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FURTHER TESTS OF THE PALEOMAGNETIC CORE-ORIENTING TECHNIQUE

By

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INTRODUCTION

In a previous study (Van Alstine and Gillett, 1980), we explored the feasibility of using paleomagnetism to orient drill core from the Mesaverde Formation. That investigation involved paleomagnetic analysis of 173 plugs obtained from corehole CA-77-2 in the southern Piceance Creek Basin, Colorado. During that study, it became apparent that the presumably Cretaceous fossil magnetization was being distorted by a drilling-induced magnetization pointing almost directly down-hole. Moreover, the scatter of magnetization directions was greater than had been anticipated, limiting the precision of the paleomagnetic orienting technique. Since the core from CA-77-2 had not been conventionally oriented (using the multi-shot camera/compass system with a Monel collar), there was no check on the accuracy of the paleomagnetic orientations.

The purposes of the present investigation were to (1) determine whether using the non-magnetic Monel collar would eliminate the drilling-induced remagnetization; (2) determine whether plugs obtained from core with a diameter larger than the 2" of CA-77-2 might yield less scattered magnetization directions; and (3) check on the accuracy of paleomagnetic core orientations, by comparing them with conventionally obtained values. An additional goal of this study was to ascertain whether the Mesaverde Formation has accurately recorded the Cretaceous geomagnetic field direction; this test involved a reconnaissance paleomagnetic analysis of fully-oriented samples obtained from surface outcrops near a borehole from which conventionally oriented core had been recovered.

SAMPLE COLLECTION

The present investigation involved paleomagnetic analysis of a total of 152 samples. Fifty of these were plugs obtained from two oriented, 3"-diameter core sections from hole DOE-GC-1 at the Book Cliffs, Utah; the GC-1 site is at the top of a ridge, on the sides of which the penetrated Mesaverde beds are well exposed. Fifty-one fully-oriented samples were obtained from an exposure about 1 km northeast of the GC-1 site and at approximately the same stratigraphic horizon (771 to 888') as the conventionally-oriented sections. The remaining 50 samples were plugs obtained from two conventionally-oriented , 4"-diameter core sections from the #1 Mesa Unit Well, Sublette County, Wyoming. These oriented cores are from depths of 9,126 to 9,148' and 10,547 to 10,569', at which levels it is uncertain whether the beds are of Paleocene (Fort Union Formation) or Late Cretaceous age.

The 152 paleomagnetic samples were collected by D. C. Bleakly of CER Corporation and D. R. Van Alstine during October and November, 1980.

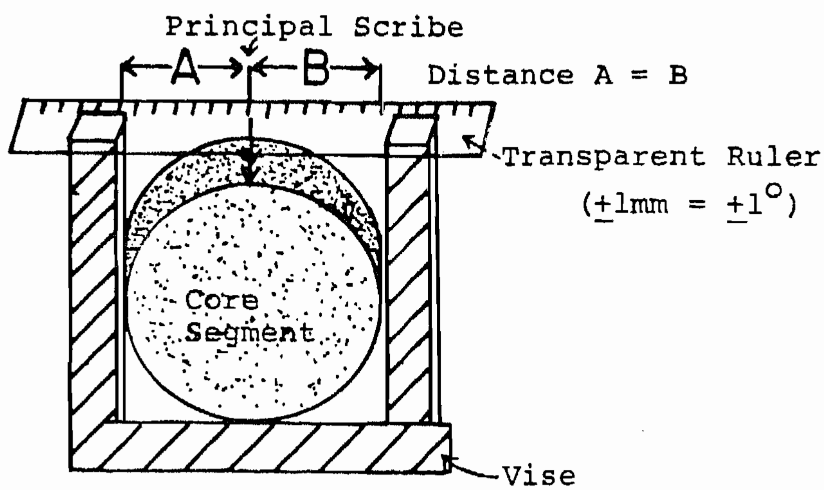
Plugs from the subsurface core were obtained using a drill press fitted with a water-cooled diamond bit. The core segment to be sampled was first mounted horizontally in a vise so that the uppermost surface of the segment was tangent to the "principal scribe line" (at the apex of the triangle formed by the 3 grocves cut by the Hügel knives). A plug, 1" in diameter and with a length nearly equal to the diameter of the core, was then drilled perpendicular to the core axis (Figure 1). A reference line was transferred to the plug using a brass orienting sleeve and non-magnetic phosphor-bronze scriber. This procedure preserves the relative declination of plugs from the same core segment and permits the angle between the magnetization vectors and the principal scribe line to be determined within about ± 1°.

Plugs were obtained from each of the major lithologies (shale, transitional, and sandstone) to test the difference in degree of dispersion of magnetization directions as a function of sediment grain size.

The surface outcrop samples were obtained using a portable gasoline-powered drill fitted wtih a water-cooled diamond bit. The samples, which were 1" in diameter and 3" to 5" long, were oriented using a brass orienting sleeve, Brunton compass, and spirit level.

LABORATORY WORK AND DATA ANALYSIS

The plugs were first trimmed to 1"-long specimens using a rock saw. The natural remanent magnetization (NRM) of the specimen was then measured using a 3-axis cryogenic magnetometer manufactured by Superconducting Technology, Inc. This system has a background noise level less than 1 x 10^{-7} emu. The magnetometer is interfaced to a PR1ME 550 computer,



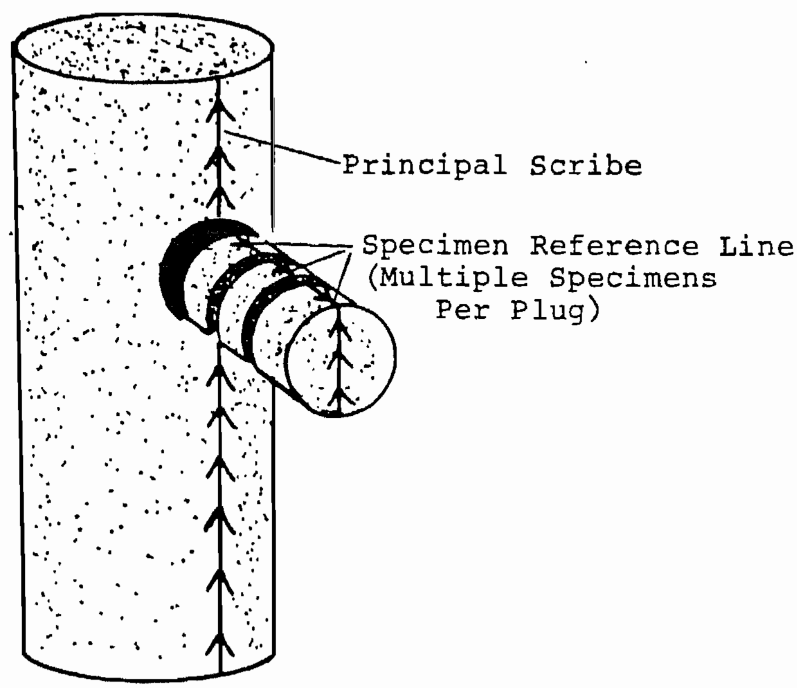


Figure 1: Procedure for obtaining oriented plugs from drill core. Multiple specimens can be cut from each plug. A brass sleeve is used to transfer a reference line to each specimen; this reference line is perpendicular to the core axis.

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allowing real-time calculation of magnetization directions and intensities. To test the stability of the NRM, each specimen was subjected to alternating-field (AF) or thermal demagnetization. Alternating-field demagnetization was performed using a Schonstedt Model GSD-1 specimen demagnetizer which provides peak fields up to 1000 oersteds (1 Oe = 0.1 millitesla). Thermal demagnetization was performed using a Schonstedt thermal demagnetizer modified for insertion of a thermocouple probe to monitor the temperature of each specimen. The magnetometer and demagnetization equipment are housed in a mu-metal room, in which the ambient magnetic field is less than 75 gammas; this retards the acquisition of viscous components of magnetization commonly found in magnetite-bearing rocks.

As many as 4 specimens were cut from each plug and subjected to a combination of demagnetization techniques to ascertain which procedure best isolates the "characteristic" or fossil magnetization from any secondary components, such as drilling-induced remanence. This was facilitated by inspection of vector demagnetization diagrams (Zijderveld, 1967), which are useful in providing simultaneous displays of the direction and intensity at each demagnetization step.

The distributions of paleomagnetic directions were analyzed using the statistical procedures of Fisher (1953) for computing the vector mean and of Van Alstine (1980) for computing the mode. In determining the paleomagnetic declination to be used for core orientation, preference was given to the mode rather than to the mean, since the mode is less biased by outliers in the distribution.

RESULTS

The precision of the paleomagnetic core-orienting technique depends on the extent to which the characteristic magnetization of the samples can be isolated. This study has revealed two sources of magnetic "noise" that distort the original paleomagnetic signature of Mesaverde/Fort Union samples: (1) Contamination by steel particles acquired during sample collection and preparation; and (2) Overprinting of the fossil magnetization by a drilling-induced magnetization pointing directly down-hole. These two problems will first be addressed before commenting on the specific paleomagnetic orientations from each core segment.

Magnetic Contamination During Sample Preparation

Magnetic contamination during sample preparation was first recognized when comparing paleomagnetic results from duplicate specimens cut from the same plugs. Directions of natural remanent magnetization (NRM) from an initial suite of 25 specimens cut from the upper GC-1 core are fairly dispersed as shown in Figure 2. For this distribution of directions, the "precision" or "concentration" parameter, k (Fisher, 1953), is 9.1. (The parameter k, which measures the disperson of directions about the mean, is estimated as $k = (N-1)/(N-R)$ where R is the length of the resultant vector after summing N unit vectors; larger values of k

