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PRELIMINARY MAGNETOSTRATIGRAPHIC CORRELATIONS IN UPPER FORT UNION FORMATION (PALEOCENE) AND LOWER WASATCH FORMATION (EOCENE) NORTHERN POWDER RIVER BASIN, WYOMING AND MONTANA

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ABSTRACT

A preliminary polarity zonation has been obtained from drill core and surface sections of the upper Fort Union Formation (Paleocene) and lower Wasatch Formation (Eocene) in the northern Powder River Basin of Wyoming and Montana. The polarity data support surface and subsurface stratigraphic correlations of coal beds in the Fort Union Formation. Stratigraphic correlations proposed for some coal beds in the Wasatch Formation, however, are not supported by the polarity data. The Truman-Parnell (Ulm-2) coal bed in the Recluse, Wyoming, area is in a zone of reversed polarity, whereas the Healy coal bed (Ulm 2) of the Buffalo area lies within an interval of normal polarity and appears distinctly younger. Preliminary correlation with the polarity time scale suggests that 1) sections of the Fort Union and Wasatch Formations studied were deposited from about 62 to 52 m.y. ago, 2) the strata accumulated at a rate of about 55 m/m.y., and 3) the Fort Union-Wasatch contact lies close to the Paleocene-Eocene boundary.

INTRODUCTION

Field geologic studies are being carried out by the U.S. Geological Survey in the Powder River Basin of northeastern Wyoming and southeastern Montana with the objective of testing and refining stratigraphic correlations of coal beds and of obtaining a better understanding of the coal resources. Detailed geologic mapping and coordinated drill core exploration form the basis of the Survey's study. However, some stratigraphic uncertainties remain because coal beds display abrupt lateral changes in thickness and they also split and join in unpredictable ways. Thus, a study of the magnetic polarity stratigraphy was begun in November 1976 in an attempt to develop a polarity zonation and time lines in the stratigraphic sections under study. Detailed temporal control obtained from polarity boundaries, and a polarity zonation, would provide an independent body of data for the evaluation of existing stratigraphic correlations of coal beds and groups of coal beds. We present here a progress report summarizing the current status of the magnetostratigraphic study of drill core and outcrop sections carried out through December 1979.

Paleomagnetism has been successfully applied to the correlation and dating of continental deposits of latest Cretaceous and early Tertiary age in the San Juan Basin of northern New Mexico (Butler and others, 1977), and in the Big Horn and Clark Fork Basins of Wyoming (Butler and others, 1980). The geomagnetic field switched polarity often enough and with enough irregularity during this time to provide a distinctive structure to the polarity time scale (LaBrecque and others, 1977). The sequence of polarity zones recorded in sedimentary strata collected from outcrops in the western basins studied by Butler and others not only could be correlated within the basins, but also were correlated with the polarity time scale.

Unlike studies in the San Juan and Big Horn Basins, the paleomagnetic investigation in the Powder River Basin has relied mainly on the analysis of drill core sections because overprinting in outcrop sections that has resulted from weathering commonly obscures the original magnetization. A preliminary polarity zonation, and correlations, are proposed which can serve as a point of departure for future studies. Additional drill core sections are needed to more firmly establish the polarity zonation, and to resolve the more speculative parts of a preliminary magnetostratigraphic framework.

GEOLOGIC SETTING

The early Tertiary continental deposits in the Powder River Basin are nearly flat-lying and crop out in a broad asymmetric synclinal depression that formed in late Cretaceous and early

Tertiary time. A north-south trending axis lies adjacent to the Big Horn Mountains in the western part of the Powder River basin, and the Black Hills bound the basin on the east (Fig. 1).

Stratigraphy

The coal-bearing strata studied are those of the upper, Tongue River Member of the Fort Union Formation (Paleocene), and of the lower part of the overlying Wasatch Formation (Eocene). Approximately 290 m of section of the Fort Union and 190 m of the Wasatch Formation were studied. The Fort Union and Wasatch consist of fluvial-paludal deposits, mainly brown, gray, and buff claystone, siltstone, and sandstone, and abundant interbedded coal. Major coal beds within the stratigraphic intervals studied are summarized on Figure 2.

An unconformity that locally separates strata assigned to the Fort Union and Wasatch Formations has long been a subject of investigation and discussion. Olive (1957, p. 14) has described characteristics of the unconformity, which he recognized from the truncation of uppermost Fort Union strata in the eastern part of the basin. Olive (1957) reports that a greater thickness of Wasatch strata underlies the lowest major Wasatch coal (Felix) in the west, and he suggests that uplift to the south and east produced the truncation and led to the subsequent deposition of a basal Wasatch aeolian sand in the eastern basin. To the west, finer grained sediment and coal continued to accumulate in swampy environments. At places where no obvious unconformity can be recognized, discrimination between the Wasatch and Fort Union Formations is determined from differences in heavy mineral content, grain size, and subtle color differences (Connor and others, 1976). One objective of the magnetostratigraphic study was to investigate the magnitude of a presumed time-gap at the boundary between the Fort Union and Wasatch Formations.

FIELD AND LABORATORY METHODS

Outcrop Sections

Three surface sections were sampled in the area of Recluse, Wyoming, to investigate the stability of magnetization and the reproducibility of the polarity zonation between the outcrop and drill core sections. The sections are 1) strata of the Fort Union Formation at Elk Creek, extending from the Cook coal bed upward to just below the Anderson coal bed (EC, Fig. 1); 2) strata of the Fort Union Formation in the 'Lands End' area of the Kline Draw $7\frac{1}{2}$°' quadrangle, extending from below the Anderson coal upward to the Roland (?) coal (of Baker) (LE, Fig. 1), and 3) strata of the Wasatch Formation in the Truman Draw quadrangle, extending from the Felix coal to the Truman coal (TD, Fig. 1).

Exposures of the Lands End section, collected largely from road cuts, were by far the freshest. The Elk Creek and Truman Draw sections were collected from natural exposures in steep slopes and gullies.

Samples at each section were collected from the finest grained deposits available. The coarser grained strata had earlier been found (from drill cores) to be poor recorders of primary magnetization. Three samples were collected at each horizon (site) to test for the local reproducibility of magnetic direction. Sites were collected at stratigraphic separations of about three meters. Outcrops were excavated to depths of about one-half meter to obtain reasonably unweathered rock. Near-horizontal, bedding surfaces were planed on undisturbed bedrock using a pocket plane. Azimuthal lines then were scribed on the surfaces using the edge of a magnetic compass, and the trends of the lines measured and recorded on the bedding plane. Samples then were detached from the outcrop and wrapped in tissue for protection during transport. In the laboratory, blocks were trimmed using a diamond saw blade and the cubical samples were placed in 2.5 x 2.5 x 1.9 cm non-magnetic plastic boxes, azimuthal lines being systematically maintained parallel to an edge of the box. Lindsay and others (1980) describe this sampling procedure and report an approximate orientation error of $\pm$ 5°.

Drill Core Sections

Twelve drill cores from the northern Powder River Basin were sampled for this study. The locations of the drill holes are shown in Figure 1. Figure 2 depicts the stratigraphic intervals penetrated by ten of the twelve drill holes for which results can be reported. Core holes drilled at Sheridan and Buffalo (S1 and B1, Figure 1), southwest of the main area of study, penetrated coal beds to which a different coal bed nomenclature is applied.

Samples were cut from segments of the cores while maintaining the up-core orientations and the samples then placed in near-cubical non-magnetic plastic boxes. Because the parent cores were not oriented azimuthally, only the inclination of the remanent magnetization could be used for the determination of polarity, but such commonly is adequate for sites at moderate and high latitudes. In one core (HWC-25), three samples were collected at each horizon, and the same relative azimuthal orientations were maintained for each group of samples to allow the internal consistency of magnetization to be evaluated. In all other cores, one sample was taken at each horizon in the finest grained beds that could be sampled. Vertical separations for the samples and sample groups ranged from <1/3 m to 3 m. In the later stages of this study, sampling of coal horizons was discontinued. The coal is very weakly magnetized and does not display a reproducible stable magnetization.

The natural remanent magnetization (NRM) of all the samples was measured with a shielded superconducting rock magnetometer that is interfaced with a computer for concurrent data analysis and compilation. The magnetometer has a sensitivity of about 1 x 10^{-7} emu.

Each sample was subjected to alternating field demagnetization using a single-axis demagnetization unit of commercial design. Approximately one quarter of the samples were subjected to stepwise AF demagnetization employing peak fields that ranged from 25 to 600 oersteds. Peak fields above 400 oersteds, in a number of cases, produced an anhysteretic remanent magnetization (ARM), a magnetization related to the treatment and not the original magnetization. The remaining three quarters of the samples were partially demagnetized in single steps in peak fields that ranged from 50 to 200 oersteds, guided by the behavior of the pilot samples.

PALEOMAGNETIC RESULTS

Intensities of Magnetization

Intensities of the natural remanent magnetization (NRM) of most samples from the outcrop sections and the drill cores were weak, of the order of 5×10^{-7} emu/cm^3. The low intensities appear to reflect a paucity of ferri- or ferromagnetic minerals in the fine grained strata. Experiments to determine the particular minerals responsible for the weak remanence were not successful. Mineral identification using thermomagnetic techniques were unsuccessful because sulfide (pyrite) masked any carrier of the stable magnetization during analysis. Abundant organic matter is present in all the sections sampled. In such a reducing environment, sulfides presumably have formed at the expense of magnetite and/or titanomagnetite, minerals that elsewhere carry the stable detrital remanence in continental deposits of similar age.

Samples from the Wasatch Formation have distinctly greater intensities of NRM ($\sim 1 \times 10^{-6}$ emu/cm^3) than intensities from samples of the underlying Fort Union Formation ($\sim 5 \times 10^{-7}$ emu/cm^3). Geochemical studies by Connor and others (1976) have shown that the Wasatch Formation contains three to four times more iron than the Fort Union Formation. They suggest that the greater iron content and greater heavy mineral content of the Wasatch reflect a first cycle sediment, whereas detritus in the older Fort Union is a second cycle sediment. These differences presumably record a change in provenance at the onset of deposition of the Wasatch, perhaps reflecting tectonic uplift along the margins of the basin that exposed crystalline source rocks to renewed erosion. First cycle sedimentary rocks derived from crystalline rocks normally contain a greater abundance of magnetite than do second cycle sedimentary rocks. A crystalline source terrane for the Wasatch Formation may account for the greater intensity of magnetization relative to the intensity of the Fort Union Formation.

The generally low intensities of the natural remanent magnetization in strata of the Fort Union Formation were further decreased by partial alternating field (AF) demagnetization. Figure 3 illustrates the progressive decrease in intensity during stepwise demagnetization of a group of 12 samples collected from the White Tail Butte cores WTB-103 and -108. The mean destructive field (MDF) for the curve shown in Figure 3 is 115 oersteds (oe), and the range of MDFs extend from 40 to 330 oe. For some samples, AF demagnetization above 50 oe decreased the intensities of magnetization below the sensitivity of the magnetometer. However, intensities of many of the samples were reduced to near the level of sensitivity; i.e., $\sim 2 \times 10^{-8}$ emu/cm^3 for a 5 cc sample. In such cases, multiple measurements of individual samples commonly showed a lack of reproducibility of the directional data, which indicated that the remanent magnetization in these rocks is not stable near the threshold of sensitivity of the magnetometer. Thus, no useful data appear to have been lost from the most weakly magnetized samples.

Directions of Magnetization

Outcrop Sections

Oriented samples collected from the outcrop allowed declination as well as inclination to be determined. However, for a number of the outcrop samples magnetic overprinting apparently imposed by weathering has negated this inherent advantage of outcrop sections. Directions of magnetization for site-means before AF demagnetization for the Lands End section are shown in Figure 4a. Many of the sites from this section possess NRM directions that cluster around a Tertiary or present normal polarity field direction, and most of the remaining sites exhibit directions that produce a 'streak' into the southeast quadrant toward a reverse polarity direction. NRM data from the Elk Creek and Truman Draw sections (not shown here) exhibit the same basic pattern, but there is greater within- and between-site scatter, and these two sections have more sites with polarity directions that cluster around a normal polarity field direction. Partial AF demagnetization of the Lands End sites at a peak field of 200 oe produced a distribution of site mean directions that is shown in Figure 4b. Nearly one-half of the sites still possess directions that cluster around the present field direction (A = axial field, Fig. 4b) or the slightly offset early Tertiary normal direction (P=Paleocene, Fig. 4) The cleaning also resulted in a grouping of reverse polarity sites that plot on the upper hemisphere (negative inclination) in the southeast quadrant, and in a few sites whose positions are intermediate between the clusters of the normal and reverse polarity groups.

