PALEOMAGNETIC CORE ORIENTING FOR THE MULTIWELL EXPERIMENT

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TABLE OF CONTENTS

INTRODUCTION

The goal of this study was to use paleomagnetism to orient drill-cores of the Upper Cretaceous Mesaverde Formation as part of the Multiwell Experiment. The feasibility of using paleomagnetism to orient Mesaverde drillcore had been explored in two previous studies (Van Alstine and Gillett, 1980; Van Alstine, 1981). In those studies, the most stable magnetization of the Mesaverde was a viscous partial thermo-remanent magnetization (VPTRM) probably acquired during mid to late Tertiary uplift. This magnetization has a consistent direction (declination, D = 0°; inclination, I = +60°) through thousands of feet of stratigraphic section over a wide region; using this reference direction, paleomagnetic core orientations from the #1 Mesa Unit well in western Wyoming and from GC-1 in eastern Utah agreed (within 9°) with conventionally-oriented (multishot) values in 5 out of 5 intervals at depths between 800 and 10,500 feet. During the Multiwell Experiment, comparison of paleomagnetic and multishot core orientations provided a check on whether this same VPTRM was recorded by the Mesaverde in the southern Piceance Creek Basin of northwestern Colorado.

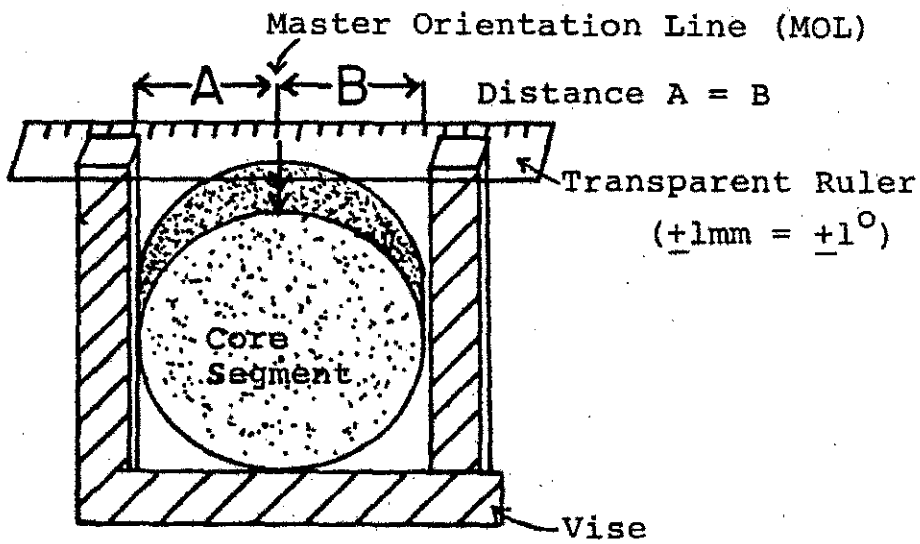
The paleomagnetic techniques developed in the previous studies were initially employed in orienting core from 11 intervals in six different core runs of MWX-1, and from two intervals in one run of MWX-2. For several of these intervals, the initial paleomagnetic orientations differed by more than 20° from the corresponding multishot values. Further analysis and inspection of the MWX core revealed an apparent bias in the paleomagnetic orientations. Removing this bias required revising the paleomagnetic sampling procedures as well as the statistical methods used to calculate the paleomagnetic orientations. The new paleomagnetic techniques were then applied in three intervals from three different runs in MWX-2 and in correcting orientations of several intervals from the MWX-1 core.

This report documents our experience in comparing two vastly different core orienting techniques. By simultaneously applying paleomagnetic and multishot methods, problems associated with each technique were dramatically revealed. The refinements in the paleomagnetic methods will be discussed in the order and context in which they were developed.

INITIAL PROCEDURES

Initial sampling, laboratory, and data analysis techniques were those employed by Van Alstine (1981). Plugs from the MWX core were collected by CER personnel near the Multiwell site, using a drill press fitted with a diamond bit cooled with diesel fuel. 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 Master Orientation Line (MOL; Figure 1). The MOL is a straight line ruled on the core after fitting together all broken core segments. The MOL generally coincides with the Principal Scribe Line (PSL), which is a distinctive groove cut into the core by one of three knives inside the core barrel; occasionally, the PSL may "drift" either to the right or left of the MOL, so that a correction must be applied before comparing the paleomagnetic and multishot core orientations.