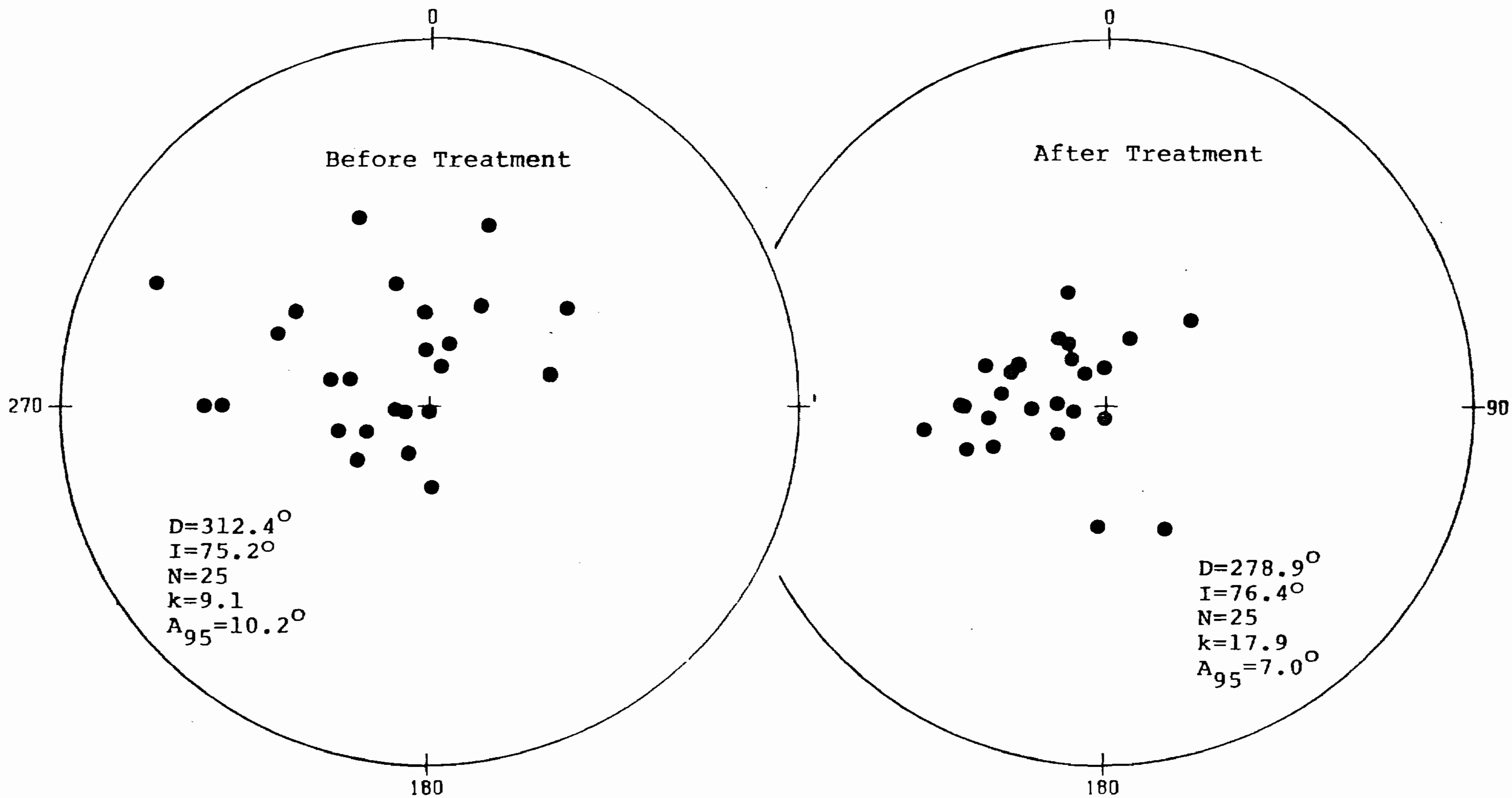

Figure 2: Directions of natural remanent magnetization (NRM) from 25 plugs obtained from core GC-1. The samples on the left have not been treated to remove steel particles acquired during sample preparation. The samples on the right have been sanded and rinsed for 20 seconds in HCl. The improved grouping of directions after treatment reflects the removal of the steel contamination. Lower hemisphere stereographic projections.

indicate a denser concentration of directions about the mean). A duplicate suite of 25 specimens was cut from these same plugs, and their surfaces were mechanically sanded (with non-magnetic abrasive paper); they were then rinsed for 20 seconds in concentrated HCl, rinsed several times in water, and then dried in a magnetically shielded room. As shown in Figure 2, the NRM directions of this second suite of specimens were considerably better grouped ($k = 17.9$) than the first suite ($k = 9.1$), and their average NRM intensity (5.1×10^{-7} emu/cm^3) was lower than the first suite (5.6×10^{-7} emu/cm^3). The improved grouping of NRM directions from the second suite of specimens and their 9% lower NRM intensities after treatment probably reflect the removal of magnetic contamination residing in surficial steel particles acquired during the plugging and sawing operations.

An even more spectacular demonstration of magnetic contamination was revealed in analyzing the 51 fully oriented surface outcrop samples. The grouping of NRM directions improves markedly for those samples subjected to mechanical sanding and acid rinsing (Figure 3); k increases from 7.5 before treatment to 42.7 after treatment. In addition, the average NRM intensity before treatment (9.6×10^{-7} emu/cm^3) is reduced by the treatment to 4.8×10^{-7} emu/cm^3. The intensity after treatment agrees within 5% with that obtained from the treated subsurface samples from the stratigraphically equivalent horizon in GC-1. The agreement in NRM intensity between the treated surface and

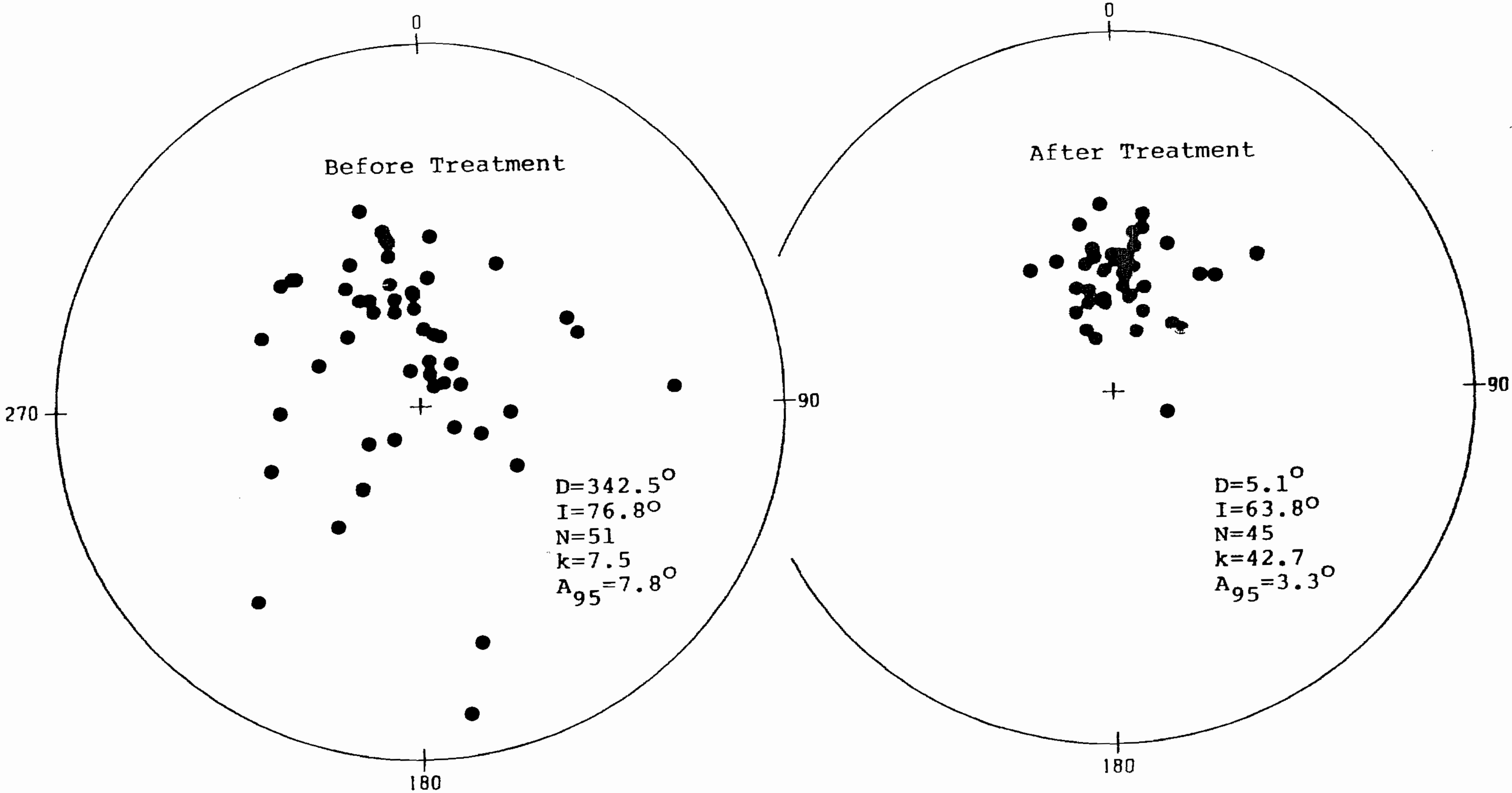

Figure 3: NRM directions from 51 fully-oriented samples collected from surface exposures near GC-1. The two stereographic projections show results from specimens before (left) and after (right) sanding and acid-rinsing to remove steel particle contamination.

subsurface samples increases confidence that the magnetic contamination from sample preparation has been removed.

The recognition and elimination of this source of magnetic noise in the Mesaverde samples markedly improves the feasibility of the paleomagnetic core-orienting technique. The precision of this method is approximately proportional to $1/\sqrt{kN}$, where N is the number of plugs obtained from a core segment, and k is the concentration parameter as defined previously.

In the two examples discussed above, more thorough sample preparation increased the k by factors of 2.0 and 5.7, respectively. This means that 50% to 18% of the number of treated specimens would be needed to achieve the same orientation precision as with untreated specimens.

In the remainder of this report, results will be presented only from suites of specimens subjected to sanding and acid-rinsing.

Drilling-Induced Remagnetization in Boreholes

In our initial paleomagnetic study of the Mesaverde Formation (Van Alstine and Gillett, 1980), we reported a curious tendency for NRM vectors from CA-22-7 plugs to have anomalously steep inclinations (up to 85°). We suggested that these steep inclinations might reflect a secondary component acquired during the drilling process, because they are about 20° steeper than any geophysically significant fields that might have been recorded. Moreover, we suggested that use of the Monel drilling collar might reduce this source of magnetic noise.

Paleomagnetic results from the present investigation and from other boreholes in magnetite-bearing rocks confirm that drilling-induced remanent magnetization (DIRM) is a very real phenomenon. In drill cores from the Columbia River basalt, downward-pointing DIRM in some cases completely dominates the in situ thermoremanent magnetizations; NRM intensities of lava flows in drill core from 5,000-foot depths are commonly 100 times greater than in the same flows exposed at the surface, and the NRM directions are nearly vertical (Van Alstine and Gillett, 1981). Drilling-induced magnetization has also been observed in paleomagnetic samples from boreholes in deep-sea basalts (e.g., Johnson, 1979; Rice et al., 1980) and in basic igneous rock at 17,000 feet in a Michigan Basin borehole (Van der Voo and Watts, 1978). In all cases, the DIRM is aligned with the axis of the drill string; hence it would affect only paleomagnetic inclinations (and not declinations) in vertically-drilled holes.