The "P" on Figure 4b represents the expected Paleocene direction, calculated from three early Tertiary poles reported from the western U.S. by Butler and Taylor (1978), Shive and Pruss (1977), and Diehl and others (1978). Site directions from the Powder River Basin obviously exhibit far too much scatter to closely record the ancient field direction. Closely anti-parallel reversed polarity directions are lacking (reversed polarity inclinations are about -20^{o}, whereas normal polarity inclinations are about $+60^{o}$). The lack of antiparallelism probably reflects an incomplete removal of secondary normal components of magnetization impressed as a consequence of chemical weathering and the formation of hematite(?), and/or the incomplete removal of viscous magnetizations carried by coarse grained, multi-domain magnetite. Nonetheless, the lack of complete antiparallelism for the reverse polarity sites does not compromise their usefulness for the development of a polarity zonation.

The demagnetization behavior of individual samples within sites of the Lands End section is shown in Figures 5 and 6. Samples of site LE-3 (Fig. 5) exhibit a noticeable improvement in the grouping with cleaning, the three samples clustering near the Tertiary normal polarity direction. On the other hand, samples from site LE-10 (Fig. 5) exhibit greater scatter with cleaning, a behavior observed from many samples collected from the outcrop sections. Figure 6 also illustrates, in more detail, erratic response to AF demagnetization. In this example, directions of all three samples of site LE-1 move away from one another, rendering determination of polarity uncertain at that horizon. Such behavior compromises the site mean direction, which calculates as a normally magnetized site with large dispersion. As a result, the polarity of the earth's field at the time of deposition of site LE-1 could not be determined.

A test was employed to determine if the three directions for each site were statistically well enough grouped to be non-random. Watson's (1956) test for randomness employs the length of the resultant vector (R) for each site. For three samples collected at a site, R must be greater than 2.62 for the directions to be non-random at the 95 percent confidence level. Application of this test resulted in identification of non-random directions in approximately 50 percent of the sites (16 of 29 sites from the Lands End section, 15 of 31 from Elk Creek, and 14 of 27 sites from Truman Draw).

Because an early Tertiary normal polarity direction is similar to the direction of the present axial dipole field, the age of normal polarity directions cannot be unambiguously determined solely on the basis of non-random site directions. Site directions need to be evaluated in light of components of secondary magnetizations removed by the cleaning, which can indicate that a pre-present field direction is being revealed by the cleaning. The least ambiguous cases involve shifts in paleomagnetic direction toward a reversely polarized direction. This then leads to an heirarchal evaluation within which intervals of reverse polarity are considered more certain than intervals of normal polarity. However, the existence of interlayered polarities, particularly where the interlayering is broad and distinct, and the rock reasonably fine-grained and uniformly bedded, suggest that the included intervals of normal polarity reflect original magnetizations. If the cleaning is not entirely successful, some intervals of reverse polarity may remain marked by normal polarity overprinting.

Figures 7, 8, and 9 depict magnetostratigraphic plots of the Lands End, Elk Creek, and Truman Draw sections, respectively. Directional data have been converted to the latitude of the virtual geomagnetic pole (VGP). This provides an easily interpretable parameter for the determination of polarity because normal and reverse polarity latitudes ideally should fall in an interval of about 60^{o} to 90^{o}. In each of the three figures, large dots represent the site-mean VGP latitude for sites that are non-random at the 95 percent confidence level. Small dots are site means that are statistically random. Figure 7, the plot of the data from the Lands End section shows graphically the range of the resultant vector (R) and the site mean intensity of magnetization. Sites having the greater intensities of magnetization tend to have greater values of R; i.e., they are more tightly grouped. Arrows adjacent to the site mean VGP latitudes indicate the directions of movement upon partial AF demagnetization. Question marks are shown where the three samples for a site did not all move in the same general direction. Sites in which the directions exhibited no appreciable movement are not annotated. A preliminary polarity zonation for each of the three sections has been constructed employing the characteristics of behavior during partial demagnetization. The polarity columns are plotted adjacent to the data. Intervals of uncertain polarity are denoted by a crosshatched pattern.

Drill Core Sections

Polarity determinations of drill core samples have relied solely on inclination data because the cores were unoriented azimuthally. The expected early Tertiary inclination is $\pm 63^{\circ}$. Therefore, if the beds retain an appreciable stable component of magnetization of depositional origin, the difference in inclination between normal and reversely polarized strata is sufficient to permit identification of differing polarities. In the Powder River Basin, drill cores are to be preferred over surface exposures because they provide comparatively fresh rock, thereby ameliorating problems associated with weathering and magnetic overprinting in the present field. Nonetheless, despite the apparently unweathered character of the drill core samples secondary magnetizations were found in many samples. Some of these secondary magnetizations were only incompletely removed by partial AF demagnetization. Figures 10 and 11 are histograms of inclinations from the East Decker Mine (EDM) and White Tail Butte (WTB) cores, which represent sections correlated by field stratigraphic studies. The expected pattern of peaks, near $\pm 63^{\circ}$, is not well developed. Rather, a large number of samples of both intermediate and steeper inclinations are present. In the East Decker Mine data, the stepped distribution of shallow inclinations, ranging from -50° to $+40^{\circ}$, is interpreted to mainly represent reversely magnetized samples that contain unremoved secondary components of normal polarity magnetization. The White Tail Butte cores exhibit a similar spectrum of inclinations, but differ from the East Decker Mine cores in that there is a greater population of steep positive inclinations. This suggests that secondary overprinting in the present normal polarity field was more severe at the White Tail Butte section than in the East Decker Mine section.

Except for hole HWC-25, one sample was collected at each level in the cores, some on closely spaced stratigraphic intervals (e.g., hole HWC-27). Thus, internal consistency tests such as the test for randomness could not be carried out. However, a criterion for recognizing and giving less weight to the more unstably magnetized samples was employed. It utilizes the degree of apparent symmetry (or asymmetry) of magnetization within individual samples. In processing, six measurements are routinely obtained from each sample, the (+) and (-) directions of three orthogonal axes x, y, and z. A ratio of the apparent induced-to-remanent magnetization is calculated for each sample using the formula:

$$I/R = \left(\frac{ {\frac{Z + (-Z)}{2}}^{2} + {\frac{X + (-X)}{2}}^{2} + {\frac{Y + (-Y)}{2}}^{2} }{ {\frac{Z - (-Z)}{2}}^{2} + {\frac{X - (-X)}{2}}^{2} + {\frac{Y - (-Y)}{2}}^{2} } \right)^{1/2}$$

No actual induced magnetization is expected because the samples are measured in a very low (<5 gamma) magnetic field that is maintained in the sensing region of the magnetometer. The ratio of induced to remanent magnetization (I/R) under these conditions thus would measure the lack of magnetic symmetry within a sample. As seen from the measurement of large numbers of samples, I/R empirically appears to reflect the stability of magnetization. Multiple measurements of samples with I/R >.20 usually do not result in the same directions, indicating a lack of a stable magnetic moment in the sample. The more weakly magnetized samples commonly exhibit the greater ratios of I/R. Specimens that have I/R >.20 are shown as small dots on the stratigraphic plots of inclination from the cores, whereas specimens with I/R <.20 are shown as larger dots. The latter are inferred to be the more reliable recorders of the original inclinations.

Polarity Zonation--Identification of original directions of magnetization in the cores, as in the outcrop sections, ranges from probable to uncertain. The least ambiguous polarity zones are controlled by samples that appear to be clearly of reversed polarity, and by samples whose inclinations have shifted distinctly toward a negative or reversed inclination during cleaning. Where shifts from a positive toward a negative inclination were observed, small but distinct increases in intensity at a low peak demagnetizing field commonly also were observed. Such behavior results from the removal of a less stably held component of normal magnetization that counteracts and thus serves to diminish the intensity of an anti-parallel reversed magnetization. Intervals of reversed polarity recognized from such characteristics provide a framework for evaluating the validity of interlayered normal polarity directions. Because some normal polarity overprinting might still mask original reverse polarity directions even after cleaning, the zones of reverse polarity reported here probably represent minimum stratigraphic intervals of reversed polarity. Because of this, reverse polarity has been assigned to some intervals of *apparent* normal polarity where systematic shifts toward reversed polarity were observed during partial demagnetization.

The lithology of samples also was used to judge reliability of indicated polarity. Coarse deposits, such as sandstone in which chemical alterations may have taken place more readily, and in which coarse grained, less stable, multi-domain magnetite is likely to be found, were given less weight in constructing a polarity zonation than data from claystone and siltstone. Coal was found to be very weakly magnetized ($\leq 1 \times 10^{-8}$ emu/cm^3), and unstable, and data therefrom were given little weight.

The polarity zonations shown in Figures 12 through 16 are considered preliminary. The proposed zonations are our best interpretation in light of the available data and the reported uncertainties. Polarity zonations for the various cores shown in Figures 12-16 are discussed in paragraphs that follow.

Recluse area, Wyoming--Two cores from White Tail Butte, WTB-103 and -108, were drilled in the lowest stratigraphic interval of the Fort Union Formation cored during the time of this study. Data shown on Figure 12 reveal that although the holes were drilled only 3 km apart the determination of a polarity zonation and a correlation for the two cores is not straightforward. The lack of apparent correlation in polarity between stratigraphically overlapping parts of the two cores was not anticipated and should not have been the result of a lateral change in age of the strata. The poor definition of polarity zones in much of the two cores presumably results from a poor recording of the magnetic field, from the accidental and random inversion of some segments of the core, or from a combination of the two processes. Data from the interval just above the Pawnee coal bed in core WTB-103, for example, suggests that physical inversion is at least partly the cause because the inclination of adjacent samples oscillates from steep normal to steep reversed. The WTB cores were sampled early during our study, at a time before the drill and sampling crews had been alerted to exercise extreme care to assure maintenance of the up-directions of the core segments.

Hanging Woman Creek--Two cores, HWC-25 and HWC-27, penetrated about 100 m of strata from the Dietz thru the Waddle coal beds. Results are shown in Figure 13. In core HWC-25, three specimens were obtained from each sampled horizon to investigate the internal consistency of the magnetization. Directions in the three samples were found to be well grouped at many horizons, but at some horizons the directions were found to be scattered. Although the polarity zonation shown in Figure 13 is subject to revision, the interval of overlap of the two cores appears to agree (i.e., the interval of dominantly reversed polarity that contains a possible short normal zone about 5 m above the Anderson coal bed). This suggests stratigraphic reproducibility of the magnetization and a stable early magnetization for non-overlapping parts of the section.

East Decker Mine--Segments of two cores that penetrate the upper Fort Union Formation at the East Decker Mine were provided by Peter Kiewet and Sons Mining Company. Proper maintenance of the original up-direction orientations of the core segments was assured by a two-color core-scribing system that was employed as the core was extracted from the core barrel. Results from the East Decker Mine cores are shown in Figure 14. There is an overall agreement in the stratigraphy and magnetics, which was expected from sections one kilometer apart. Most of the apparent zones of normal polarity in both cores come from single core segments. Multiple samples from these segments confirmed the existence of single polarities. The stratigraphic consistency of the position of the normal polarity zones in both cores supports the existence and validity of the polarity zonation.

Western Recluse Model--Two cores were sampled that were drilled as part of the Western Recluse Model study area (WRM-1 and -2). Both cores penetrated about the same stratigraphic interval in the lower part of the Wasatch Formation. Data from the two cores indicate that the strata that were penetrated are nearly or entirely of reversed polarity (Fig. 15), indicating a general stability and reproducibility of magnetization, and thus validity of the polarity zonation.