A plug 1" in diameter and with a length nearly equal to the 4" diameter of the core was then drilled perpendicular to the core axis (Figure 1). A reference scribe line was transferred to the plug using



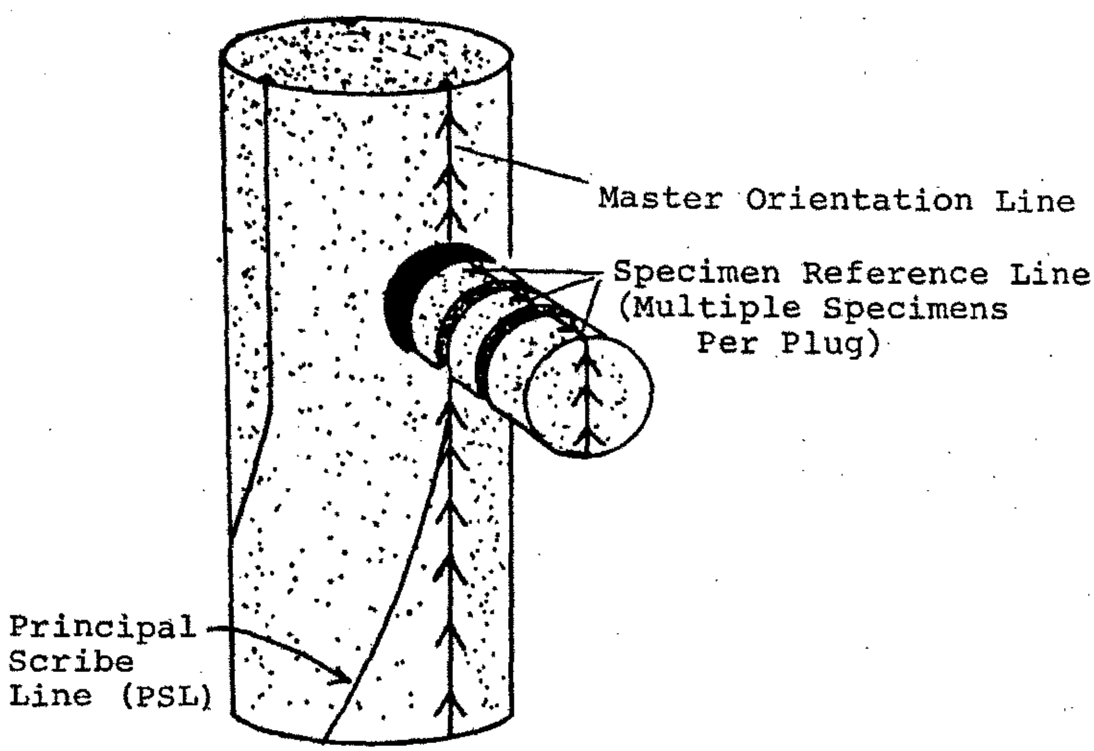


Figure 1: Procedure for collecting oriented plugs from drill core. A brass sleeve is used to transfer a reference line to each plug; this reference line is perpendicular to the core axis. The plugs are drilled on the Master Orientation Line, which may deviate from the Principal Scribe Line.

a brass orienting sleeve and non-magnetic phosphor-bronze scriber. This procedure preserves the relative declination of plugs from the same core interval and permits the angle between the magnetization vectors and the MOL to be determined within ~2°. Preference in sampling each interval was given to the finest-grained sediment (mudstone), which yielded the most precise paleomagnetic directions in the previous studies.

In the Sierra Geophysics Paleomagnetics Laboratory, the plugs were then trimmed to 0.9"-long samples using a rock saw. Generally the samples were cut so that their center was on the long axis of the core. To remove steel particle contamination acquired during plugging and sawing, all samples were sanded and/or rinsed in HCl; this was found by Van Alstine (1981) to be crucial in paleomagnetic studies of the very weakly magnetized Mesaverde Formation.

The natural remanent magnetization (NRM) of each sample was measured using a 3-axis cryogenic magnetometer manufactured by Superconducting Technology, Inc. This system has a background noise level less than 1×10^{-7} emu. The magnetometer is interfaced to a mainframe computer, allowing real-time calculation of magnetization directions and intensities.

To test the stability of the NRM, pilot samples from the first oriented core runs of MWX-1 (Runs 11 and 12) were subjected to progressive alternating-field (AF) and thermal demagnetization. Alternating-field demagnetization was performed using a Schonstedt Model GSD-5 tumbling specimen demagnetizer which provides peak fields up to 1000 oersteds (1 oersted = 0.1 millitesla). Thermal demagnetization was performed using a custom-built, non-inductively-wound, three-zone furnace with a large isothermal region (thermal gradients <3°C); samples are cooled in a separate chamber in which the ambient field is <2 gammas (nT). All measurements and demagnetization procedures were carried out in a 120-sq-ft magnetically shielded room in which the ambient field is <0.3% of the Earth's magnetic field. This improves the accuracy of the paleomagnetic analysis by minimizing the contribution of viscous remanent magnetization (VRM) to the magnetization of the samples.