In the present investigation, DIRM is most spectacular in the lower (10,547 to 10,569') of the two oriented core segments from the #1 Mesa Unit Well. The initial suite of 25 specimens yielded NRM directions well clustered around a mean of D = 331.3°, I = +85.4°, k = 75.6 (Figure 4). These samples were then subjected to AF demagnetization at 6 steps between 50 and 300 oersteds. As shown in Figure 4, the

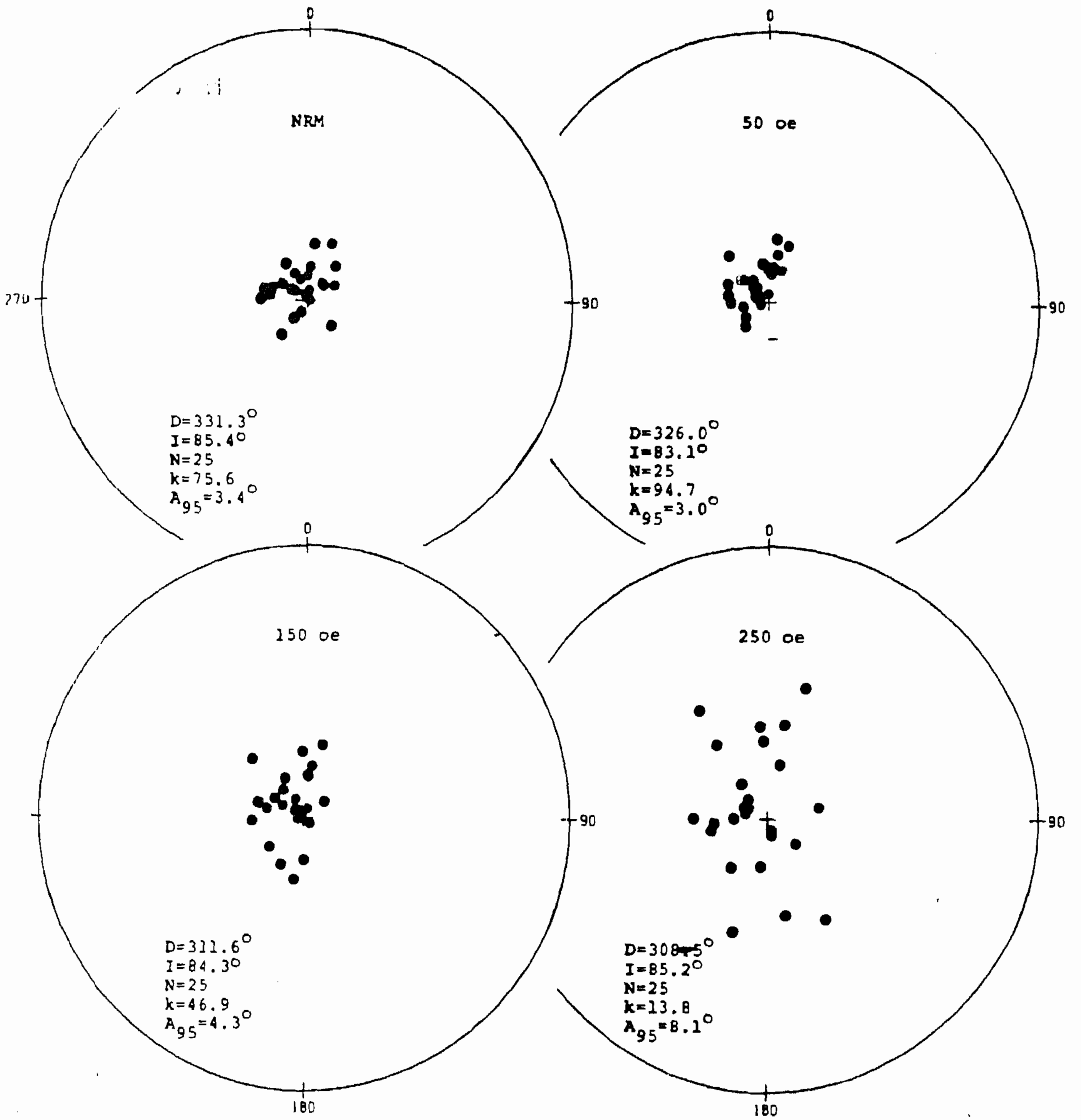

Figure 4: Magnetization directions upon AF demagnetization of the lower oriented core segment (10,547 to 10,569 feet) in the #1 Mesa Unit Well. Note that the NRM directions (top left) have very steep inclinations, reflecting a strong bias by drilling-induced magnetization (DIRM), pointing directly down-hole (inclination = 90°). The DIRM is more stable than the fossil magnetization at all demagnetization steps except at 50 oersteds (top right).

distribution of magnetization directions achieves its shallowest inclination and best grouping at 50 oe (D = Figure 4 326.0°, I = 83.1°, k = 94.7); it then steepens in inclination and becomes more diffuse at higher demagnetization steps.

These initial AF demagnetization experiments were discouraging because they suggest that much of the fossil magnetization of the Fort Union/Mesaverde Formations might be less stable to AF demagnetization than the secondary DIRM. It is far more common in paleomagnetism for magnetizations residing in magnetite to be <u>less stable</u> than the primary component; this is the principle behind the AF "cleaning" technique. In the Fort Union/Mesaverde Formations, it appears that AF cleaning above 50 Oe preferentially removes the paleomagnetic "signal" and enhances the "noise."

Guided by our experience with Columbia River basalt borehole samples and by knowledge that secondary magnetizations can be removed efficiently by thermal demagnetization, a second suite of specimens was cut from the #1 Mesa Unit plugs and subjected to progressive thermal demagnetization. This experiment is highly illuminating for two reasons. First, the distribution of NRM directions for the second suite of samples has a 10° shallower inclination (but similar declination) than the first suite, even though both suites of specimens received the same sample preparation treatment (Figure 5). This suggests that the dis-

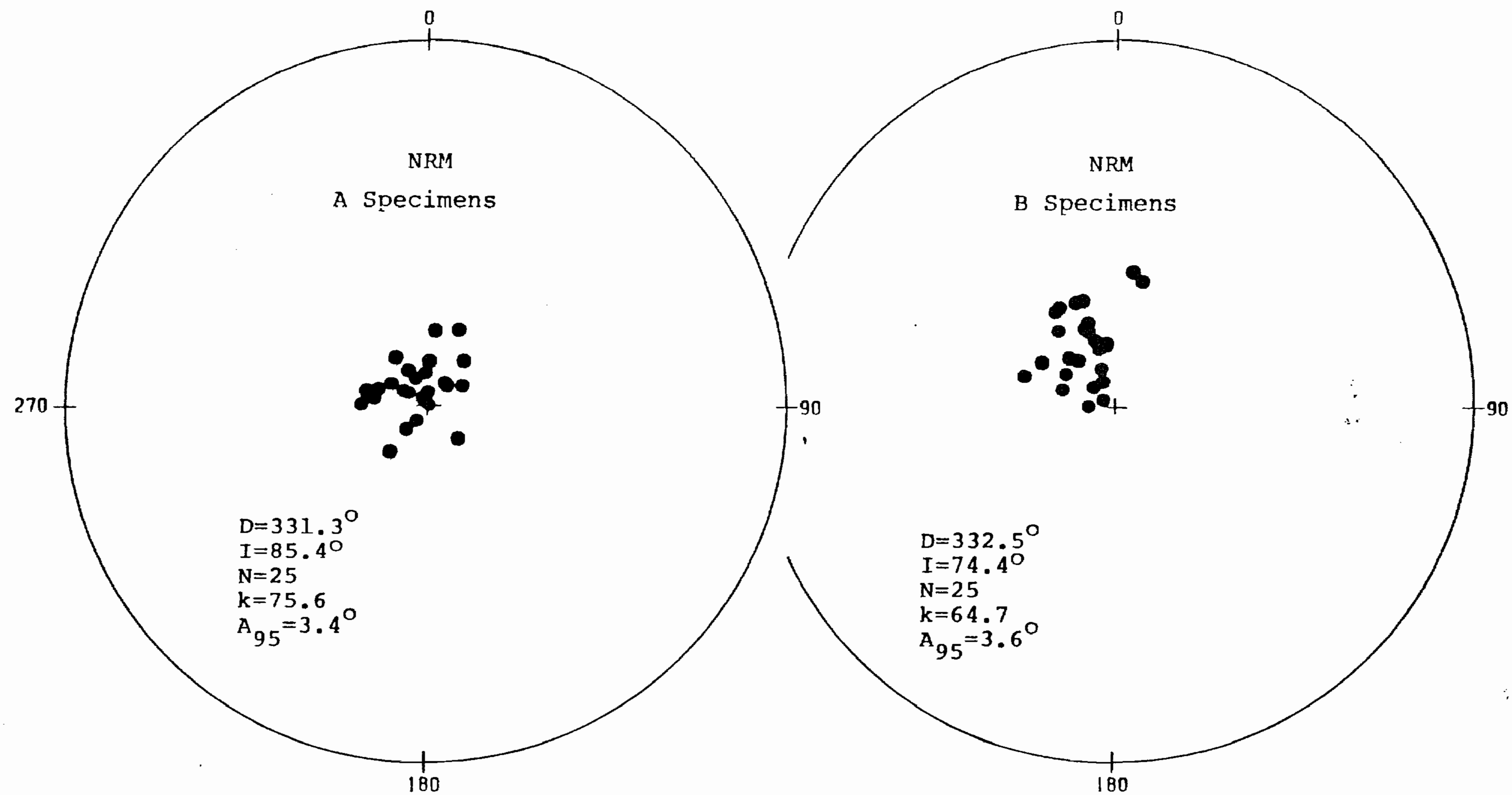

Figure 5: NRM directions from two suites of specimens cut from 25 plugs from the #1 Mesa Unit core (from a depth of 10,547 to 10,569 feet). Both suites of specimens received the same sample preparation treatment (sanding followed by acid rinsing). Note that the A specimens have 11° steeper inclinations, indicating a stronger bias by drilling-induced remanence (*DIRM*). Evidently, DIRM is heterogeneously distributed in the plugs.

tribution of the DIRM component within the core is "spotty" over a scale of one inch, since the two specimens from each plug were contiguous. It seems valuable, therefore, to measure NRM directions from two specimens from each plug; the specimen with the lower inclination would be more useful for paleomagnetic core orientation.