Sheridan, Wyoming--One core (S-1) had been drilled by the the Branch of Engineering Geology, U.S. Geological Survey, prior to the initiation of this study. Before our sampling, the core had been cut into short segments and placed in glass jars. Apparently, many segments were inverted during this procedure because many alternating and steep, positive and negative inclinations were obtained from the segmented core. If the data are interpreted literally, about 30 changes in polarity would be represented, which is far too many for the 100 m of core and the narrow time range thought to be represented by the cored section. For this reason no paleomagnetic data are reported for the Sheridan core.

Buffalo, Wyoming--One core (B-1) had been drilled by the Branch of Engineering Geology, U.S. Geological Survey prior to this study. As for hole S-1, the core was cut into segments and placed in glass jars. Results for core B-1 are shown in Figure 16. Some of the data from this core are highly suspect (particularly in light of results from core S-1), the polarity record suggesting that some core segments were inverted during handling. However, data from the lower part of the core, below the Healy coal, exhibit a fair consistentency, suggesting a valid polarity.

Magnetostratigraphic Correlations

Magnetostratigraphic correlations can be made if polarity zonations obtained from the drill hole and outcrop sections can be demonstrated to reflect the polarity of the field during deposition. Although the present quantity as well as quality of data from the northern Powder River Basin precludes an overall and unambiguous correlation, some important parts of the polarity zonation appear reproducible on local and regional scales, and some provisional magnetostratigraphic correlations have emerged. Figure 17 depicts use of the polarity zonations for the individual core holes to construct a preliminary correlation diagram. The general poor magnetic quality of the outcrop sections has relegated their use to a supporting role, at best, for purposes of correlation.

The Paleocene Fort Union Formation is preponderantly reversely polarized. Although some intervals of reversed polarity are less firmly established than desired, the locations of several thin zones of normal polarity appear to correlate between sections. A very thin zone of normal polarity closely underlies the Anderson coal bed at the Hanging Woman Creek and East Decker Mine core sections, and also is seen at the Lands End and White Tail Butte outcrop sections. This zone of normal polarity within a general interval of reverse polarity appears to represent the same polarity zone, and if so, deposition of the Anderson coal in the region began at essentially the same time. A second thin zone of normal polarity closely overlies the Anderson coal at the Hanging Woman Creek and White Tail Butte sections.

Two zones of normal polarity are found near the top of the Fort Union Formation at the Hanging Woman Creek section and also are found at the same general stratigraphic position at the Lands End outcrop section. The Smith coal at Lands End is within the lower interval of normal polarity, whereas at Hanging Woman Creek the top of the Smith coal is above the interval of normal polarity. This suggests that the upper part of the Smith coal is younger at Hanging Woman Creek than at Lands End. Southwest of Hanging Woman Creek a normal polarity zone at the top of the East Decker Mine section may correlate with the normal polarity zone beneath the Smith because both appear to lie about the same distance above the Anderson coal. Our preliminary study thus suggests that the major coal beds in the upper part of the Fort Union Formation in the northern Powder River Basin are broadly contemporaneous, but locally there is evidence for deposition in a time-transgressive environment.

Paleomagnetic data from the Eocene Wasatch Formation provide new data bearing on the regional correlation of coal beds. The very thick Healy coal bed near Buffalo has been correlated by Glass (1976, Fig. 3) with the ULM-2 coal of the Ulm area in the central basin. In the Recluse area the Ulm-2 of Olive (1957) has been shown to split into the Truman and Parnell coal beds

(Haddock and others, 1976, and Kent and others 1977). The Truman and Parnell coals are at the top of a thick zone of reversed polarity, whereas the Healy overlies (and contains) a zone of normal polarity, which in turn overlies a reversed polarity zone of unknown thickness (Figure 17). The Healy coal (Ulm-2 of Ulm area) thus does not correlate with the Truman-Parnell coal (Ulm-2 of Recluse area). We propose (Figure 17) that the Healy is younger than the Truman-Parnell, because the polarity structure above the Healy does not appear to correlate with that beneath the Truman-Parnell. This conclusion has since been arrived at independently by B. H. Kent, (written comm., 1981), who by means of geologic mapping, found the Truman Coal to lie about 200' below the Healy (Ulm-2) coal.

Correlation with Polarity Time Scale

A preliminary composite polarity zonation is proposed from the sections studied (Figure 17). For comparison, the polarity time scale of LaBrecque and others (1977), as recalibrated by Mankinen and Dalrymple (1979), is shown for the time interval 65 to 50 m.y. (lower Paleocene to middle Eocene). We here review information bearing on the age of the Fort Union and Wasatch Formations before considering possible correlations with the polarity time scale. Included are paleontologic control, and a deposition rate that has been estimated from another early Cenozoic terrestrial basin.

The only diagnostic fossils from the stratigraphic intervals studied are vertebrates reported from the lower Wasatch Formation. Two vertebrate localities have been found at different stratigraphic levels above the contact of the Fort Union and Wasatch Formations. Delson (1971) reported an earliest Eocene fauna from about 90 m above the contact. Culbertson and Mapel (1976) cite a communication from G. E. Lewis who identified vertebrates from the Burgess coal zone (230 m above the contact of the Fort Union and Wasatch Formations) as being from the early part of the early Eocene. Tschudy (1977) suggests that the palynological boundary between the Paleocene and Eocene occurs within about 30 m beneath the Felix coal, a level somewhat higher than the boundary that commonly is drawn between the Fort Union and Wasatch Formations. No diagnostic fossils have been reported from the Tongue River Member of the Fort Union Formation in the area of study. However, vertebrate fossils found elsewhere suggest a middle to late Paleocene age (Leffinqwell, 1966, p. 19). The age of the Tongue River Member, based on pollen analysis, is reported only as Paleocene (Leffinqwell, 1966).

An approximate duration of time represented by the approximately 500 m of section studied in the northern Powder River Basin can be estimated by assuming a sedimentation rate similar to that obtained from another late Cretaceous-early Cenozoic terrestrial sedimentary basin of the western interior. Butler and others (1980) report a polarity zonation that has allowed an average sedimentation rate of 80 m/m.y. to be calculated for Late Cretaceous and Paleocene strata of the San Juan Basin, New Mexico. Extrapolation of this rate to the Powder River Basin results in an estimation of about 6 m.y. for deposition of the Paleocene and Eocene section studied. Deposits of the Fort Union Formation, about 290 m thick, would represent about 3.5 m.y. Because the unconformity between the Fort Union and Wasatch Formations may represent a significant hiatus, the interval of time required for the deposition of the section studied could be appreciably greater than 6 m.y. A minimum duration of 1 m.y. for the hiatus is estimated from the 60 meters of uppermost Fort Union strata absent and presumably truncated in the eastern sections. The length of the inferred hiatus between the Fort Union and Wasatch Formations can be estimated if reasonable correlations can be made for the two units with different parts of the polarity time scale.

The polarity zonation for the Fort Union Formation appears characterized by dominantly reversed polarity containing zones of normal polarity near the base and top. Based on a visual best fit, the normal polarity zone at the base is provisionally correlated with marine magnetic anomaly 26. (We emphasize, however, that the polarity data from the lower parts of the White Tail Butte cores, which are the sole control for the zonation, are of poor quality, and that the proposed correlation with the time scale thus is very tentative.) An apparent interval of dominantly normal polarity in the middle Fort Union section then would correlate with anomaly 25, and the better established interval of dominantly reversed polarity above would presumably represent the interval between anomalies 25 and 24. Two possible very short duration normal polarity intervals are present within this reversed interval, which may correlate with the thin normal polarity zones in the Fort Union. The two-fold zone of normal polarity near the top of the Fort Union Formation then presumably would correlate with anomaly 24. A sedimentation rate of about 55 m/m.y. is derived from this correlation, shown in Figure 17. This deposition rate is plausible although somewhat less than that which has been estimated for the San Juan Basin. Alternatively, if the dominantly normal polarity zones at the base and top of the Fort Union section are correlated with anomalies 25 and 24, a calculated sedimentation rate of 83 m/m.y. would be obtained, which could be in closer agreement with the rate estimated for the San Juan Basin. Such a correlation, however, requires that the comparatively thick zone of normal polarity in the middle of the Fort Union is a result of overprinting. Additional magnetostratigraphic control is needed across this interval.

The polarity zonation for strata of the lower Wasatch Formation is poorly defined. As a consequence, only a highly provisional correlation can be proposed with the polarity time scale at this time. The long interval of reversed polarity obtained from the Western Recluse Model and Truman Draw sections is inferred to correlate with the long interval of reversed polarity that overlies anomaly 23 in the early Eocene. The mixed polarity in the Buffalo core section, which includes a prominent interval of reversed polarity, then would correlate with the succeeding part of the polarity time scale for the Eocene, one that includes anomaly 22 and extends into anomaly 21. The two thin zones of normal polarity in the upper half of core B-1 thus may correlate with two thin zones of normal polarity above anomaly 22.

The foregoing tentative correlation indicates that the Wasatch section studied was deposited in the interval from about 55.5 m.y. to 52 m.y. ago. Such a time span would result in an estimated sedimentation rate of about 55 m/m.y. for the 190 m of section, the same rate that has been provisionally derived for strata of the upper Fort Union Formation.

Correlations with the polarity time scale proposed for the Fort Union and Wasatch Formations (Figure 17) imply that anomaly 23 is missing. This situation results if a section of rock recording a time span of about 1 m.y. had not yet been sampled, agreeing with the minimum length of an hiatus calculated from the thickness of strata known to be missing. Alternatively, a greater hiatus may exist at the unconformity. No drill core section studied spans the stratigraphic interval, which to the west represents at least part of the time interval in question. Such a section is needed to help establish or to modify the magnetostratigraphic framework that is proposed in Figure 17. Some strata that appear to bridge the gap in the magnetic data are exposed near and above the Lands End (LE) section. However, these outcropping beds are deemed poorly suited for magnetostratigraphy on the basis of composition, grain size, and degree of weathering. A generalized lithologic section from these intermediate beds, measured by B. H. Kent (1980, written communication), has been added adjacent to the Lands End magnetostratigraphic section to portray the physical stratigraphy in the Recluse area. The stratigraphy in the Recluse area serves as a tie point for stratigraphic correlations in the northern Powder River Basin. The base of the Wasatch at Lands End is drawn at the base of the thick aeolian sandstone which all workers agree is Wasatch. A thicker lower Wasatch section is exposed to the west along the Powder River, where it consists of finer grained deposits. These strata presumably contain some, if not much, of an apparently unsampled polarity record associated with and adjacent to anomaly 23.

Butler and others (in press) are proposing that the position of the Paleocene- Eocene boundary in the polarity time scale should be lowered and placed in an interval of reversed polarity between anomalies 25 and 24. This would have the effect in the correlations shown in Figure 17 of placing into the Eocene, beds of the Fort Union that are well below the currently accepted Fort Union-Wasatch contact. Moreover, strata of the lower Wasatch for which a very early Eocene age locally has been assigned from fossil vertebrates also would appear to be at variance with such a revision. We thus are retaining and employing the modified time scale of LaBrecque and others (1977) pending additional work in the Powder River Basin and in other Cenozoic basins of the West.

SUMMARY

Salient results of this study are:

1) The sedimentary strata are for the most part very weakly magnetized. Stable magnetizations are found in the finest grained, non-coaly rocks. Coal of the northern Powder River Basin is generally unstably magnetized, and the instability appears to reflect the presence of sulfides that presumably formed in highly reducing environments of deposition.

2) In some surface exposures, weathering has degraded the quality of the stable remanence, and present field overprints are removed with difficulty, if at all. Secondary magnetizations presumably reside in hematite or hydrated ferric oxide derived from the oxidation of magnetite and/or sulfides.

3) For the Fort Union Formation, correlations between sections based on polarity generally support the previous stratigraphic correlations. In the Wasatch Formation a recently proposed revision to the correlation of some coal-bearing strata is supported by the polarity data; the Healy coal (Ulm-2) of the Buffalo and Ulm areas is distinctly younger than the Truman-Parnell Coal (Ulm-2) of the Recluse area.