The optimum demagnetization treatment of the Multiwell samples was found to be thermal demagnetization at low temperatures of 103°±4°C; this was also found to be the optimum treatment for Mesaverde samples in the study by Van Alstine (1981). Alternating-field and thermal demagnetization at higher steps preferentially destroyed the reference paleomagnetic signal, enhancing the relative contribution of secondary magnetizations acquired during drilling and plugging.

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 affected by outliers in the distribution.

The clustering of paleomagnetic directions from the MWX cores was highly variable. In this study, clustering of paleomagnetic directions from each core interval was measured by the Fisherian "concentration parameter," k (Fisher, 1953); the higher the k, the more concentrated the distribution of directions and the fewer plugs needed to achieve a given level of orientation precision. In the GC-1 and #1 Mesa Unit cores studied by Van Alstine (1981), k ranged between 22 and 78. In the Multiwell Experiment, k ranged between 15 and 1,610.

Mudstones consistently yielded the best groupings of paleomagnetic directions, whereas directions from fine to medium sandstones were more scattered. This correlation probably reflects the higher magnetic stability of the finer-grained sediments, which is to be expected from theory and which was also observed for the GC-1 and #1 Mesa Unit cores. Overall, the paleomagnetic behavior of the MWX samples was similar to that of the GC-1 and #1 Mesa Unit cores, including an average NRM intensity of about 5×10^{-7} emu/cm^3.

INITIAL CALCULATIONS OF CORE ORIENTATIONS

The initial paleomagnetic directional information from the MWX cores is presented in Table 1. To convert paleomagnetic directions into core-orientations with respect to present-day true north, it is necessary to compare these directions with the reference paleomagnetic apparent polar wander path for North America. Table 2 shows the reference paleomagnetic poles for North America from the late Cretaceous to present, and Table 3 lists the corresponding reference paleomagnetic directions that would be observed at the MWX site. In principle, the core orientations can then be calculated directly from the equation:

$$O_{MOL} = D_{Ref} - D_O$$

where O_{MOL} is the orientation of the MOL in positive degrees east, D_{Ref} is the reference paleomagnetic declination, and D_O is the observed

Table 1: SUMMARY OF INITIAL PALEOMAGNETIC DIRECTIONAL INFORMATION FROM MWX CORE

Core Segment	(D_o)* Declination	$(I_o)^{\xi}$ Inclination	(N_{mode}/N_{tot})† N	k**	B_{95}++	ΔD_{95}^{δ}
Run 11 (MWX-1) (4704.3-4712.0)	37°	78°	11 (17)	53	6.3°	31.8°
Run 12 (MWX-1) (4803.1-4815.3)	117	74	9 (15)	45	7.7	29.1
Run 24 (MWX-1) (5431.7-5440.7)	220	68	17 (20)	55	4.9	13.2
Run 24 (MWX-1) (5441.8-5448.0)	124	73	14 (15)	78	4.5	15.6
Run 25 (MWX-1) (5495.7-5503.7)	231	64	12 (15)	114	4.1	9.4
Run 25 (MWX-1) (5504.0-5513.7)	169	70	13 (15)	153	3.4	10.0
Run 41 (MWX-1) (6442.3-6463.2)	158	87	17 (19)	105	3.5	∞
Run 41 (MWX-1) (6503.3-6514.5)	221	72	12 (15)	94	4.5	14.7
Run 46 (MWX-1) (7870.5-7886.8)	240	81	9 (15)	24	10.8	∞
Run 46 (MWX-1) (7901.7-7908.9)	140	73	13 (15)	102	4.1	14.2
Run 46 (MWX-1) (7951.0-7959.6) A.	174	41	8 (9)	18	13.6	18.2
B.	5	65	5 (5)	26	15.2	38.3

Table 1. (Continued)

Core Segment	(D_o)* Declination	(I_o)ξ Inclination	(N_{mode}/N_{tot})† N		k**	B_{95}++	ΔD_{95}^{δ}
Run 47 (MWX-2) (4879.7-4886.3)	163°	+61°	11	(15)	69	5.6	11.6°
Run 47 (MWX-2) (4893.4-4907.5)	326	+82	14	(16)	21	8.8	∞

NOTES:

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* 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
$\Delta D_{95} = \arcsin(\sin B_{95}/\cos I_o)$.

