure 181. Equatorial Crossover Points for Sites in the western USA

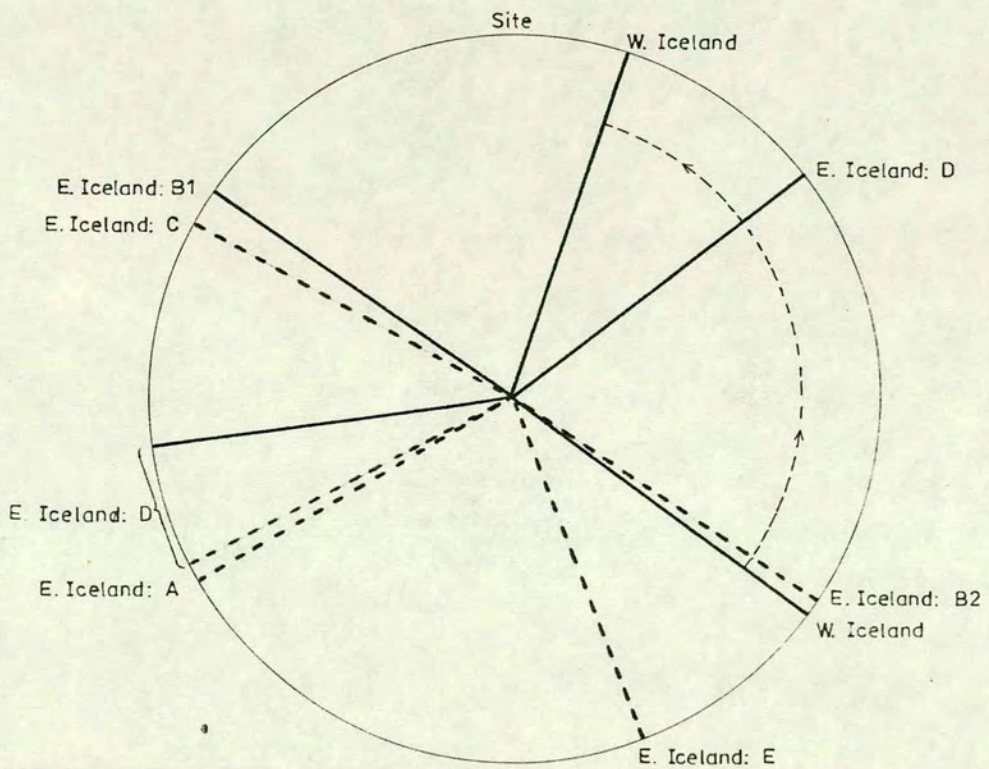


Figure 182. Equatorial Crossover Points for Sites in Iceland

and normal to reversed transitions to the far-side (Figure 182). The amount of non-dipole variation is known to be higher in Iceland during stable polarity, so it would appear that large amounts of non-dipole field variation disrupt the transitional paths when the dipole is weak.

The results from Europe and the Argentine Basin do not show any site dependence as suggested by Hoffman and Fuller (1978). There appears to be a pair of favoured directions about 180° apart with alternation between these paths occurring for limited periods as at Crete. The alternation may be disrupted by unusually large non-dipole fields in fact at Iceland these fields probably disrupt the majority of the transitions. If the dipole dynamo reverses according to the Hoffman model this is not always seen at the surface due to the presence of stationary or drifting non-dipole fields. In fact the longitudinal dependence noted by Hoffman and Fuller may be caused by stationary non-dipole sources. These will give near-sided or farsided paths if the source is located in the core below the site. Two or more radial dipoles growing in strength simultaneously with decrease of the axial dipole will produce this behaviour at more than one point on the Earth's surface. Only if the radial dipoles change in magnitude with respect to each other will there be any longitudinal drift of the transitional path.

Thus it would seem that each transition is characterized by different non-dipole fields in different proportions. The results for the Matuyama-Brunhes transition show that much more global coverage is necessary to be able to define the extent and influence of each of these sources.

CHAPTER 8

CONCLUSIONS

The palaeomagnetism of a variety of sediments has been studied; and, as may have been expected, these sediments record the Earth's magnetic field with varying degrees of accuracy.

Depositional detrital remanent magnetization is the resultant of the sum of a number of grains, each aligned by forces including the magnetic field. The accuracy of the orientation can be measured by comparing the remanent intensity with the potential remanent intensity if all grains were aligned parallel. Susceptibility is the most convenient method of estimating the relative potential of sediments, and this was surprisingly constant for all depositional sediments, averaging $10\mu\text{G}/\text{Oe}$. Intensity normalized by susceptibility, i.e. Q-ratio, gives an indication of the effectiveness of alignment. The low energy environments are much better for palaeomagnetic recording as indicated by the higher Q-ratios for the lacustrine clays at Bagaggera and Pontida (0.5 to 1.0). The marine clays at Crostolo and Panaro also give high Q-ratios, however the lowest values are seen in the coarse, sandy, fluviatile deposits at Stirone and Crostolo (<0.1). The generally high coercivities, and the hysteresis characteristics suggest that the dominant magnetic mineral is magnetite although often weathering of the continental deposits has produced some haematite.