4) Correlation of a preliminary composite polarity zonation with the polarity time scale suggests that the upper Fort Union and lower Wasatch Formations were deposited in the time interval from about 62 to 52 m.y. age (marine magnetic anomalies 26 to 21). A polarity record for about 1 m.y. of time (from about 57 to 56 m.y.) appears unrecorded in the sections studied, arising in part from unsampled strata in the uppermost Fort Union and lowermost Wasatch Formations, and perhaps also in part from an hiatus at an unconformity that at least locally separates the formations. The Paleocene-Eocene boundary in the northern Powder River Basin, on the basis of field stratigraphy, lies within the unsampled interval and appears to generally accord with the boundary assigned to the polarity time scale of LaBrecque and others (1977). If the boundary in the polarity time scale is lowered following the suggestion of Butler and others (1981), strata of the upper Fort Union Formation would be of early Eocene age.

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FIGURE CAPTIONS

Figure 1.--Index map of northern Powder River Basin, showing locations of drill holes and surface outcrops sampled for this study.
WRM 1, T 52N, R 74 W, Sec 6; WRM 2, T 53 N, R 75 W, Sec. 11; Lands End, T 56 N, R 75 W, Sec. 4; Truman Draw Quadrangle, T 53 N, R 74 W, Sec. 7; Elk Creek, T 56 N, R 71 W, Sec. 19; WTB-108, T 56 N, R 73 W, Sec. 24; WTB-103, T 56 N, R 72 W, Sec. 31; EDM-1727, T 9 S, R 40 E, Sec. 13; EDM-1726, T 9S, R 41 E, Sec. 18; B-1, T 51 N, R 82 W, Sec. 35; HWC-25, T 9 S, R 44 E, Sec. 7; HWC-27, T 9 S, R 43 E, Sec. 14.

Figure 2.--Coal bed stratigraphy in north-central Powder River Basin showing approximate stratigraphic intervals penetrated by drill cores and studied from surface sections.

Figure 3.--Plot of normalized intensity of magnetization versus peak alternating demagnetization field for 12 samples from drill cores WTR-103 and -108. Error bar represents $\pm$ 1 about mean values.

Figure 4.--Equal area stereographic plots of site mean direction of magnetization for sample sites from Lands End section; a) NRM, and b) 200 oe. A = axial dipole field direction. P = expected Paleocene's field direction calculated for latitude and longitude of Powder River Basin, using poles of Butler and Taylor, 1978, Diehl and others, 1978, and Shive and Pruss, 1977.
Solid symbols--lower hemisphere; open symbols--upper hemisphere.

Figure 5.--Equal area stereographic plots of individual sample directions of magnetization for two sites for Lands End section, showing direcitonal changes upon partial alternating field demagnetization. Numbers indicate peak alternating field values.

Figure 6.--Equal area stereographic plot of directions of magnetizations during progressive alternating field demagnetization for three samples from Lands End Site No. 1.

Figure 7.--Generalized lithologic column for Lands End section and stratigraphic plots of site-mean latitudes of the interval geomagnetic pole (VGP), length of resultant vectors and intensities of magnetization. Dashed line on length of resultant vector plot separates statistically random site (R <2.62, small dots) from statistically non-random sites (R >2.62, large dots). Arrows adjacent to site-mean VGP's reflect directions and amount of movement produced by AF demagnetization. Black-normal polarity; white-reversed polarity; diagonal pattern-indeterminate.

Figure 8.--Generalized lithologic column and stratigraphic plot of site mean VGP latitude for the Elk Creek section. See Figure 7 caption for explanation of symbols.

Figure 9.--Generalized lithologic column and stratigraphic plot of site mean VGP latitudes for the Truman Draw section. See Figure 7 caption for explanation of symbols.

Figure 10.--Histogram showing distribution of sample inclinations for White Tail Butte cores WTB-108 and -103, following AF demagnetization at 200 oe.

Figure 11.--Histrogram showing distribution of sample inclinations for East Decker Mine cores EDM 1726 and 1727 (combined), following AF demagnetization at 200 oe.

Figure 12.--Generalized lithologic section, stratigraphic plot of inclinations and apparent polarity zonation for White Tail Butte cores WTB-103 and -108. Large dots represent samples with I/R <.20; small dots I/R >.20. Arrows adjacent to inclination values represent direction and amount of movement upon AF demagnetization for samples that displayed changes $\geq 5^{o}$. Black (white) bars represent intervals of apparent normal (reversed) polarity; diagonal pattern represents intervals in which polarity is indeterminate as a result of either large gaps in sample spacing or data that cannot be unambiguously assigned to either polarity.

Figure 13.--Generalized lithologic section, stratigraphic plot of inclinations, and apparent polarity zonation for Hanging Woman Creek cores HWC 25 and 27. Symbols as in Figure 12.

Figure 14.--Generalized lithologic section, stratigraphic plot of inclinations and apparent polarity zonation for East Decker Mine cores EDM-1726 and -1727. Symbols as in Figure 12.

Figure 15.--Generalized lithologic section, stratigraphic plot of inclinations and apparent polarity zonation for Western Recluse Model cores WRM land 2. Symbols as in Figure 12.

Figure 16.--Generalized lithologic section, stratigraphic plot of inclinations and apparent polarity zonation from Buffalo core B-1. Symbols as in Figure 12.

Figure 17.--Proposed correlations, based on coal beds and polarity zonations, of the drill cores and outcrop sections investigated. Composite polarity zonation constructed using data considered most reliable. Proposed correlation of composite polarity zonation with polarity time scale of LaBrecque and others (1977) modified slightly from Mankinen and Dalrymple (1979) shown at right. Section R represents typical lowermost Wasatch Formation section in Recluse, Wyoming, area.

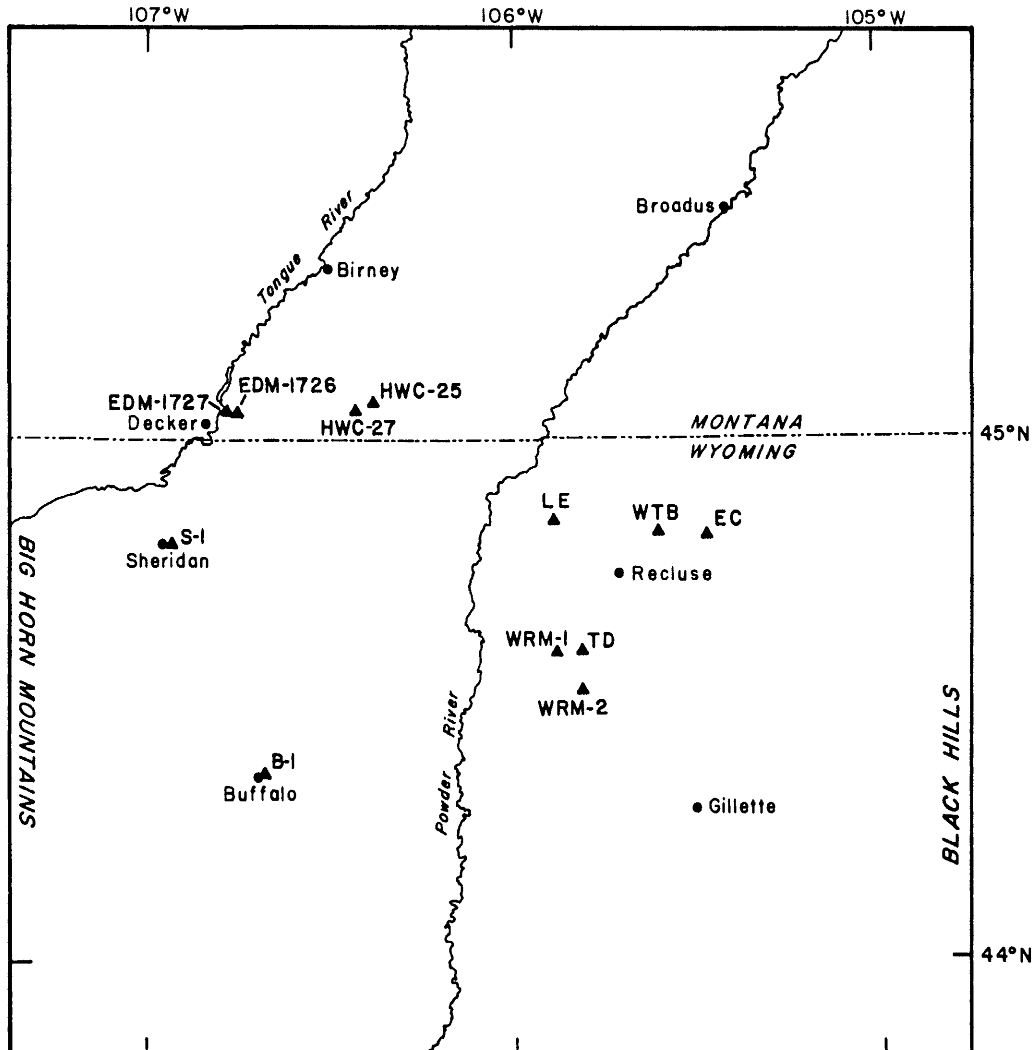

107°W
106°W
105°W
45°N
44°N
Tongue
River
Birney
Broadus
EDM-1727
EDM-1726
HWC-25
HWC-27
Decker
MONTANA
WYOMING
LE
WTB
EC
S-1
Sheridan
Recluse
WRM-1
TD
WRM-2
Powder
River
B-1
Buffalo
Gillette
BIG HORN MOUNTAINS
BLACK HILLS

Fig. 1

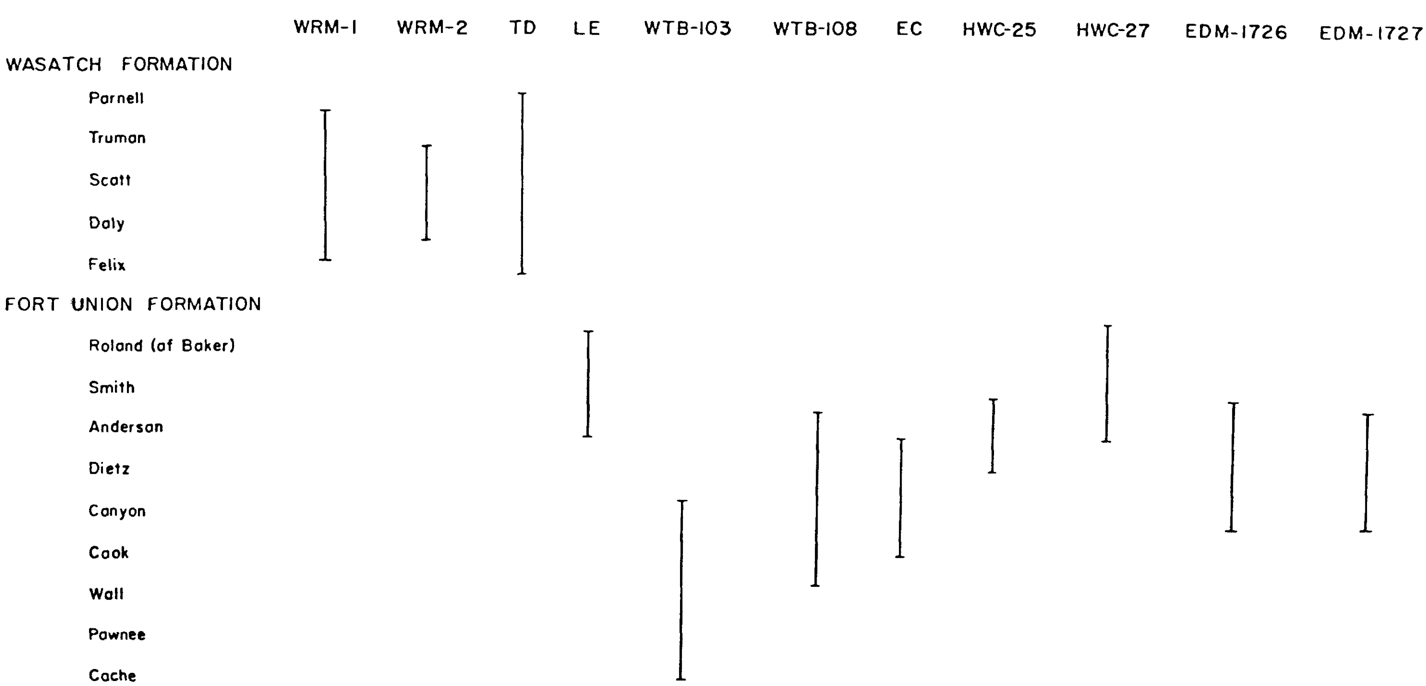

WRM-1
WRM-2
TD
LE
WTB-103
WTB-108
EC
HWC-25
HWC-27
EDM-1726
EDM-1727
WASATCH FORMATION
Parnell
Truman
Scott
Daly
Felix
FORT UNION FORMATION
Roland (of Baker)
Smith
Anderson
Dietz
Canyon
Cook
Wall
Pawnee
Cache