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

Age	Latitude (°N)	Longitude (°E)
Late Cretaceous	67.2	189.9
Paleocene	78.9	194.3
Eocene	82.1	178.2
Oligocene-Miocene	85.0	138.0
Late Cenozoic	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 $\alpha_{95} < 5^{\circ}$, except the Paleocene pole, for which $\alpha_{95} = 10^{\circ}$.

TABLE 3

REFERENCE PALEOMAGNETIC DIRECTIONS AT THE MWX SITE*

Declination (D_{Ref})	Inclination (I_{Ref})	Age
330.1°	64.7°	Late Cretaceous
346.7	63.3	Paleocene
349.9	60.4	Eocene
354.3	56.8	Oligocene-Miocene
360.0	58.9	Late Cenozoic

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

paleomagnetic declination in the specimen coordinate system. (This equation differs slightly from that of Van Alstine (1981) because the specimen coordinate system has since been rotated by 180° to facilitate the orientation calculation.)

Deriving accurate core orientations from the paleomagnetic data requires that the correct reference magnetization direction be known. Because the reference paleomagnetic direction had not been previously determined for the Mesaverde of the Piceance Creek Basin, two sets of core orientations are listed in Table 4, depending on whether a late Cretaceous or a late Cenozoic magnetization direction is assumed. At the MWX site, the difference between these magnetizations is 30°. By comparing these values with orientations derived from the multishot technique, the correct magnetization direction can be determined.

DISCOVERY OF BIAS IN THE INITIAL PALEOMAGNETIC RESULTS

The initial paleomagnetic directions were more consistent with a late Cenozoic magnetization direction in 82% (9/11) of the sampled intervals with an adequate data base. (Results from Runs 11 and 12 are not considered, because of problems in collecting paleomagnetic plugs, and because of uncertainties in the location of the multishot photographs with respect to the paleomagnetic plugs.) This suggested that the Mesaverde in the MWX core had indeed recorded the same Cenozoic VPTRM observed in the previous studies. Even using the Cenozoic reference direction, however, the initial paleomagnetic and multishot core orientations diverge by more than 30° in 4 out of 11 intervals, and by more than 10° in 8 out of 11 intervals (Table 4).

TABLE 4

COMPARISON BETWEEN INITIAL PALEOMAGNETIC AND MULTISHOT MWX CORE ORIENTATIONS

Core	Run #/Interval	Pmag. Orientation[†] vs. Mag. Age Cret.	Cenoz.	Multishot[††] Orientation	Discrepancy[§]
MWX-1	Run 11 (Mudstone) (4704.3-4712.0)	293°	323°	19° (1) ?	?
MWX-1	Run 12 (Mudstone) (4803.1-4815.3)	213°	243°	208° (1) ?	?
MWX-1	Run 24 (Mudstone) (5431.7-5440.7)	110°	140°	140° (3)	0°
MWX-1	Run 24 (Mudstone) (5441.8-5448.0)	206°	236°	271° (1)[20°L]	+35°
MWX-1	Run 25 (Mudstone) (5495.7-5503.7)	99°	129°	108° (3)[10°L]	-21°
MWX-1	Run 25 (Mudstone) (5504.0-5513.7)	161°	191°	215° (1)[20°L]	+24°
MWX-1	Run 41 (Med ss) (6442.3-6463.2)	172°	202°	350° (6)	+148°
MWX-1	Run 41 (f-vf ss) (6503.3-6514.5)	109°	139°	182° (4)	+43°
MWX-1	Run 46 (F-vf ss) (7870.5-7886.8)	90°	120°	90° (4)	-30°
MWX-1	Run 46 (Mudstone) (7901.7-7908.9)	190°	220°	235° (3)[8°L]	+15
MWX-1	Run 46 (Med ss) (7951.0-7959.6)	A.156°(N=9)	186°	194° (2)	+8°
		B.325°(N=5)	355°	194° (2)	-161°
MWX-2	Run 47 (Mudst-sltst) (4879.7-4886.3)	167°	197°	233° (2)[5R, 35L]	+36°
MWX-2	Run 47 (Slt-vf ss) (4893.4-4907.5)	4°	34°	42° (3)	+8°

Table 4 (Cont'd.)

NOTES:

† Paleomagnetic core orientations of the MOL as a function of late Cretaceous (left) or late Cenozoic (right) magnetization age.