The second major result of the thermal demagnetization experiments was the suggestion that thermal demagnetization at low temperatures (~110°C) was even more effective in preferentially removing DIRM than was AF demagnetization. As shown in Figure 6, thermal demagnetization at 110°C produced a well-grouped distribution of directions with an inclination of 70.8°. This inclination is within 5° of the reference Cretaceous(67.3°)/Paleocene(65.9°) inclination, suggesting that at this demagnetization step, the DIRM "noise" is much weaker than the Cretaceous/Paleocene "signal." At higher temperatures, the distribution became more diffuse, indicating that the signal-to-noise ratio was being reduced.

From the results of these AF and thermal demagnetization experiments, it appears that very gentle thermal demagnetization (~110°C) or AF demagnetization (~50 Oe) yields the maximum ratio of fossil magnetization to secondary DIRM.

The results of applying these techniques to the 4 oriented core segments will now be presented in more detail.

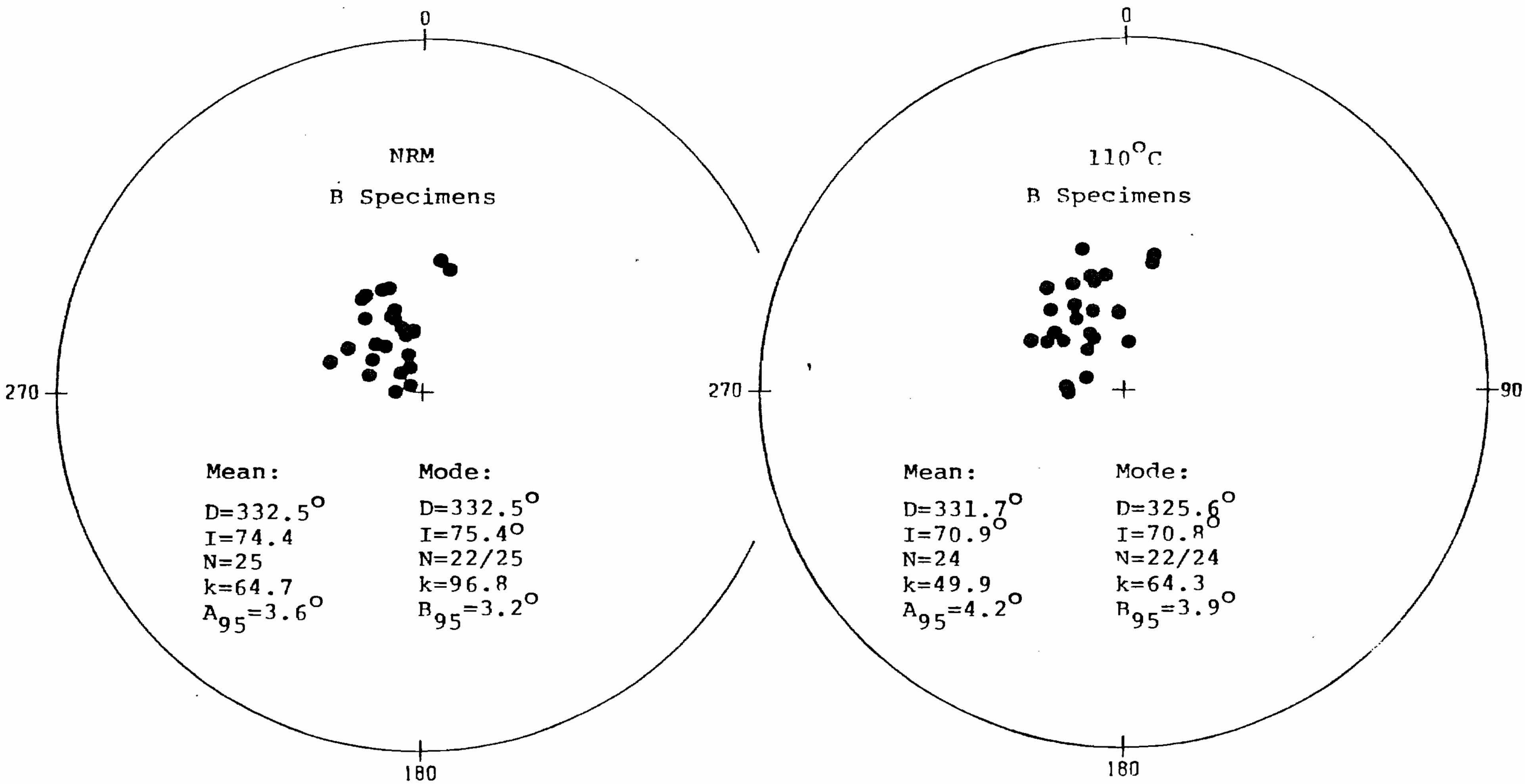

Figure 6: Magnetization directions of the B suite of specimens (#1 Mesa Unit Well) showing results from thermal demagnetization at 110°C. Note that the thermally demagnetized specimens have 5° shallower inclinations than the NRM directions. This reflects preferential destruction of the DIRM component, which has a 90° inclination (directly down-hole).

GC-1 Upper Core

Twenty-five plugs were obtained from a section of conventionally oriented core from the 771.0 to 782.0'-level in GC-1. The sampled lithologies range from black, carbonaceous shale (2 plugs) to gray, fine-grained sandstone (11 plugs) and include 12 plugs of "transitional" beds (Appendix 1).

Magnetization directions before and after thermal demagnetization to 110°C are shown in Figure 7. At higher temperatures the distributions became more diffuse. The thermal demagnetization resulted in improved grouping of directions (k increased from 29.0 to 43.8) and a slight shallowing of the average inclination (from 73.3° to 71.8°). However, this inclination, even after thermal demagnetization, is 7° steeper than the Cretaceous reference inclination, suggesting that the magnetization directions are still biased by unremoved DIRM.

The mode of the distribution of directions after thermal treatment lies at D = 272.6°, I = 71.8° (in the specimen coordinate system) and has a β_{95} (estimated 95% confidence limit) of 4.7°. The 3 most widely divergent directions are all from sandstone, suggesting that the coarser-grained lithologies are less precise recorders of the fossil magnetization.

An initial suite of specimens cut from these plugs had been subjected to progressive AF demagnetization. However, these samples were demagnetized before the problem of steel

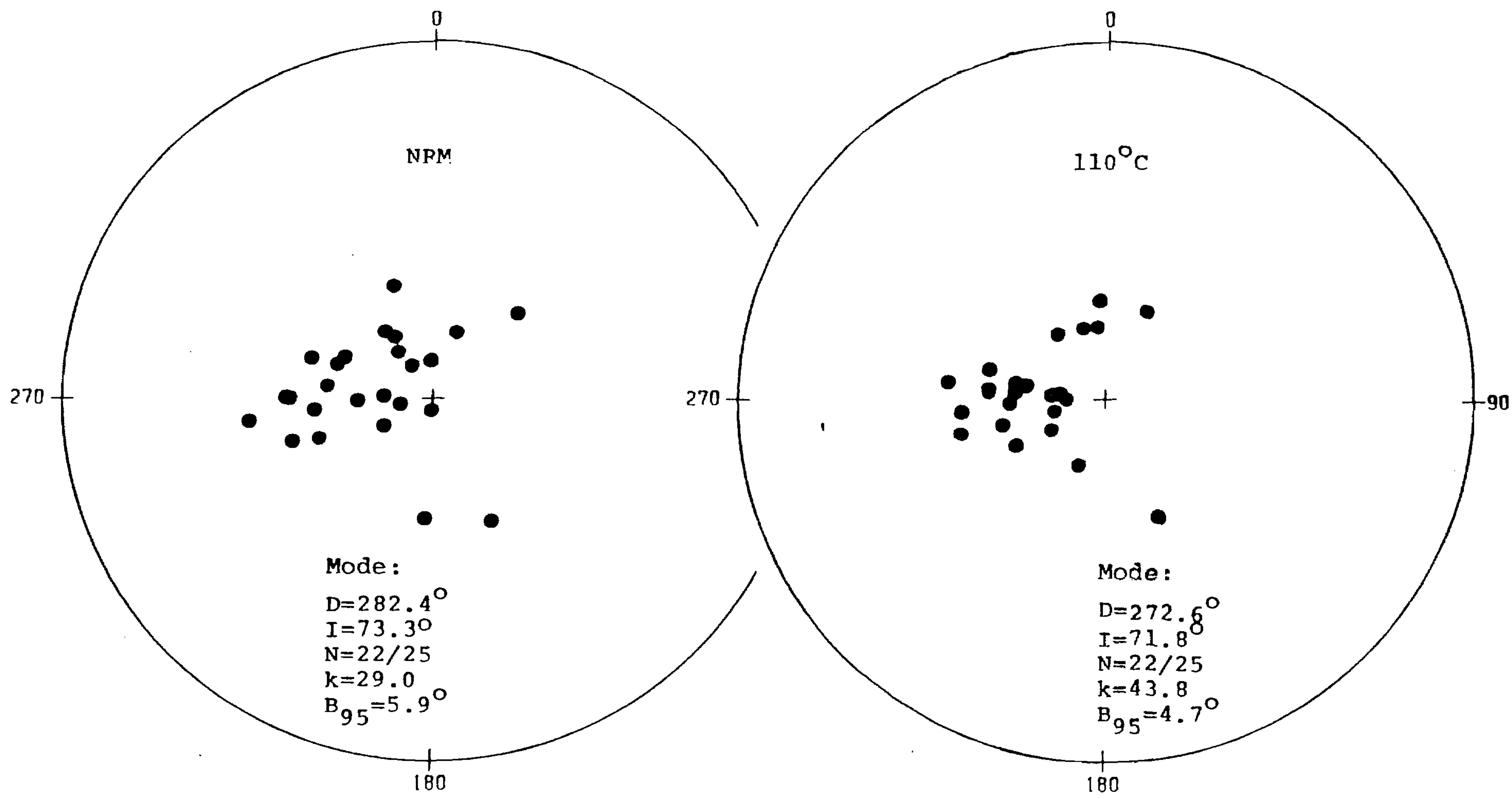

Figure 7: Magnetization directions from 25 plugs from the GC-1 upper core (771.0 to 782.0'). Shown are the results before (left) and after (right) thermal demagnetization at 110°C.

particle contamination had been recognized. Thus, the results from these specimens are not shown, although they yielded a more diffuse distribution with a mode similar to that identified above.

GC-1 Lower Core

Twenty-six plugs were obtained from the 870.3 to 887.7' level of GC-1. Above 879.3' the samples are predominantly light-gray, fine-grained sandstone with some laminations and soft-sediment deformation. At 879.9', one plug was obtained from a coal seam. From 880.4' and below, all 9 samples are from dark, carbonaceous shale (Appendix 1).