Fig. 2

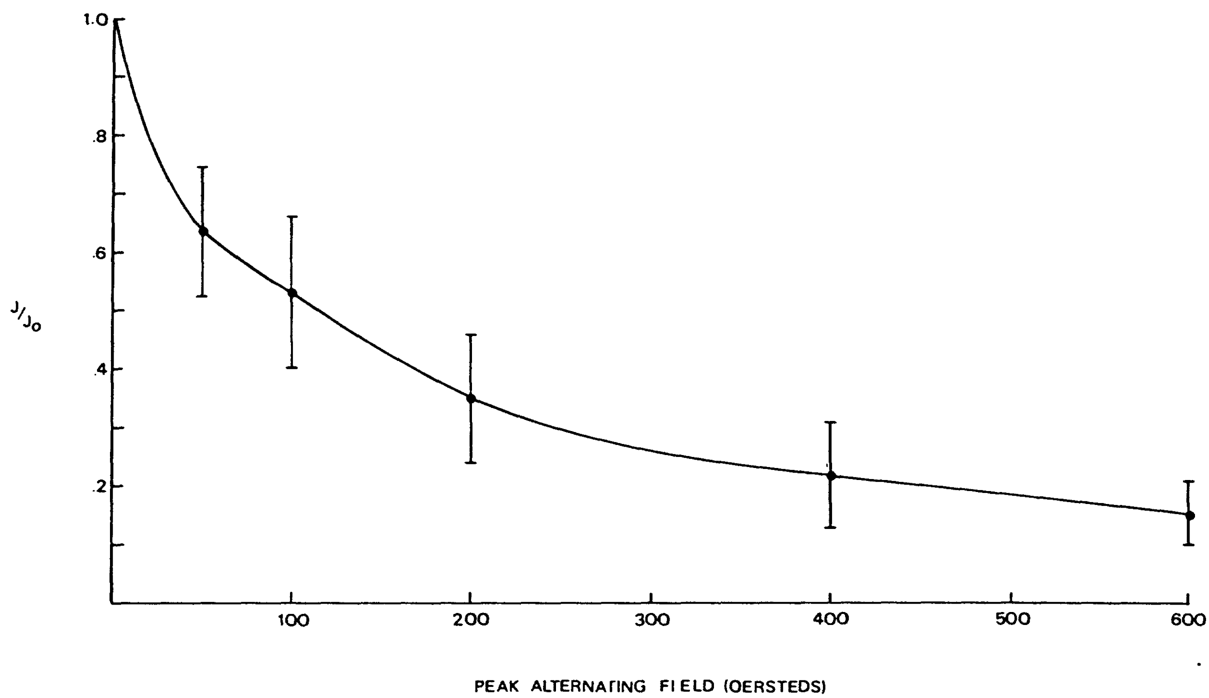

1.0
.8
.6
.4
.2
J/Jo
100
200
300
400
500
600
PEAK ALTERNATING FIELD (OERSTEDS)