†† Multishot orientations of the MOL, based on averaging the number of photographs indicated in parentheses and applying the PSL drift correction indicated in brackets.

§ Discrepancy between multishot and paleomagnetic core orientations of the MOL (multishot minus paleomag. values), and assuming a Cenozoic magnetization age.

These discrepancies between the initial paleomagnetic and multishot orientations for the MWX cores were greater than had been anticipated from the previous study of Van Alstine (1981). Moreover, the magnitude and sense of the discrepancies at first did not seem to be predictable; even in mudstones yielding tight groupings of paleomagnetic directions, the paleomagnetic orientations commonly deviated from the multishot values by more than the formal statistical confidence limits (ΔD_{95}; Table 1).

One source of discrepancy between paleomagnetic and multishot core orientations is drift of the PSL with respect to the MOL, which reached a maximum of 35° for Run 25. For all intervals in which a drift correction was applied, the paleomagnetic and multishot values were brought into closer agreement, but still did not coincide. Determining the source of the residual discrepancy required reexamination and comparison of the paleomagnetic and multishot data with the actual MWX-1 core.

The key to understanding the source of discrepancy between the two orienting techniques was found in the "Rosetta interval," Run 25 of MWX-1. The first proof of bias in the paleomagnetic data came upon detailed examination of the core by D. R. Van Alstine and D. C. Bleakly on February 8, 1982. Thirty plugs had been analyzed from Run 25 between depths of 5,496 and 5,514 feet. Fifteen of the plugs were taken above a connection made at 5,504 feet, and the other 15 plugs were taken below the connection (Figure 2). Because a tight fit could be made of the core across the connection, it was possible to measure directly the angle between the sets of plugs above and below the connection. Although this angle was measured to be 103°, the

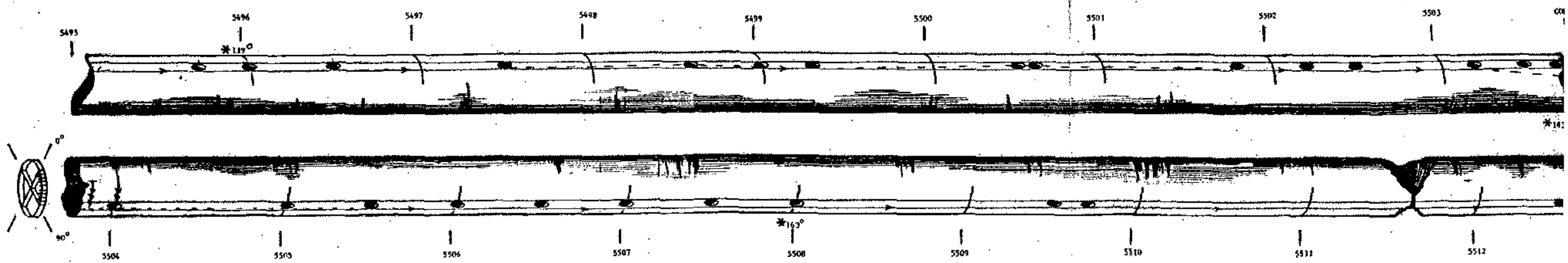

Figure 2:

MWX-1
Run 25 Paleomagnetic Plug Sequence
5495-5514 feet

Master Orientation Line (MOL)
Principal Scribe Line (PSL)
Sample Location
PSL Rotation Angle
Sample Location Rotation Angle
PSL Trace
Multishot Photograph

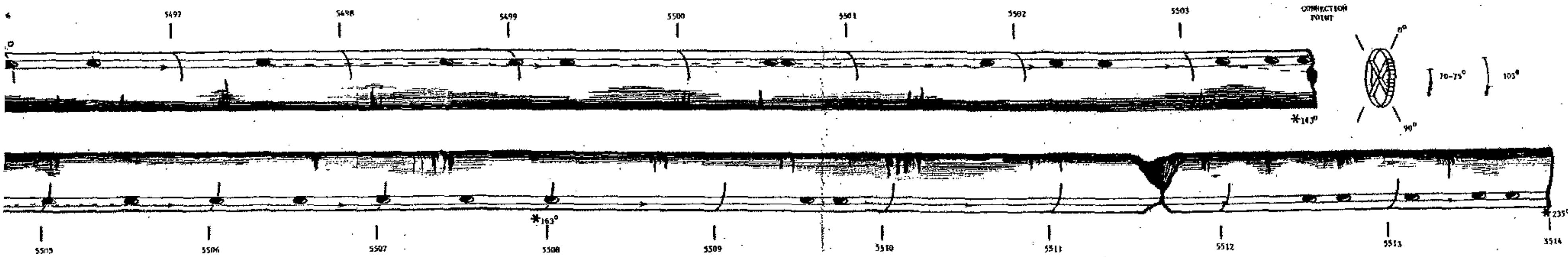

Figure 2:

MWX-1
Run 25 Paleomagnetic Plug Sequence
5495-5514 feet

Master Orientation Line (MOL)

Principal Scribe Line (PSL)

Sample Location

PSL Rotation Angle

Sample Location Rotation Angle

PSL Trace

Multishot Photograph *

paleomagnetic orientations had indicated a difference of only 62°. This meant that the paleomagnetic orientations were in error by 20° to 40°, even though their ΔD_{95} values (Table 1) were ≤10°. (Inspection of this interval also revealed a multishot photograph that was in error by ~70°; a photograph taken at 5508 feet had an azimuth of 163° and another photograph at 5514 feet had an azimuth of 235°, even though drift of the PSL over this interval was <15°.)

The discrepancy between the paleomagnetic orientations across the connection can be traced to a systematic, secondary magnetization acquired during plugging. Because the core lies horizontally during plugging, a magnetization directed vertically down the barrel of the drill-press bit would impart an apparent horizontal component (i.e., I = 0°) pointing directly away (i.e., D = 180°) from the MOL. The more the "true" paleomagnetic declination in the plug deviates from the direction of drill press bias, the more the estimate of the true declination will be biased by any unremoved secondary magnetization imparted during plugging. Thus, the discrepancy between the paleomagnetic and multishot orientations for Run 25 can be explained by the fact that the true paleomagnetic directions from each interval lie on either side of the bias direction and hence have been "pulled together."

This directional bias caused by drill press remanent magnetization (DPRM) has been observed in other paleomagnetic studies of subsurface drillcore (e.g., Van Alstine and Gillett, 1981, 1982; Bleil, 1980). In our paleomagnetic studies of drillcore from Columbia River basalt, distributions of NRM directions commonly show DPRM bias (Figure 3), even though each plug was from a different core segment that was unoriented in azimuth with respect to adjacent segments.