Paleomagnetic results from this core are difficult to interpret. The magnetization directions after thermal cleaning at 110°C form a trimodal distribution that is related to stratigraphic position (Figure 8). Plugs #51 to #63 (870.3' to 877.8') yield a mode with declination D = 313.9°; plugs #64 to #68 (878.4' to 880.4') yield D = 234.3°; and plugs #69 to #76 (881.7' to 887.7') yield D = 60.7°. The stratigraphically highest group has the greatest dispersion (k = 22) and the highest proportion of sandstone (79%), the middle group is intermediate (k = 41, 40% sandstone), and the lowest group is least dispersed (k = 78) and contains only carbonaceous shale. It was expected that these samples would yield a bimodal distribution, because there were two sets of scribe marks between depths of 881.6' and 882.4' (cf. Figure 9). It appeared that at 882.4' the drill string had been lifted "off-bottom," rotated counterclockwise by

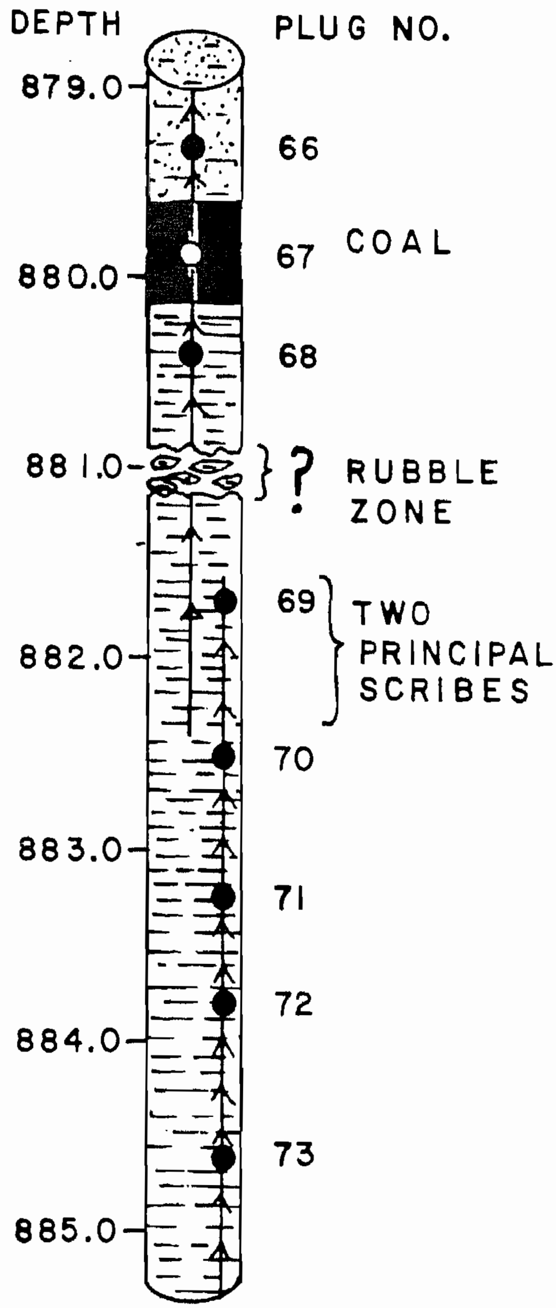

Figure 9: Sketch showing plug locations, principal scribe line, and core integrity for part of the lower GC-1 oriented core segment. Plugs #67 and #68 are shown in their corrected positions (see text).

34° (the measured angular separation between the two sets of principal scribe lines), and then set down for drilling the remainder of this run.

Surprisingly, the paleomagnetic results in the lower half of this core segment seem to indicate a relative rotation of 174°. To investigate the cause of this discrepancy, the core was re-examined by D. C. Bleakly at the U.S.G.S. Core Repository in Denver. The relationships between the plug locations, scribe lines, and core integrity are shown in Figure 9. In addition, this examination revealed that the core segment from which #67 had been obtained was inverted in the core box and that #68 had been plugged on a non-principal scribe line. (Only corrected magnetization directions are shown in Figure 8.)

The most likely interpretation of the multimodal paleomagnetic data is that the drill string had been lifted off bottom and the principal scribe rotated in the interval represented by a rubble zone between plug numbers 68 (880.4') and 69 (881.7'); these two plugs are in black, carbonaceous shale similar to that of plugs #70 to #76. An alternative explanation is that a paleomagnetic reversal or excursion fortuitously occurred between these two sample horizons; however this explanation is completely ad hoc.

From the paleomagnetic data, it would appear that another rotation of the principal scribe line occurred between plugs #63 (877.8') and #64 (878.4'). However, this interpretation is less certain than for the lower part of this core since the upper 13 plugs are predominantly from sandstone, which might be expected to be less precise recorders of the paleomagnetic field.

These results from the lower GC-1 core represent our first encounter with a multimodal distribution of magnetization directions from holes GC-1 and #1 Mesa Unit well of this study or from CA-77-2 of our earlier investigation. This increases confidence that the peculiar distribution is caused not by a geophysical change in the paleomagnetic field but by a mechanical rotation of the principal scribe line. This example underscores the importance of recording discontinuities in the core during the plugging operation and in taking an adequate number of plugs (∿5) per fitted-together section of core to test for consistency of the paleomagnetic directions.

#1 Mesa Unit Upper Core

Twenty-five plugs were obtained from the 9,125.8 to 9,147.8' level of the #1 Mesa Unit Well. The sampled lithologies consist of black, carbonaceous shale (3 plugs), gray siltstone (9 plugs), and gray, very fine (4 plugs) to fine-grained (9 plugs) sandstone (Appendix 1).

Two suites of specimens were cut from these plugs. The first suite (A) was to be subjected to progressive AF demagnetization and the second suite (B) to progressive thermal demagnetization. Both distributions of NRM directions exhibit a dominance of steep inclinations, undoubtedly reflecting appreciable DIRM (Figure 10). The suite A spec-

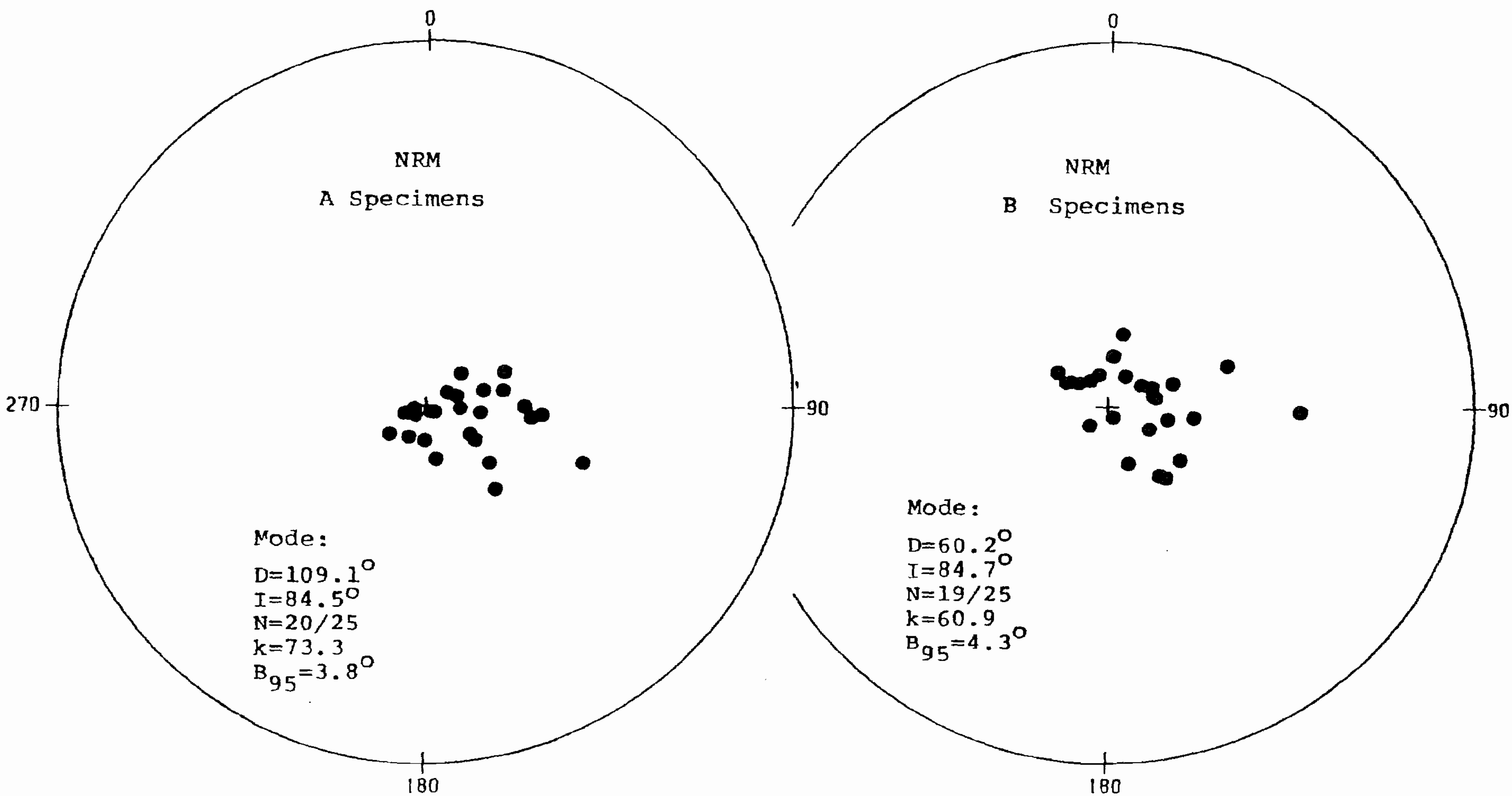

Figure 10: NRM directions from two suites of specimens cut from 25 plugs from the #1 Mesa Unit Well (from a depth of 9,125.8 to 9,147.8 feet). Both suites of specimens received the same sample preparation treatment. Note that the A specimens are less biased by the DIRM, which points directly down-hole (inclination = 90°).

imens have shallower inclinations than the suite B specimens, again suggesting that the DIRM component is heterogeneously distributed within each plug. Moreover, a pronounced lithological dependence of DIRM contribution is observed: in the coarser-grained sandstone, the DIRM is preferentially developed and/or less easily separated from the fossil magnetization (Figure 11).

The most accurate core orientation can therefore be derived from the 12 siltstone and shale plugs. To decrease the uncertainty in the estimate of the mode, the AF-cleaned (50 Oe) directions were combined with the thermally-cleaned (110°C) directions from the siltstone and shale to yield the distribution (Figure 12) with a mode at D = 120.3°, I = 73.9°, β_{95} = 5.1°.