Fig. 3

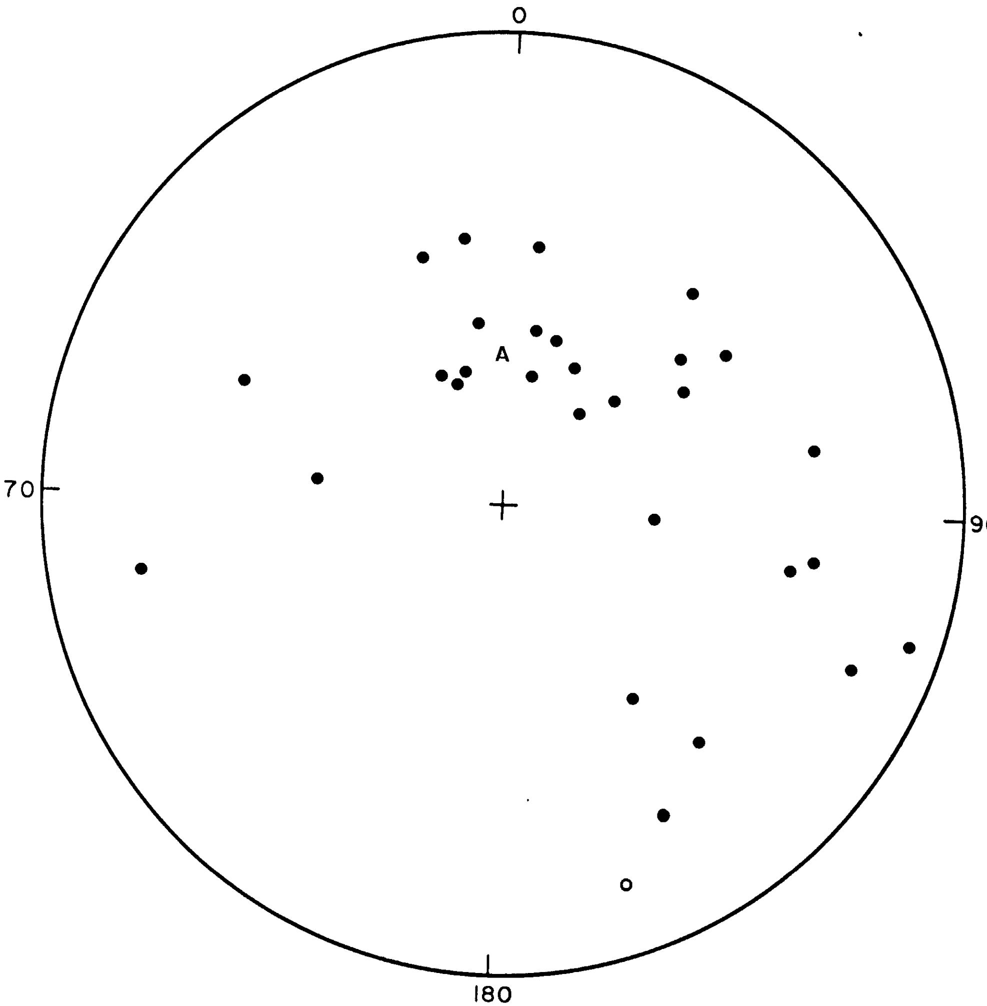


Fig. 4a

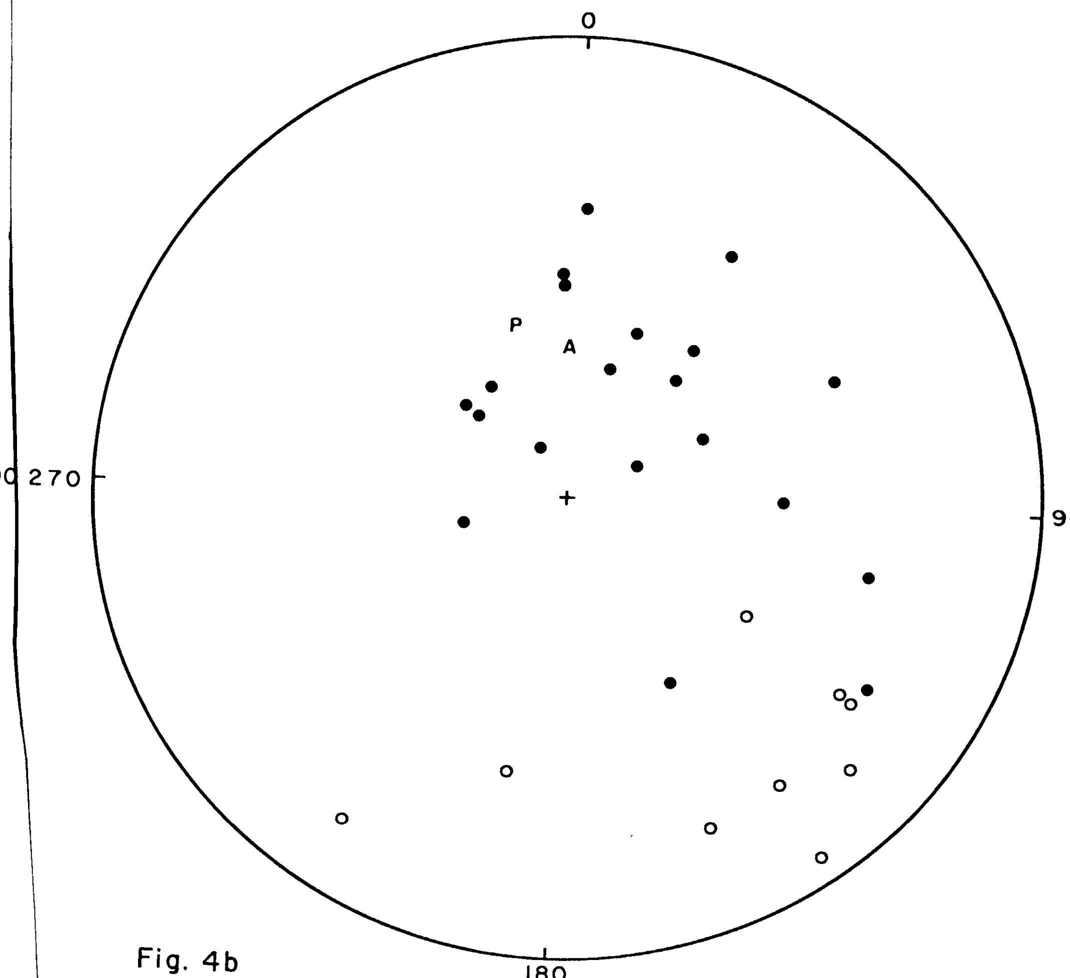


Fig. 4b

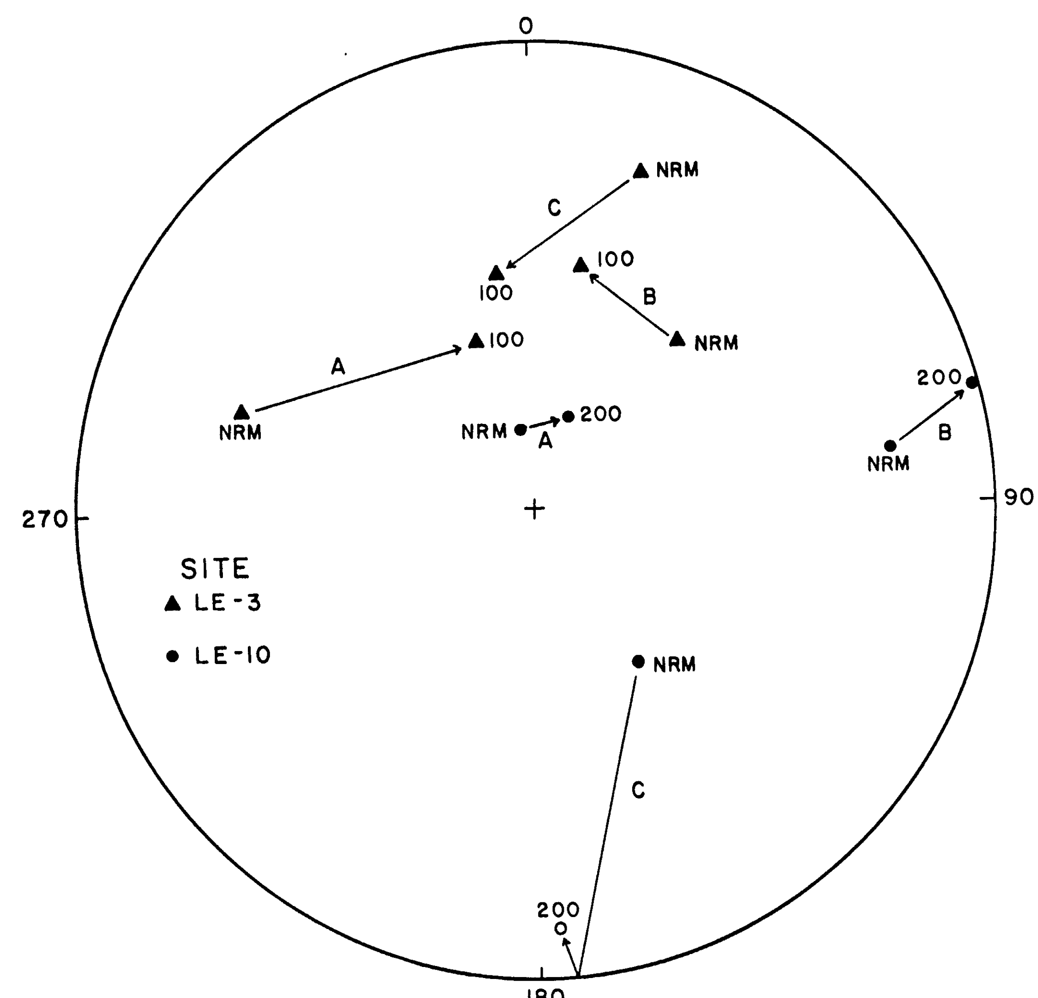
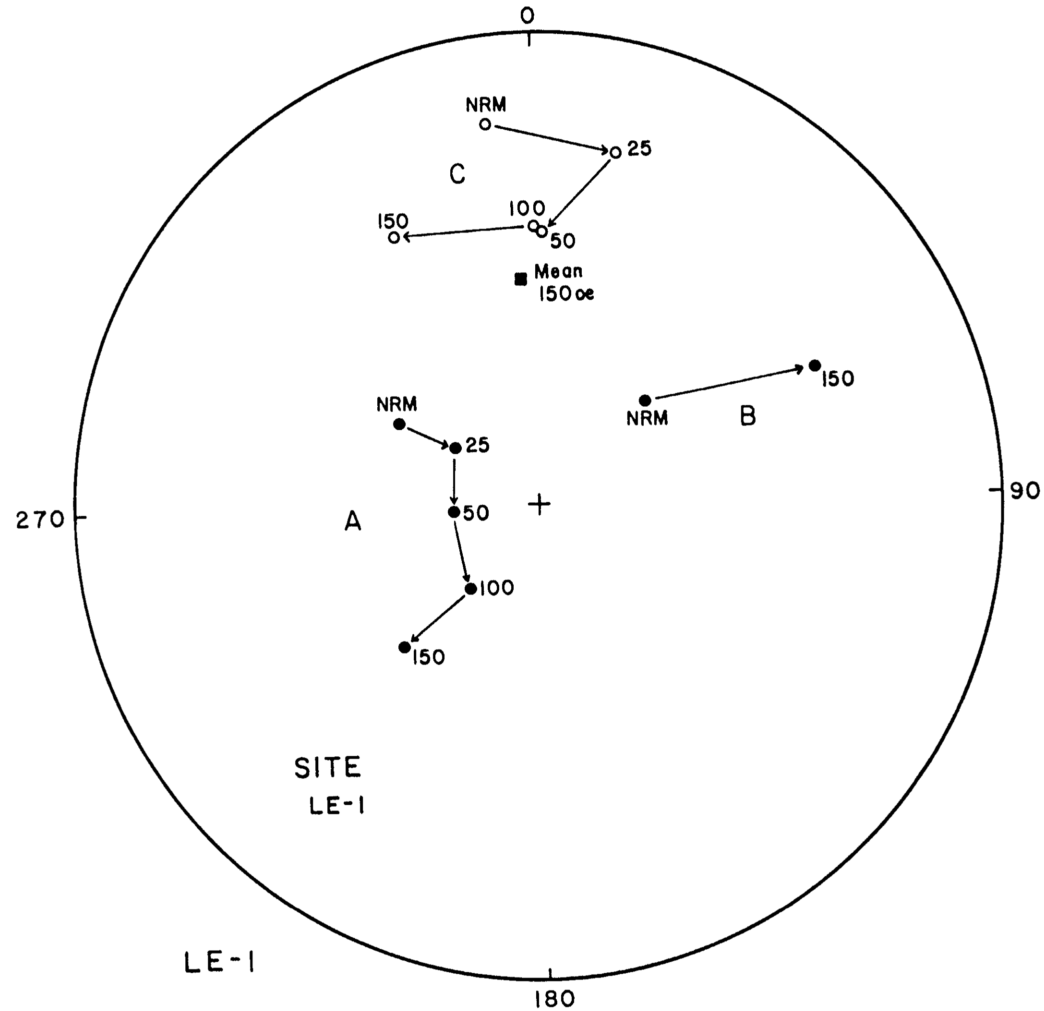
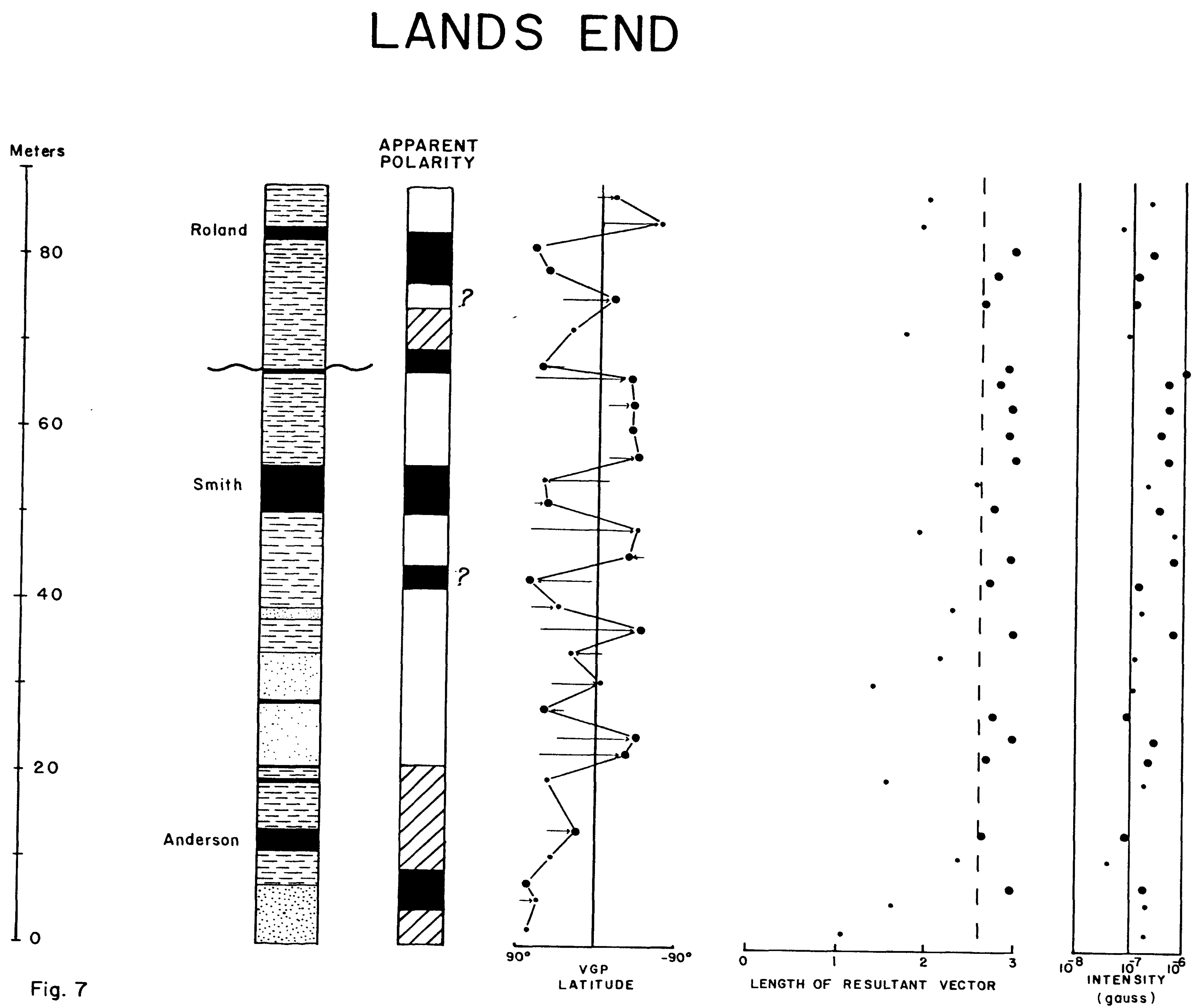

0
90
180
270
NRM
C
100
100
B
NRM
A
100
NRM
NRM
200
A
200
NRM
B
SITE
LE-3
LE-10
NRM
C
200

Fig. 5


0
90
180
270
NRM
25
C
100
150
50
Mean
150 oe
NRM
B
150
NRM
25
A
50
100
150
SITE
LE-1

LE-1

Fig. 6



LANDS END
Meters
80
60
40
20
0
Roland
Smith
Anderson
APPARENT
POLARITY
?
?
90°
-90°
VGP
LATITUDE
0
1
2
3
LENGTH OF RESULTANT VECTOR
10^{-8}
10^{-7}
10^{-6}
INTENSITY
(gauss)

Fig. 7

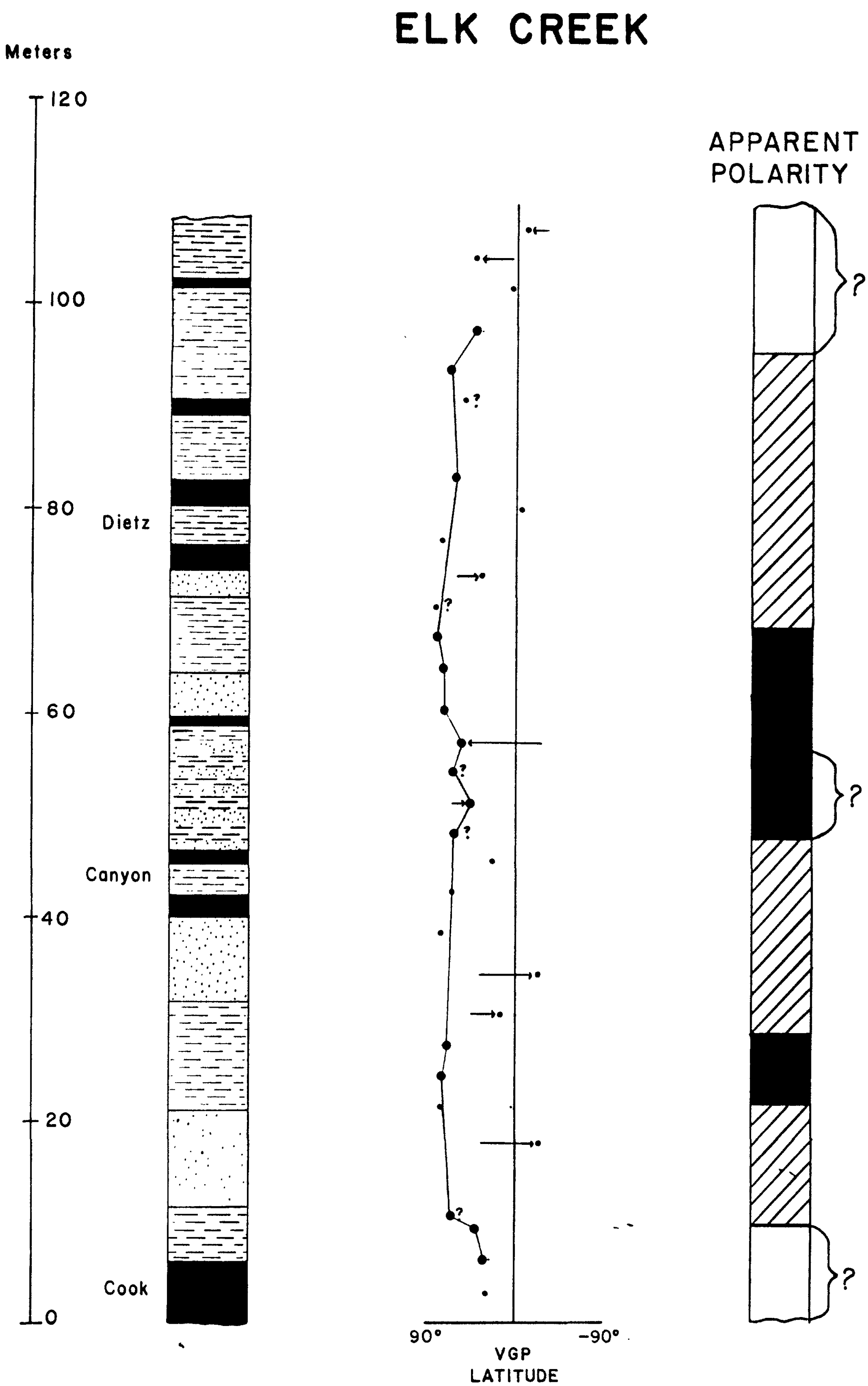

ELK CREEK
Meters
120
100
80
60
40
20
0
Dietz
Canyon
Cook
90°
-90°
VGP
LATITUDE
APPARENT
POLARITY
?
?
?