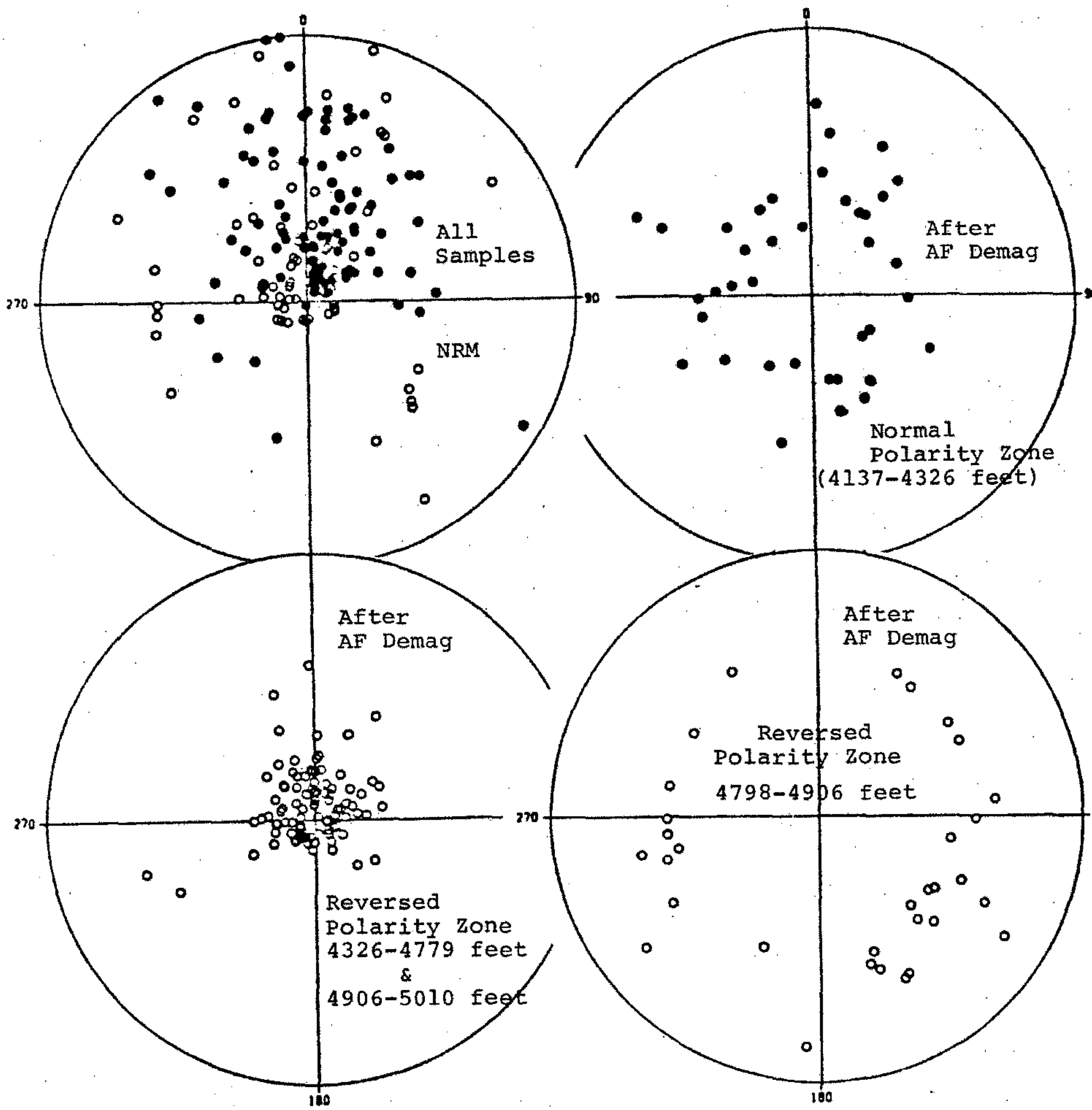

Figure 3: Paleomagnetic directions in drillcore of Columbia River basalt from depths between 4137 and 5010 feet in corehole DC-7 (from Van Alstine and Gillett, 1981). Note the bias of NRM declinations (top left) toward 0°, which is directly down the barrel of the drill press bit in the specimen coordinate system of that study. After AF demagnetization (3 other stereonet plots), the directions show very little declination bias, indicating that most of the drill press remanent magnetization has been removed. All directions are from different plugs that are unoriented in azimuth with respect to one another.

The biasing magnetization acquired during plugging is probably a form of drilling-induced remanent magnetization (DIRM). Although DIRM is commonly observed in subsurface drillcore (cf. Van Alstine and Gillett, 1981, 1982; Johnson, 1979), it usually reflects a magnetization imposed predominantly during subsurface drilling, rather than during plugging. Any DIRM acquired during drilling points directly down-hole and hence would not cause any bias in NRM declinations. Indeed, a steep, downward-pointing DIRM component was observed in the previous studies of Mesaverde drillcore, indicating that the Mesaverde is susceptible to acquisition of DIRM.

In summary, the bias of paleomagnetic directions from Run 25 can be attributed to residual DIRM acquired during plugging with the drill press. Apparently, thermal demagnetization of MWX plugs cannot remove this magnetization imposed by the drill press, just as it cannot remove all the DIRM imposed by subsurface coring.

RESOLUTION OF THE PROBLEM USING NEW PALEOMAGNETIC METHODS

Inspection of core from Run 25 suggested a new technique for circumventing the bias caused by DPRM. This method is based on vector analysis of paleomagnetic directions from two sets of plugs collected from the same interval of core but plugged at a different (but known) angle with respect to the MOL. If these plugs were totally unbiased by DPRM, then the observed paleomagnetic declinations for the two groups would differ by the known angle and would have the same inclinations. Hence, the degree to which (1) the mean declinations of the two groups do not differ by the known angle, and (2) the inclinations of the two groups differ from each other, allows the DPRM biasing component to be determined. The direction and magnitude of the mean biasing vector can then be calculated by assuming that the true angle between the sets of plugs is known, and that the amount of DPRM in both sets of plugs is the same on the average. Both of these assumptions are reasonable: with modest care, the angle between the two sets of plugs can be measured to within a few degrees, and the amount of DPRM within both sets can be made rougly equal by ensuring that all plugs are taken from the same lithology, at alternating depths, and with the same drill bit. Once an average DPRM vector is calculated, it can be subtracted from the vector means of the two groups to yield corrected means that are much better estimates of the true (VPTRM) magnetization direction.

The success of this vector analysis method is apparent from recalculating the paleomagnetic orientations from Run 25 (Figure 4). Paleomagnetic orientations based on NRM directions from both the upper and lower intervals in Run 25 differ from the corresponding multishot values by 26°. After thermal demagnetization to 107°C, these discrepancies are reduced to 15° and 21°, respectively. In contrast, applying the vector analysis technique to the 107°C paleomagnetic data reduces the discrepancies to 5° and 1°. This example shows that the vector analysis method is far more powerful than thermal demagnetization alone in removing the DPRM component and in determining accurate core orientations.