#1 Mesa Unit Lower Core

Twenty-five plugs were obtained from the 10,547.0 to 10,569.1' level of the #1 Mesa Unit Well. The sampled lithologies consist of gray shale (2 plugs), gray siltstone (8 plugs), and gray, very fine-grained (13 plugs) to fine-grained (2 plugs) sandstone (Appendix 1).

Results of progressive AF and thermal demagnetization of two suites of specimens cut from these plugs have been presented in a previous section of this report. It should be noted here that after thermal cleaning, nearly every plug from this core section yielded a magnetization direction close to the mode of specimen directions. In this interval, only 8% of the specimens had lithologies coarser than very

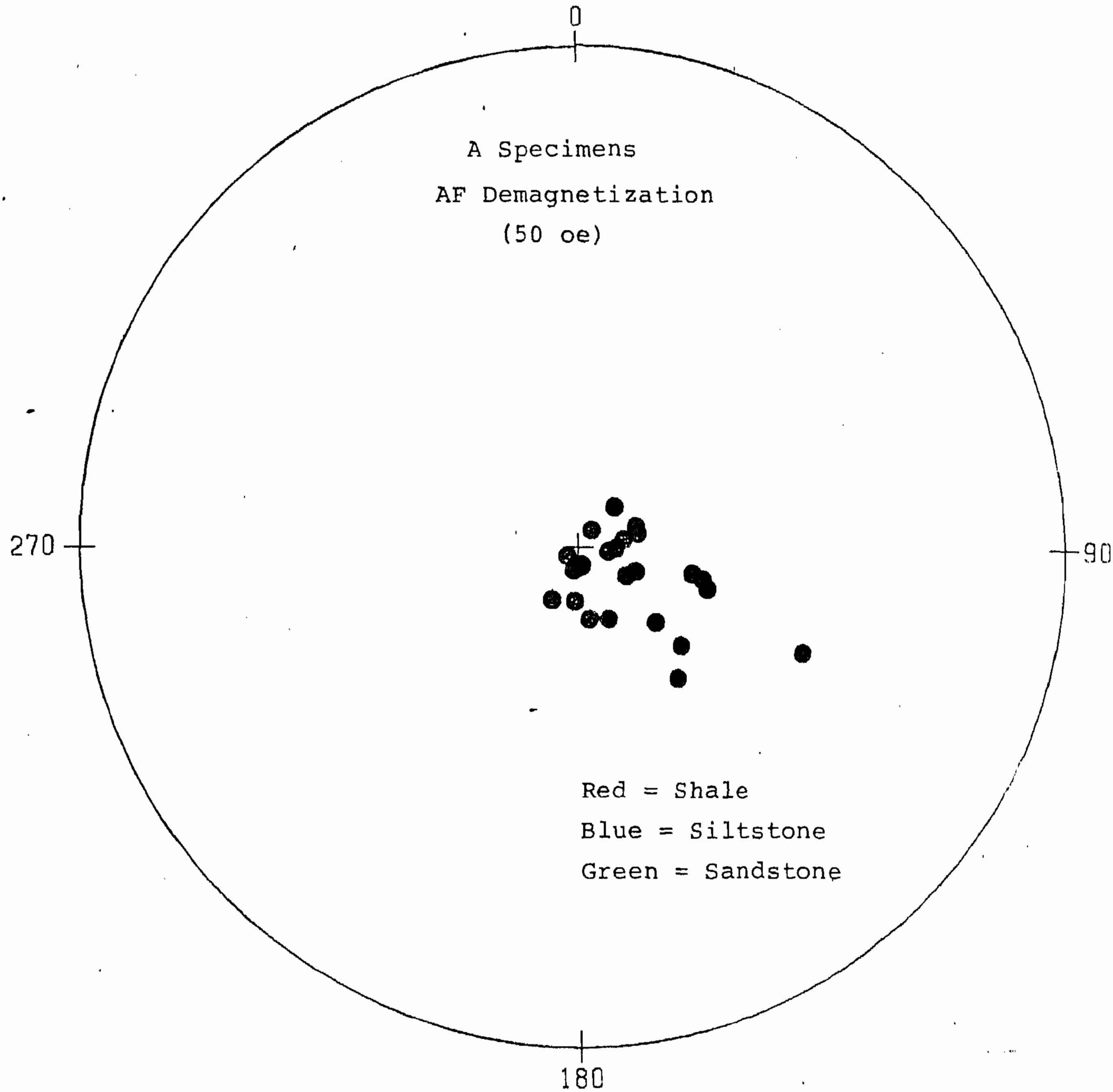

Figure 11: Magnetization directions after alternating-field demagnetization at 50 oersteds of the A suite of specimens from the upper core of #1 Mesa Unit Well. Note that sandstone specimens (green points) have significantly steeper inclinations than siltstone (blue) and shale (red). This suggests that coarser-grain lithologies are more affected by the vertically-directed drilling magnetization.

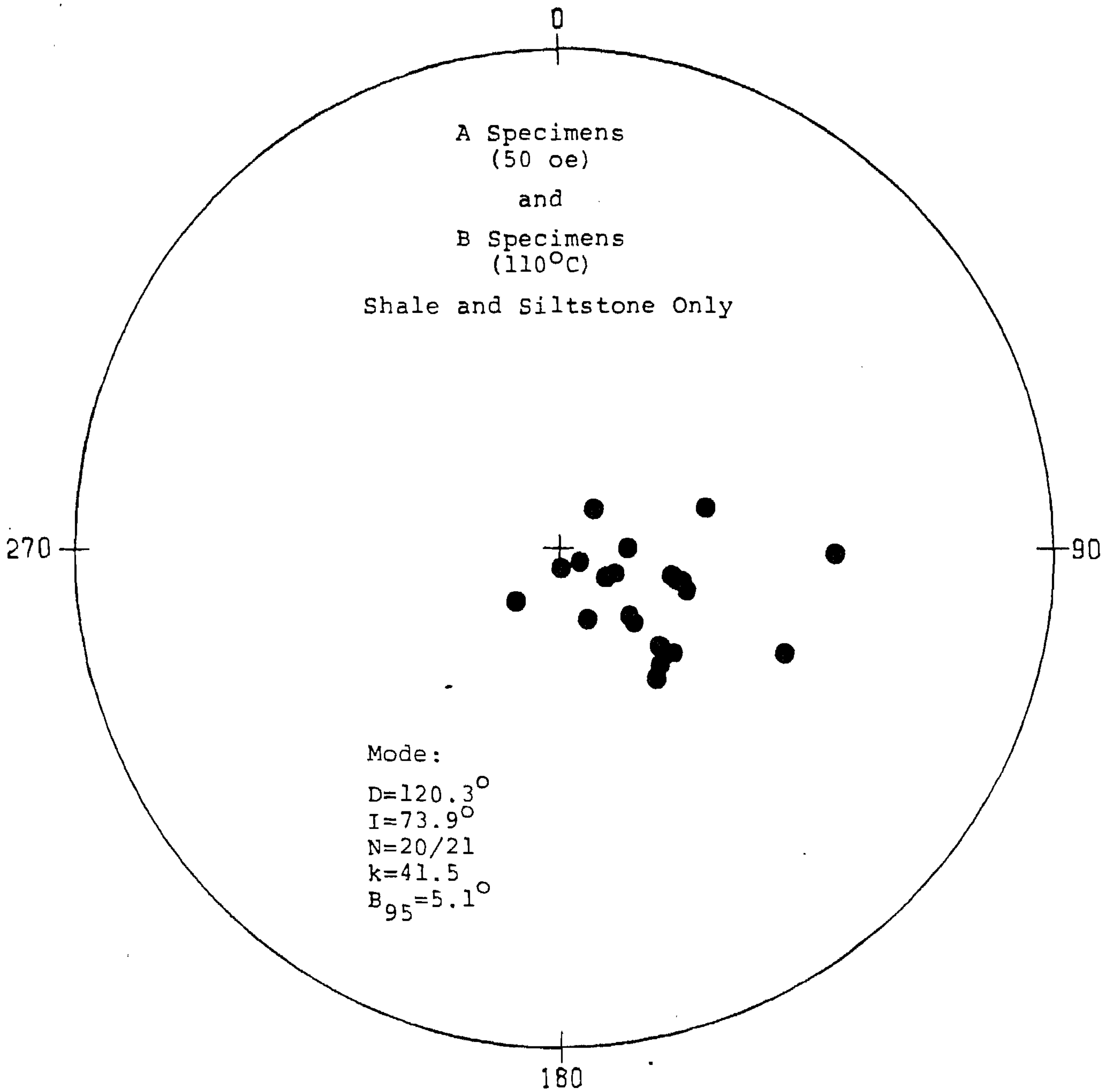

Figure 12: Magnetization directions from shale and siltstone plugs of the upper core of #1 Mesa Unit Well (9,125.8 to 9,147.8'). This distribution includes specimen directions from the combined 50 Oe AF demagnetization (Suite A) and 110°C thermal demagnetization (Suite B) steps.

fine-grained sandstone. This is in marked contrast with the upper #1 Mesa Unit Core, in which 36% of the plugs are fine-grained sandstone, yielding scattered magnetization directions biased by DIRM. Thus, unless acquisition of DIRM can be avoided, or unless a better technique is developed to separate DIRM from the primary magnetization, lithologies coarser than very fine-grained sandstone should not be sampled for core orientation using paleomagnetism.

PALEOMAGNETIC ORIENTATION OF CORE SEGMENTS

The Age of the Mesaverde Magnetization.

Thus far, it has been demonstrated that the Mesaverde/ Fort Union Formations contain a geophysically-significant component of magnetization with an inclination $\leq 74°$. The paleomagnetic directional information from each oriented core segment is summarized in Table 1. To orient a core segment solely on the basis of its paleomagnetic signature, however, requires that the age of this magnetization be known. There is no *a priori* reason for doubting that this magnetization was acquired penecontemporaneously with deposition. However, the paleomagnetic literature contains numerous examples where a primary magnetization has been overprinted or completely reset by later diagenetic or tectonic events.

To investigate the age of the characteristic magnetization of the Mesaverde Formation, we performed a paleomagnetic study of 51 fully oriented samples obtained in an outcrop 0.6 miles northeast of the GC-1 well. The sampled

Table 1: SUMMARY OF PALEOMAGNETIC DIRECTIONAL INFORMATION FROM GC-1 AND #1 MESA UNIT ORIENTED CORE SEGMENTS

Core Segment	(D_o)* Declination	$(I_o)^{\xi}$ Inclination	$(N_{mode}/N_{tot})^{\dagger}$ N	k**	B_{95}++	ΔD_{95}^{δ}
GC-1 upper (771.0-782.0')	272.6°	71.8°	22/25	43.8	4.7	15.2°
GC-1 lower						
870.3-877.8'	313.9	61.4	12/13	21.8	9.5	20.2
878.4-880.4'	234.3	69.4	5/5	41.0	12.1	36.6
881.7-887.7'	60.7	51.1	7/7	77.9	6.9	11.0
#1 Mesa Unit upper 9,125.8-9,147.8'	120.3	73.9	20/21	41.5	5.1	18.7
#1 Mesa Unit lower 10,547-10,569'	325.6	70.8	22/24	64.3	3.9	11.9

* Declination of the mode of specimen directions, in the specimen coordinate system

ξ Inclination of the mode of specimen directions

† N_{tot} is the total number of specimen directions in the vector sample.
N_{mode} is the number of specimen directions with a mean equal to the mode of the total vector sample.