Fig. 8

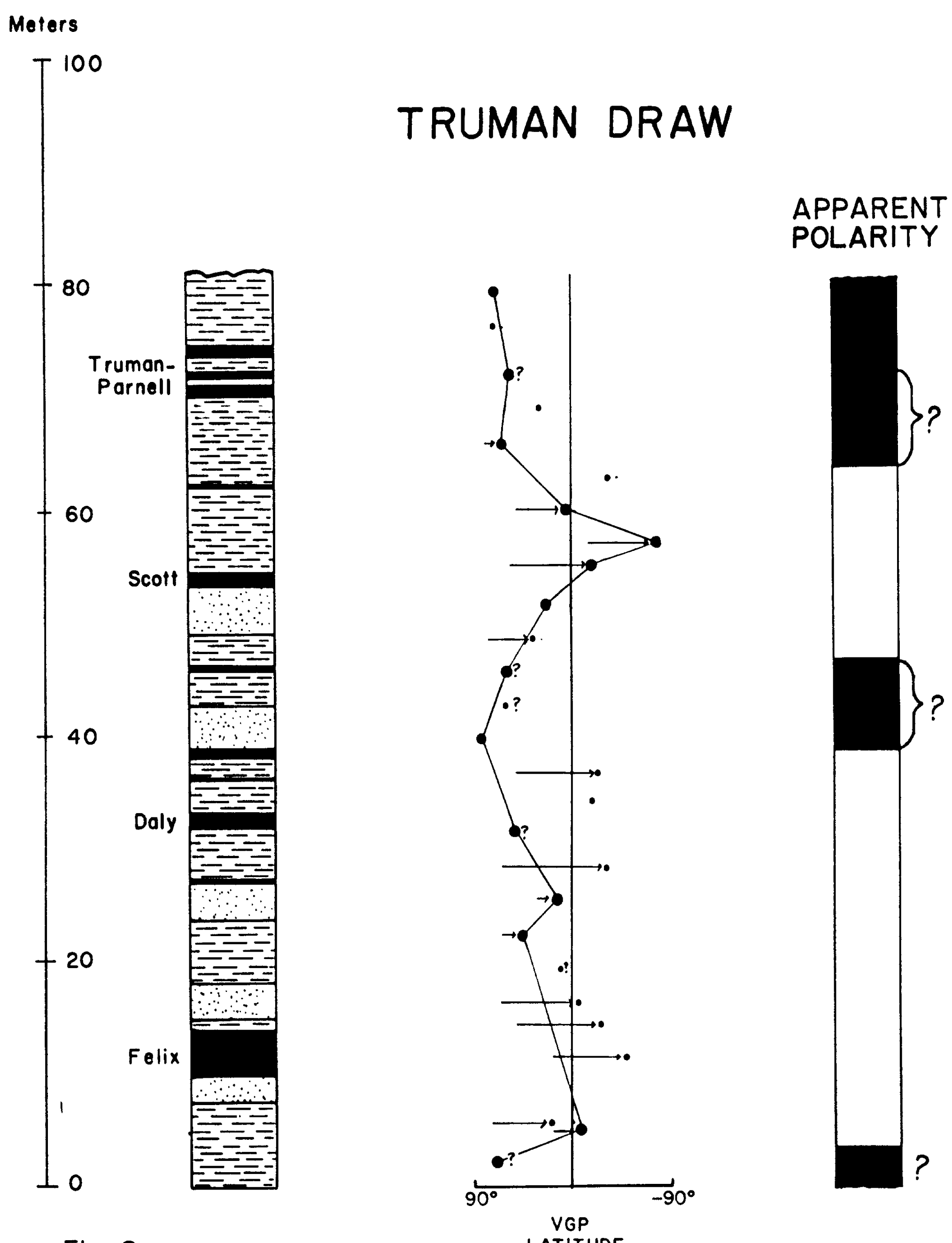
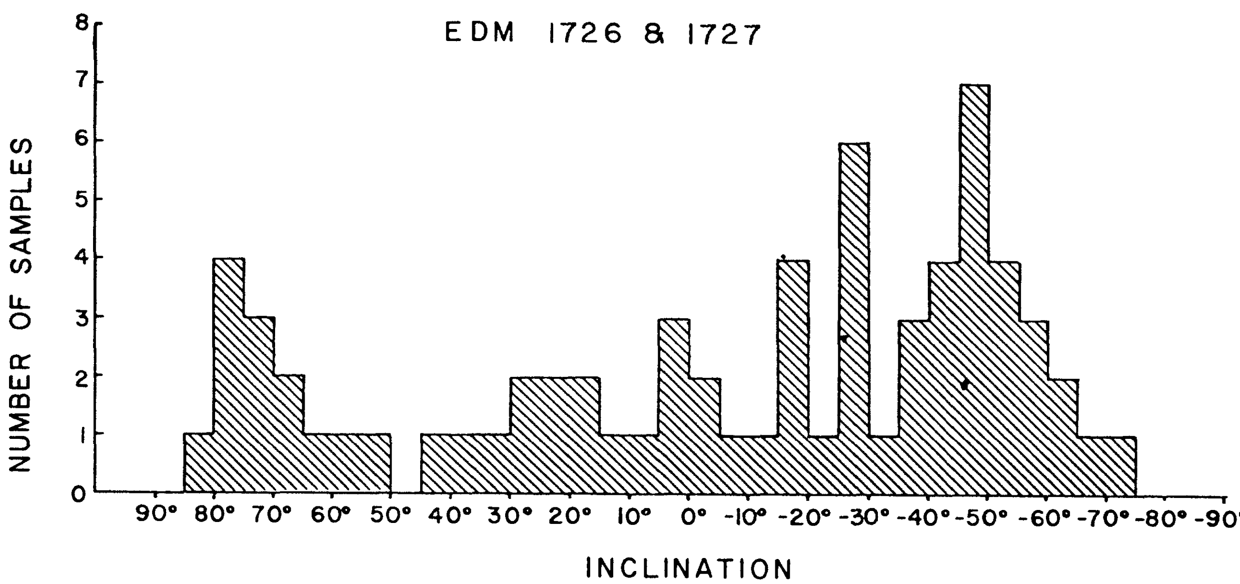

TRUMAN DRAW
Meters
100
80
60
40
20
0
Truman-
Parnell
Scott
Daly
Felix
90°
-90°
VGP
LATITUDE
APPARENT
POLARITY
?
?
?

Fig. 9


EDM 1726 & 1727
NUMBER OF SAMPLES
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1
2
3
4
5
6
7
8
90° 80° 70° 60° 50° 40° 30° 20° 10° 0° -10° -20° -30° -40° -50° -60° -70° -80° -90°
INCLINATION

Fig. 10

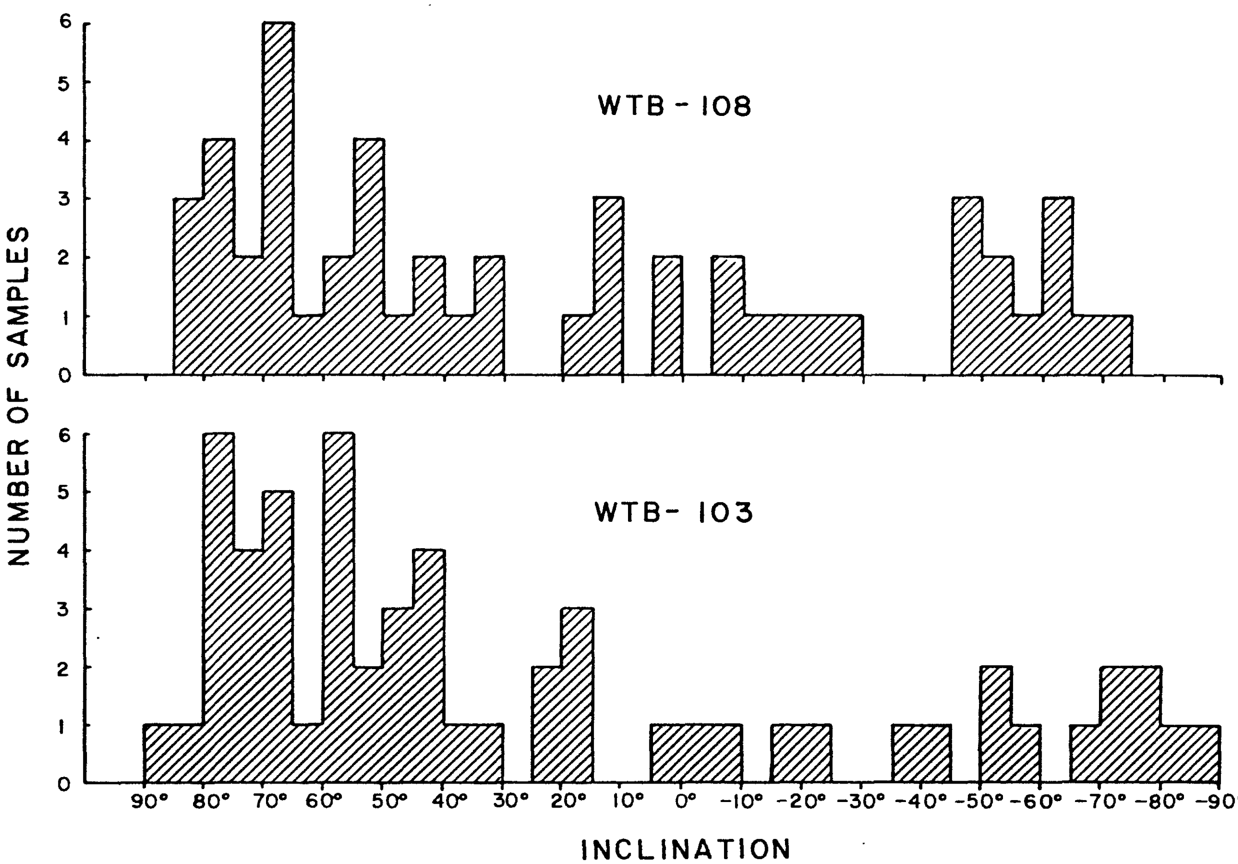
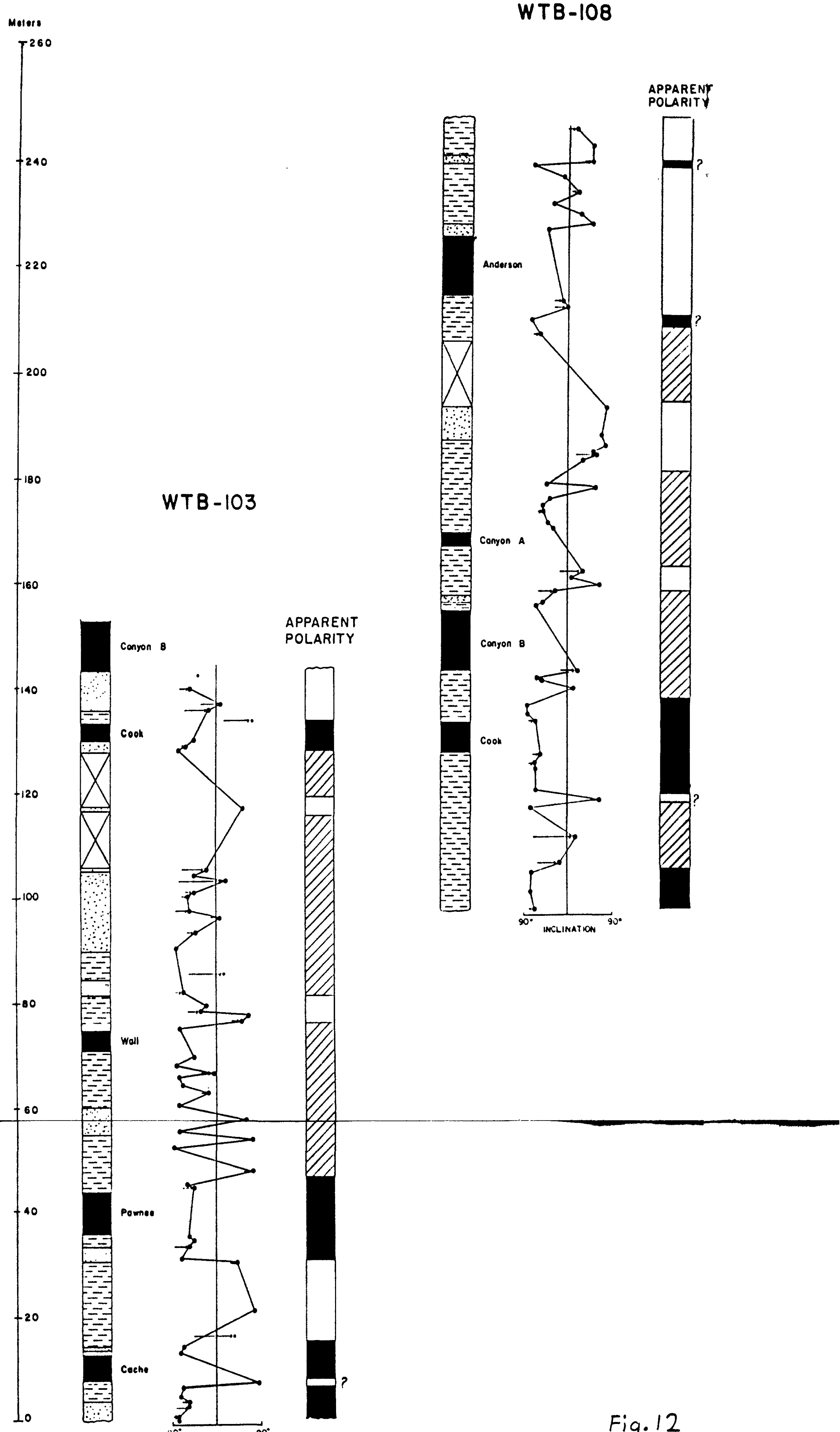