The palaeosols generally have higher susceptibilities (up to $100\mu\text{G}/\text{Oe}$), suggesting an increase in magnetic mineral concentration. Q-ratios are high at Bagaggera (0.8 to 1.0) but moderate in the Po Valley (0.2 to 0.3). Some of the soils have very high coercivities including the Rivalentella soil, and that developed on the flysch at

Bagaggera, suggesting haematite; but many of the soils have low median destructive fields indicating multi-domain magnetite. The soil forming processes probably oxidize the finer grained magnetite which is either removed, or precipitated as haematite.

EXCURSIONS

Short reversals and excursions fit into most theoretical analyses of magnetostratigraphic behaviour, however the tendency of some workers to interpret every anomalous direction as an excursion has led to scepticism about their existence as geomagnetic phenomena. It is, however, clear, from a reasoned study of palaeomagnetic results, that excursions and short reversals do exist. The most notable of these are the Mono Lake Excursion and the Blake Event. More work will have to be carried out in order to resolve recent geomagnetic history and discover whether the Imuruk, Mono, and Mungo Excursions are linked by a common drifting source, manifesting itself at different times at different points on the Earth's surface. The solution of this problem may produce important constraints for the dynamo mechanism.

Two more phenomena are seen in the Brunhes: the Emperor Event at about 465,000 yr. b.p. and the Laurano Excursion at 680,000 yr. b.p. Study of the statistical distribution of reversed directions dated within the Brunhes suggests that if volcanic activity is independent of polarity (and there is no reason for it to be dependent) then only 20,000 of the past 730,000 years have been reversed. This implies that the four phenomena mentioned had lives averaging 5,000 years, which is barely enough time for the field to reverse completely, so all the Brunhes Excursions may only be localized.

Less attention has been paid to the Matuyama and preceding epochs so the four excursions added to the Mankinen and Dalrymple

timescale in Figure 158 may be supplemented after further work. Global coverage of the Cobb, Neuquen, Searles Valley, and Argentine Basin Excursions is not great enough at present to determine whether these are excursions, or short reversed intervals. Nevertheless it is certain that the reversal frequency for the past 4 million years has been greater than suggested by Cox (1975). It may be as high as 5 per million years, with an additional two unsuccessful attempts in each million year period.

TRANSITIONS

Hoffman (1982) has argued that if the axisymmetric flooding model does not hold for all transitions, then at least it holds for the Matuyama-Brunhes transition. The results of Tiepido from this work as well as the results of Stranska Skala, Suchdol, etc. show that even the Matuyama-Brunhes is more complex than originally thought. There would appear to be an additional disturbing influence causing eastward components in the transitional field at Tecopa and in Europe, as well as westward components in Siberia.

The results of Europe and the Argentine Basin do not show a clear near-sided or far-sided pattern. There may be a weak bimodality in paths for each area, but if so, then this is independent of the sense of the transition. The pattern for successive reversals suggested by Hoffman as a method for distinguishing between axisymmetric or stationary transitional fields will only hold if the axisymmetric field is similar for both transitions, or if the non-dipole field remains stationary throughout the stable field interval separating the two transitions. That neither pattern holds in Europe or in the Argentine Basin suggests that there is no overall pattern for transitions, but that each transition has its own structure. Hill-

house and Cox (1976) suggested that the non-dipole field becomes stationary during a transition due to loss of electromagnetic coupling through decrease in the axial dipole field strength. In this case there is no reason for these stationary fields to occur in the same place for consecutive transitions.

A possible transitional field structure involves growth of non-dipole foci causing collapse of the main dipole at a critical point. This in turn causes the non-dipole foci to stop drifting, allowing further growth. Ultimately these foci will decrease as the main dipole reasserts itself. Many non-dipole foci growing in unison will give longitudinally confined paths; if these foci are positive, that is downward pointing, then the sites vertically above will record near-sided paths. Occasionally the rate of growth or decay of two of these foci will be different and this will result in longitudinal drift of the transitional path.

Excursions will be caused by abnormal growth of the non-dipole foci, with in some cases, minimal decrease of the main dipole as in the case of Lake Mono and Pontida, which gives an exaggerated secular variation loop. Collapse of the main dipole with recovery in the same sense will give a longitudinally confined excursion, similar to the Laurano Excursion or those studied by Hoffman (1981) from Australia, Hawaii, and Amsterdam Island.

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ACKNOWLEDGEMENTS

I would like to thank my supervisor, Professor K.M. Creer for his guidance and for helpful discussions throughout my four years in Edinburgh. In addition I have benefitted from discussion with many other members of staff in the Geophysics department, including Doctors Charlie Barton, Richard Bradshaw, Peter Readman, Roy Thompson and Piotr Tucholka.

I would like to thank Alex Jackson and Alan Pike for assistance in the laboratory and also Jennifer Jackson for help at the beginning of my course. Thanks are also due to Robert Young who helped with the major part of the sampling during the summer of 1981.

Many Italian colleagues have assisted me, and I would like particularly to thank Dottore Mauro Cremaschi, Professori Giuseppe Orombelli and Giovanni Papani, and Giuseppe Bertozzi both for their help in the field, and for their wonderful hospitality.

My gratitude is also extended to my colleagues on board the Glomar Challenger especially John Usher and Amy Altman.

Part of this work was carried out on a NERC Grant, however I am grateful to my father who made possible the completion of my thesis.

Susan Leslie Brown has assisted me with fieldwork, with measurement, by typing the thesis, and in many other ways too numerous to mention.