** k is the estimate of the precision parameter (Fisher, 1953) for the N_{mode} samples.

++ B_{95} is the half-angle of the cone of 95% confidence about the mode (Van Alstine , 1980).

δ ΔD_{95} is the estimated 95% confidence limits for the declination
$\Delta D_{95} = \arcsin(\sin B_{95}/\cos I_o)$.

section was about 40' thick, dips less than 2°, and contains beds probably within 100 stratigraphic feet of the oriented core sampled from the subsurface.

It is important to note that the thickness of the Mesaverde Formation at the Book Cliffs indicates an average sedimentation rate of about 2,000 years/foot. Thus, the mean paleomagnetic direction from a 40' thick section would be expected to have averaged out the high frequency (over decades) secular variation of the geomagnetic field. The mean direction from this 40' section should be close to the "time-averaged" magnetic pole, which (being an axially geocentric dipole) lies within 2° of the position of the geographic pole when the magnetization was acquired.

For rocks magnetized within the last few million years, the average magnetic declination is 0° (i.e., pointing true north). In rocks of increasingly older age, however, the average paleomagnetic directions deviate by increasingly large angles. This slow directional change (0.2-2.0°/ million years) is thought to result from plate-tectonic motion of North America and from "true polar wandering," or movement of the solid body of the Earth with respect to the astronomically defined spin axis.

During most of the Cretaceous, the paleomagnetic (and probably geographic) pole was in the Bering Strait as viewed from North America (Table 2). This means that Cretaceous sediments deposited in the region of the Book Cliffs should have recorded a magnetic declination of 330° (Table 3;

TABLE 2: REFERENCE PALEOMAGNETIC POLES FOR NORTH AMERICA, LATE CRETACEOUS TO HOLOCENE*

Age	Latitude (^{o}N)	Longitude (^{o}E)
Late Cretaceous	67.2	189.9
Paleocene	78.9	194.3
Eocene	82.1	178.2
Oligocene-Miocene	85.0	138.0
Holocene	90.0	180.0

*From data compiled by Van Alstine (1979) supplemented with recent early Tertiary results (e.g., Jacobson et al., 1980; Diehl et al., 1980. These paleomagnetic poles have α_{95} <5^{o}, except the Paleocene pole, for which α_{95} = 10^{o}.

TABLE 3: REFERENCE PALEOMAGNETIC DIRECTIONS AT GC1 AND #1 MESA UNIT SITES*

GC1 (Location: 39.3°N, 109.3°W)		#1 Mesa Unit Well Location: 42.8°N, 109.8°W)		Age
Declination (D_{ref})	Inclination (I_{ref})	Declination (D_{ref})	Inclination (I_{ref})	
330.3	64.9°	328.3°	67.3°	Late Cretaceous
347.0	63.2	346.2	65.9	Paleocene
350.0	60.3	349.4	63.2	Eocene
354.2	56.6	353.9	59.9	Oligocene-Miocene
360.0	58.6	360.0	61.7	Holocene

*Calculated from reference poles of Table 2 using the axial dipole formula (e.g., McElhinny, 1973).

calculated from the axial dipole formula using paleomagnetic data compiled by Van Alstine, 1979).

Surprisingly, the NRM directions from the Mesaverde surface-outcrop samples yield a mode at D = 0.8°, I = 62.7°, β_{95} = 2.7° (Figure 13). This direction differs by only 4° from the Holocene geomagnetic direction (D = 0.0°, I = 58.6°) at the Book Cliffs, but by 14° from the Late Cretaceous reference direction (D = 330.3°, I = 64.9°).

One interpretation of this result is that it merely reflects remagnetization of these beds by oxidation during weathering. The samples from the surface outcrop appear considerably more oxidized (rusty-colored) than the corresponding subsurface samples, which are gray. Another possibility is that the NRM of these samples is a viscous remanent magnetization (VRM) acquired during the Brunhes normal polarity epoch (<700,000 years B.P.).

Several observations, however, suggest that neither surface oxidation nor VRM can completely account for the characteristic magnetization of the surface Mesaverde samples. First, the average NRM intensity of the surface outcrop samples (4.8×10^{-7} emu/cm^3) is similar to the average NRM intensities of the two subsurface oriented core sections from GC-1 (5.1×10^{-7} emu/cm^3 and 3.0×10^{-7} emu/cm^3). If surface weathering had converted the magnetite to hematite or limonite, the intensty of magnetization should have greatly decreased, since the saturation magnetization of magnetite is about 100 times stronger than that of hematite. Second, even the characteristic magnetization directions of the few fine-grained (siltstone) surface samples are directed along the Earth's present-axial-dipole field direction; if VRM were the main contributor to the NRM, it might be absent or poorly developed in the fine-grain samples. Third, as shown in Figure 13, the average NRM directions from the surface samples are stable to AF demagnetization to 200 Oe (D = 5.5°, I = 63.1°, β_{95} = 2.8°); stable to thermal demagnetization at 190°C (D = 355.1°, I = 56.5°, β_{95} = 5.2°), which is higher than the thermal stability limit of goethite; and stable to thermal demagnetization at 190°C followed by AF demagnetization to 200 Oe (D = 358.5°, I = 56.0°, β_{95} = 3.7°). Yet, an appreciable fraction (~80%) of the NRM intensity can be removed by AF demagnetization to 300 oe; this indicates that the magnetic species has a coercivity (i.e., resistance to AF demagnetization) typical of magnetite.

These observations suggest that the NRM of the Mesaverde surface samples is a stable, single component of magnetization residing in magnetite. The approximate alignment of this magnetization with the present axial dipole field suggests that this magnetization was acquired in the middle to late Cenozoic; there has been only about 5° of apparent wandering of the paleomagnetic pole since the Eocene (Table 2).

It is possible, therefore, that the original Cretaceous detrital remanent magnetization (DRM) of the Mesaverde

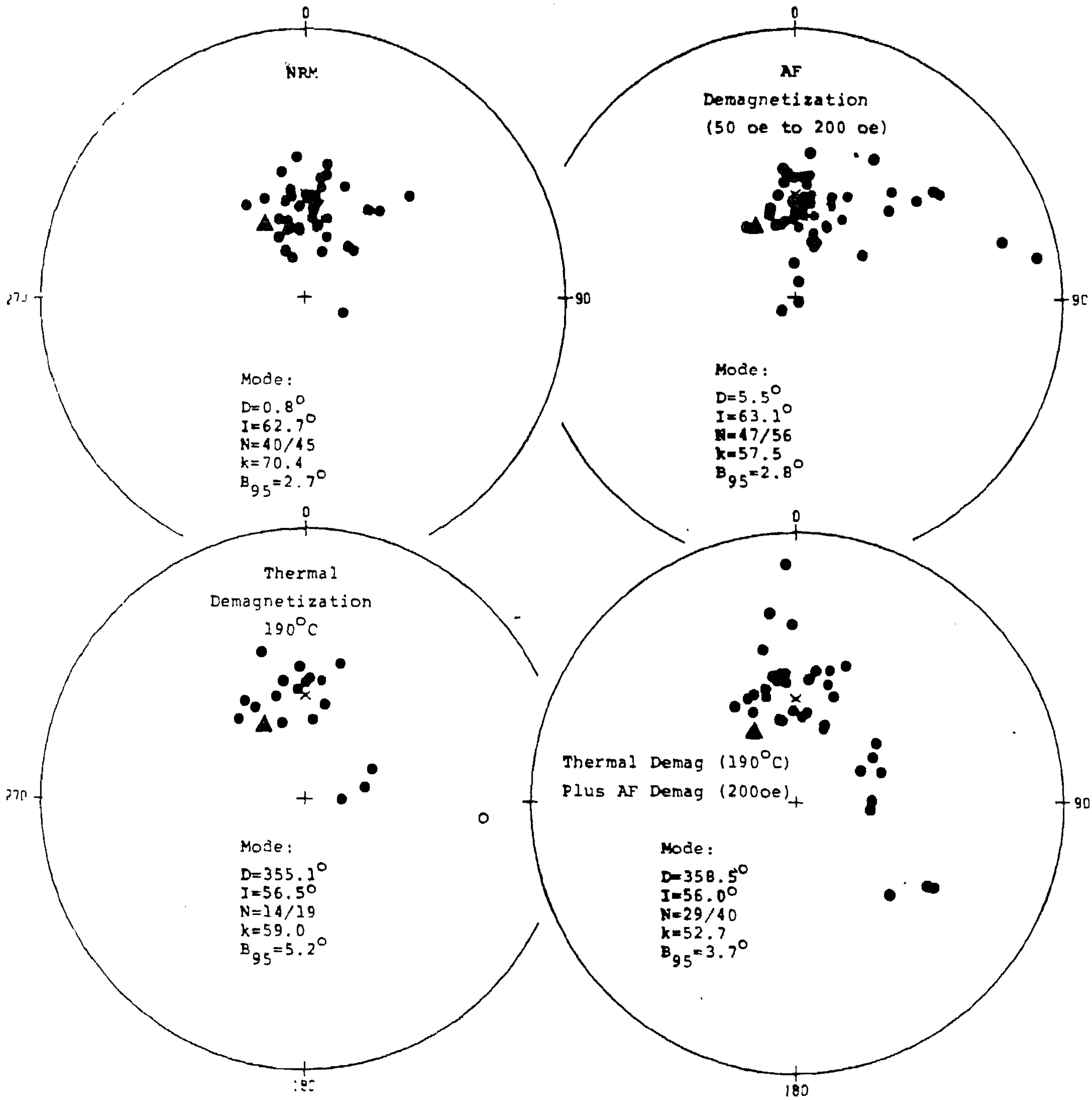

Figure 13: Magnetization directions from fully oriented samples collected from Mesaverde surface outcrops 1 km northeast of the GC-1 site. The NRM directions (top left) have a mode within 4° of the present axial dipole field direction (represented by the X), but differ by 14° from the expected Late Cretaceous reference direction (triangle). This magnetization is resistant to both AF and thermal demagnetization; it may have been imposed during mid to late Tertiary warping and uplift of the beds.