NUMBER OF SAMPLES
WTB - 108
WTB- 103
0
1
2
3
4
5
6
90° 80° 70° 60° 50° 40° 30° 20° 10° 0° -10° -20° -30° -40° -50° -60° -70° -80° -90°
INCLINATION

Fig. 11



Meters
260
240
220
200
180
160
140
120
100
80
60
40
20
0
WTB-103
Canyon B
Cook
Wall
Pawnee
Cache
APPARENT POLARITY
WTB-108
Anderson
Canyon A
Canyon B
Cook
90°
INCLINATION
90°
APPARENT POLARITY
?

Fig. 12

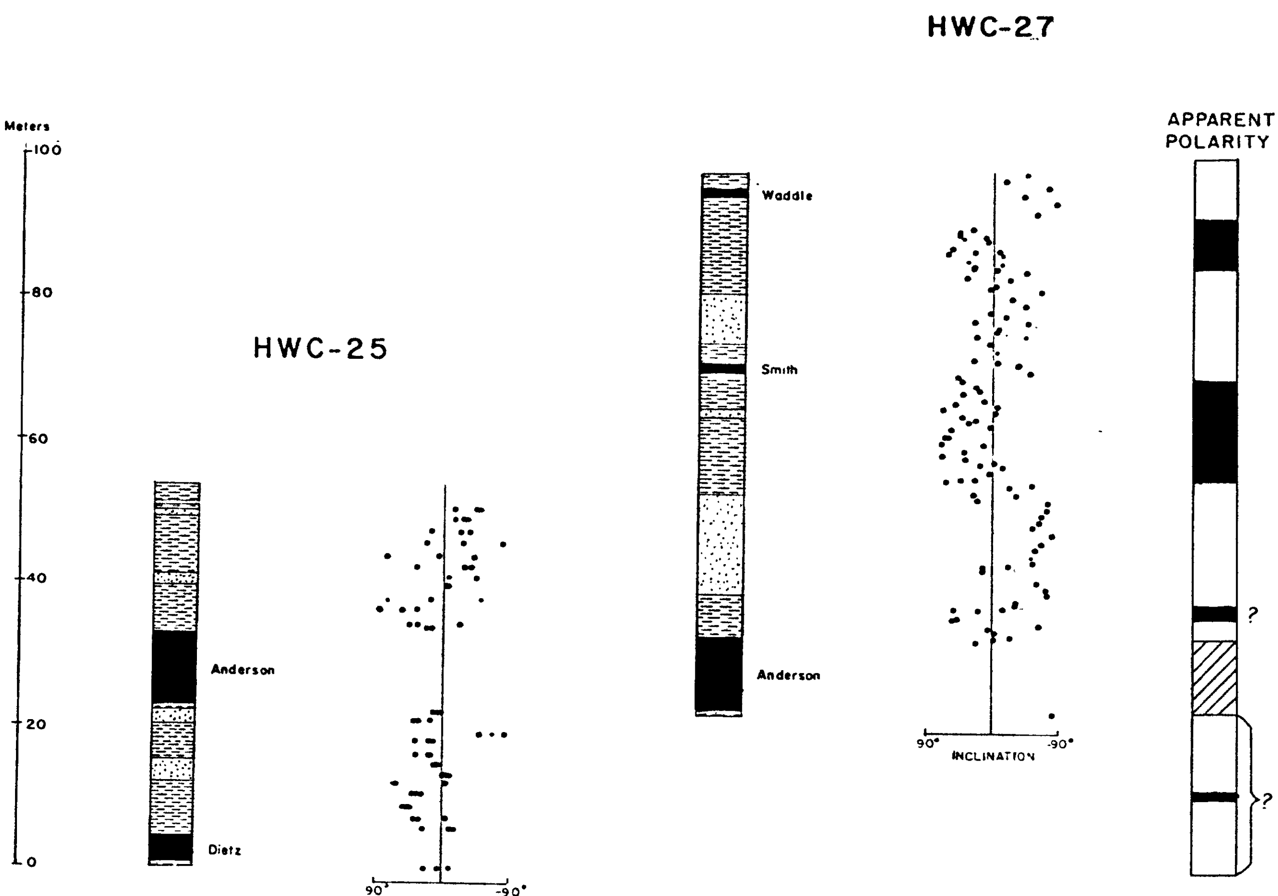

Meters
100
80
60
40
20
0
HWC-25
Anderson
Dietz
90°
-90°
INCLINATION
HWC-27
Waddle
Smith
Anderson
90°
-90°
INCLINATION
APPARENT POLARITY
?
?

Fig. 13

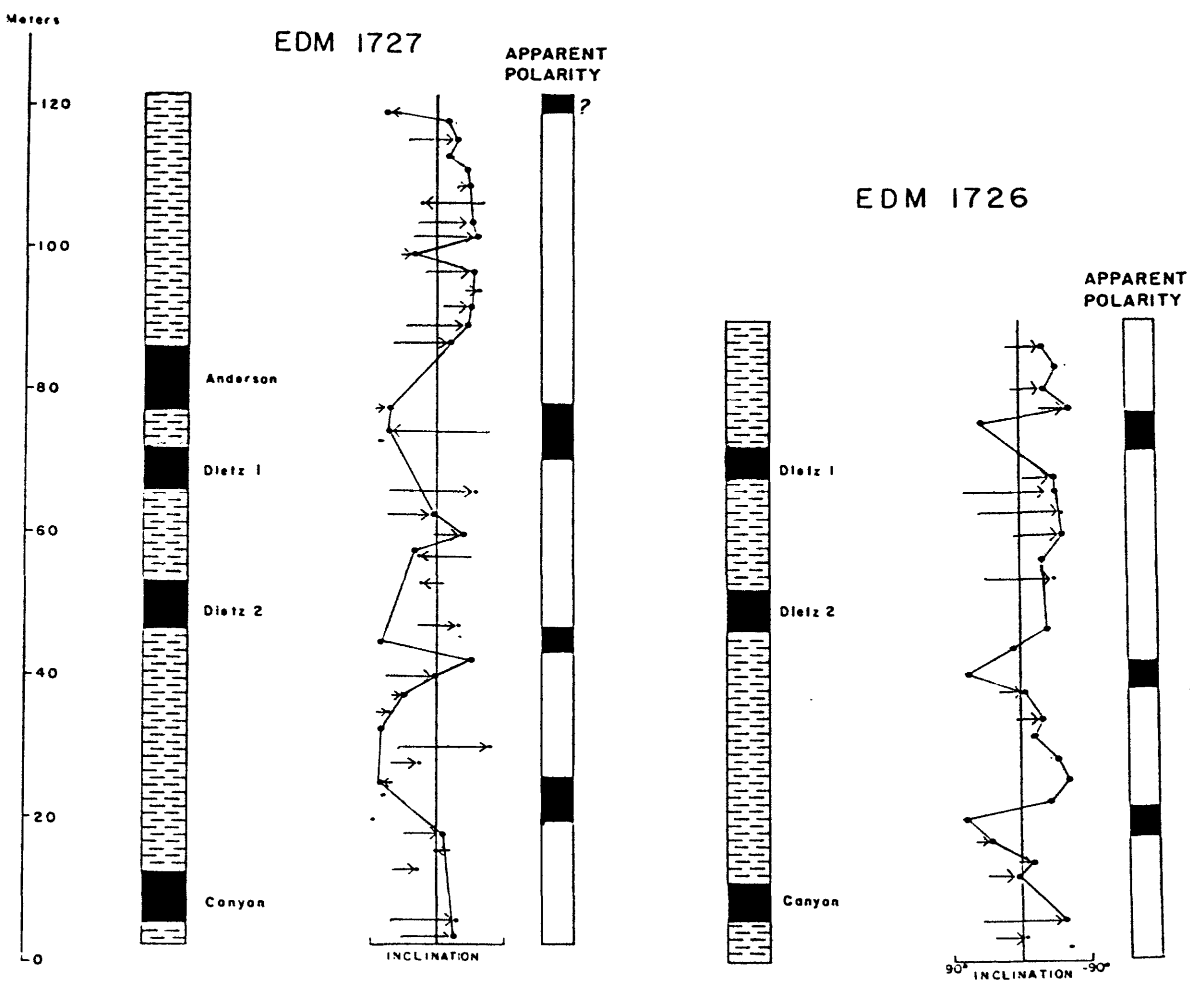

Meters
120
100
80
60
40
20
0
EDM 1727
APPARENT
POLARITY
?
Anderson
Dietz 1
Dietz 2
Canyon
INCLINATION
EDM 1726
APPARENT
POLARITY
Dietz 1
Dietz 2
Canyon
90°
INCLINATION
-90°

Fig. 14