Formation at the Book Cliffs has been overprinted or reset by a partial thermoremanent magnetization (PTRM) acquired during Eocene and post-Eocene structural deformation and uplift of this region. Secondary magnetizations acquired at times of uplift and tectonism are ubiquitous in magnetite-bearing sedimentary rocks of the southern Great Basin (e.g. Gillett and Van Alstine, 1979). These secondary magnetizations are commonly very stable and would be just as useful for paleomagnetic core-orientation as a primary DRM.

Until the origin of the characteristic magnetization of the Mesaverde is investigated in more detail, however, there will be an ambiguity of up to 30° in paleomagnetic core orientations, depending on the assumed age of the magnetization. Consequently, in Table 4, we have indicated two possible sets of orientations for the GC-1 cores; one set assumes that the magnetization dates from the Late Cretaceous (reference declination D_{ref} = 330.3°) and the other set assumes the magnetization dates from the late Cenozoic (D_{ref} = 0.0°).

For the #1 Mesa Unit cores, there is an additional uncertainty regarding the age of the sampled beds; they may be either from the Fort Union Formation of Paleocene age or from underlying beds of late Cretaceous age (D. C. Bleakly, personal communication). Thus, for the #1 Mesa Unit core segments, we have listed three sets of possible core orientations; one set assumes a Late Cretaceous magnetization age (D_{ref} = 328.3°), one assumes a Paleocene age (D_{ref} =

TABLE 4: PALEOMAGNETIC CORE ORIENTATIONS AS A FUNCTION OF MAGNETIZATION AGE

Core	Magnetization Age: Late Cretaceous	Holocene
GC1-upper	237.7°E	267.4°E
GC1-lower		
870.3-877.8	196.4°E	226.1°E
878.4-880.4	276.0°E	305.7°E
881.7-887.7	89.6°E	119.3°E

#1 Mesa Unit	Late Cretaceous	Paleocene	Holocene
Upper	28.0°E	45.9°E	59.7°E
Lower	182.7°E	200.6°E	214.4°E

NOTE: Orientations of the principal scribe line with respect to geographic (true) north are calculated from the observed declinations (D_o) in the specimen coordinate system as follows:

$$O_{ps} = D_{ref} - D_o + 180$$

Ops is the orientation of the principal scribe in positive degrees East (clockwise) D_{ref} is the average magnetic declination for the geological time when the magnetization was acquired.

346.2°), and one set assumes a Late Cenozoic age (D_{ref} = 0.0°).

Improving Paleomagnetic Core Orientation

As outlined above, orienting drill cores solely on the basis of paleomagnetism can be ambiguous unless the age of the magnetization is known. This problem could be resolved in two ways. First, a more detailed paleomagnetic study could be undertaken of surface exposures in the vicinity of the multiwell site. This study would verify that the Mesaverde Formation at that site has experienced the tectonic event(s) that apparently overprinted any original Cretaceous magnetization in the Book Cliffs region. Some petrographic and rock magnetic analyses could be made of these paleomagnetic samples to determine whether surface oxidation has grossly affected the magnetic minerology.

Second, the ambiguity of the paleomagnetic core orientations could be eliminated by performing paleomagnetic orientation in conjunction with a limited amount of conventional orienting. Conventional orientations could be obtained every 500 to 1,000 vertical feet as a calibration of the paleomagnetic reference declination. This would have the added benefit of improving the accuracy of the paleomagnetic orientations by correcting for any post-magnetization structural rotation of the beds. The conventional orientations would not only help calibrate the paleomagnetic orientations but would also elucidate the age of the magnetization, if there were a systematic angular discrepancy between the conventional and paleomagnetic values.

Conclusions

Three major conclusions have emerged from this second investigation of paleomagnetic core-orienting in the Mesaverde Formation.

1. Thorough sample preparation is required for optimum grouping of paleomagnetic directions.

Contamination by steel particles acquired during sample collection and preparation has been found to be a major contributor to magnetic noise in the Mesaverde Formation. After subjecting specimens to mechanical grinding and acid rinsing, the dispersion of magnetization directions is considerably reduced. Typical k values of between 40 and 65 were obtained after more thorough sample preparation. This is a considerable improvement over results from our initial study, in which k values were typically between 10 and 30. Since the number of plugs required to obtain any given precision is inversely proportional to k, the removal of magnetic noise by more thorough sample preparation makes the paleomagnetic core orientation technique much more feasible.

2. Paleomagnetic inclinations are steepened by drilling-induced remagnetization.

The Mesaverde/Fort Union subsurface plugs contain two components of magnetization. One component, the magnetic "signal", probably is aligned with the Cretaceous to Cenozoic paleomagnetic fields, which have inclinations of 57° to 67° at the well sites. The other component, representing DIRM or magnetic noise acquired during the drilling process, points directly down-hole (inclination = 90°). Since these two components are difficult to separate, the observed magnetization directions are vector sums with ~7° steeper inclinations than the _in situ_ magnetization.

The consequence of 7° of inclination bias imposed by DIRM is that twice as many plugs need to be obtained to achieve the same level of orientation precision as could be obtained with no DIRM present. We are currently investigating techniques for more effectively separating DIRM from the _in situ_ magnetizations and for avoiding DIRM acquisition in the drill string. Neither using a Monel collar nor drilling larger diameter core have eliminated the problem of DIRM acquisition. It appears that lithologies coarser than very fine sandstone are most affected by DIRM. Thus, the most precise orientations with the fewest plugs could be obtained by sampling lithologies with the finest grain size. Moreover, it seems that the DIRM is heterogeneously distributed within each plug; improved orientation precision could therefore be obtained more efficiently by measuring two specimens per plug, rather than obtaining twice the number of plugs.

3. There is uncertainty in the age of magnetization of the Mesaverde and hence in the correct reference declination.

A major surprise of this study was that magnetization directions found in Mesaverde surface exposures near GC-1 point toward a mid to late Cenozoic pole and not toward the expected Late Cretaceous pole.

If this is not merely an artifact of weathering, then paleomagnetic orientations of subsurface core would be in error by 30° if a Cretaceous declination had been assumed as the reference direction. This source of error can be eliminated by determining the age of the magnetization of the Mesaverde Formation at the multi-well site. The magnetic age could be ascertained either (1) from a paleomagnetic study of surface exposures near the site, or (2) from a cross-check of paleomagnetic and conventionally oriented core segments. Only a small amount of conventionally oriented core (e.g., one check every 500 to 1,000 feet) would be needed to calibrate the paleomagnetic reference direction.

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APPENDIX 1

GC-1 Upper Core Segment

Plug No.	Lithologic Description	Depth (Feet)
1	gray sandstone	771.0
2	gray sandstone	771.5
3	gray sandstone-transitional	772.5
3.5	gray siltstone	773.1
4	black, carbonaceous shale	773.5
4.5	black, carbonaceous shale	773.8
5	transitional	774.1
6	transitional, soft sediment deformation	774.5
7	transitional	775.4
8	transitional	775.8
9	transitional-black	776.2
10	transitional-black	776.7
11	transitional-black	777.3
12	dark gray sandstone	777.7
13	gray, fine gr sandstone	777.9
14	transitional	778.5
15	transitional	778.8
16	½ sandstone, ½ transitional	779.4
17	sandstone	779.7
18	sandstone	779.9
19	sandstone	780.3
20	sandstone	780.6
21	sandstone with tan shale inclusions	781.1
22	sandstone with few shaly stringers	781.7
23	sandstone	782.0

GC-1 Lower Core Segment

Plug No.	Lithologic Description	Depth (Feet)
51	gray, fine gr sandstone	870.3
52	gray, fine gr sandstone	871.0
53	gray, fine gr sandstone-finely lamin.	871.6
54	gray, fine gr sandstone	872.3
55	transitional-soft sediment deformation	872.9
56	gray, fine gr sandstone	873.5
57	gray, fine gr ss with black lamin.	874.0
58	gray, fine gr sandstone	874.9
59	gray, fine gr ss with soft sed def.	875.4
60	white, fine ss-transitional	875.9
61	transitional	876.7
62	sandstone	877.2
63	sandstone	877.8
64	sandstone-transitional soft sed def	878.4
65	sandstone	878.8
66	transitional	879.3
67	coal	879.9
68	carbonaceous shale	880.4
69	carbonaceous shale	881.7
70	carbonaceous shale	882.5
71	carbonaceous shale	883.2
72	carbonaceous shale	883.8
73	carbonaceous shale	884.6
74	carbonaceous shale	885.5
75	carbonaceous shale	886.4
76	carbonaceous shale	887.7

GC-1 Upper Core Segment

Plug No.	Lithologic Description	Depth (Feet)
1	gray sandstone	771.0
2	gray sandstone	771.5
3	gray sandstone-transitional	772.5
3.5	gray siltstone	773.1
4	black, carbonaceous shale	773.5
4.5	black, carbonaceous shale	773.8
5	transitional	774.1
6	transitional, soft sediment deformation	774.5
7	transitional	775.4
8	transitional -	775.8
9	transitional-black	776.2
10	transitional-black	776.7
11	transitional-black	777.3
12	dark gray sandstone	777.7
13	gray, fine gr sandstone	777.9
14	transitional	778.5
15	transitional	778.8
16	½ sandstone, ½ transitional	779.4
17	sandstone	779.7
18	sandstone	779.9
19	sandstone	780.3
20	sandstone	780.6
21	sandstone with tan shale inclusions	781.1
22	sandstone with few shaly stringers	781.7
23	sandstone	782.0

GC-1 Lower Core Segment

Plug No.	Lithologic Description	Depth (Feet)
51	gray, fine gr sandstone	870.3
52	gray, fine gr sandstone	871.0
53	gray, fine gr sandstone-finely lamin.	871.6
54	gray, fine gr sandstone	872.3
55	transitional-soft sediment deformation	872.9
56	gray, fine gr sandstone	873.5
57	gray, fine gr ss with black lamin.	874.0
58	gray, fine gr sandstone	874.9
59	gray, fine gr ss with soft sed def.	875.4
60	white, fine ss-transitional	875.9
61	transitional	876.7
62	sandstone	877.2
63	sandstone	877.8
64	sandstone-transitional soft sed def	878.4
65	sandstone	878.8
66	transitional	879.3
67	coal	879.9
68	carbonaceous shale	880.4
69	carbonaceous shale	881.7
70	carbonaceous shale	882.5
71	carbonaceous shale	883.2
72	carbonaceous shale	883.8
73	carbonaceous shale	884.6
74	carbonaceous shale	885.5
75	carbonaceous shale	886.4
76	carbonaceous shale	887.7