All subsequent paleomagnetic core orienting for the Multiwell Experiment was performed using the vector analysis technique. For all runs, the angle between the two sets of plugs was chosen to be 180°; this angle guaranteed that, for each interval, the mean of one of the

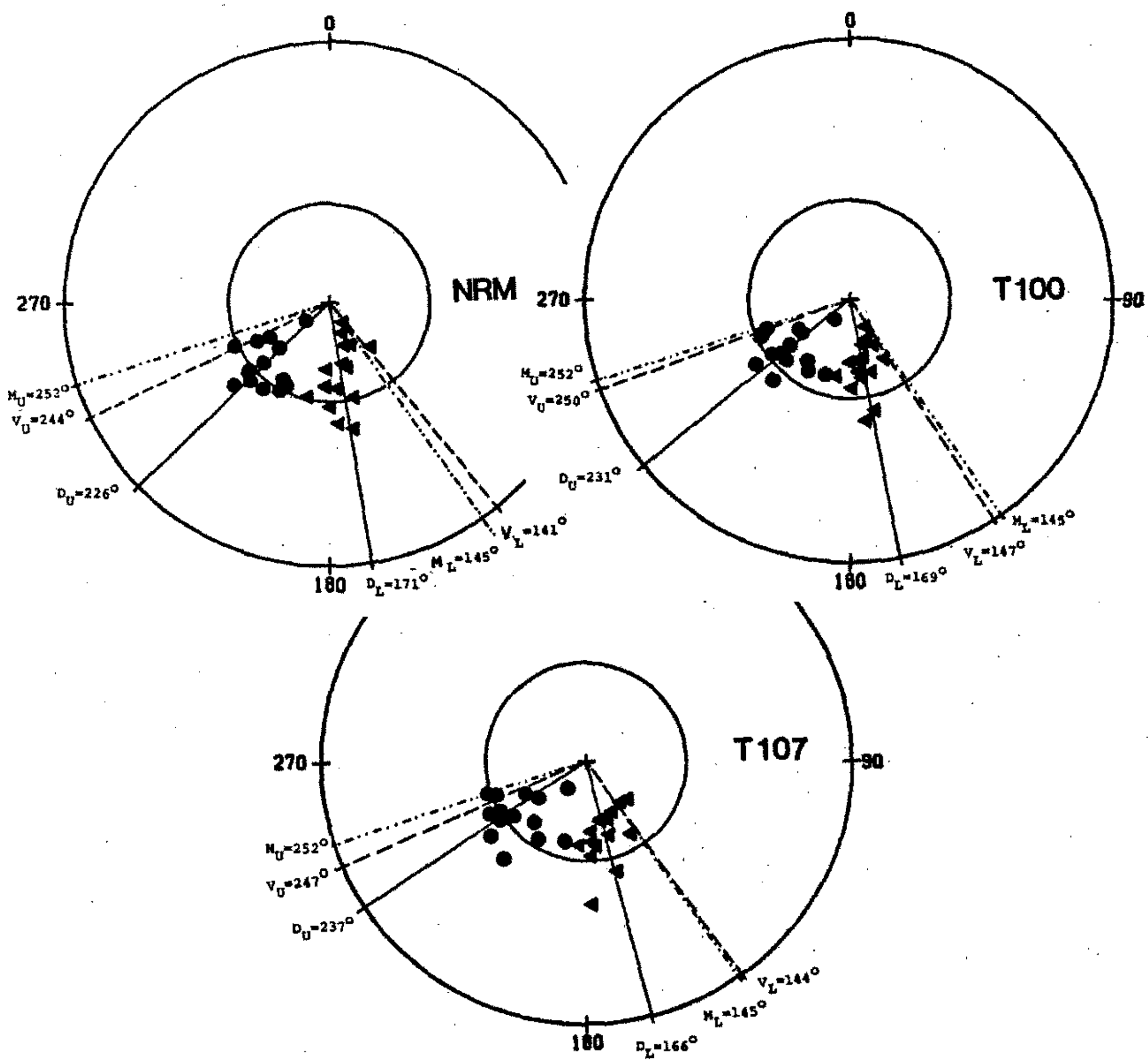

Figure 4: Stereographic projection showing paleomagnetic directions from two mudstone intervals of Run 25, MWX-1. Solid circles represent paleomagnetic directions from individual plugs between 5495.7 and 5503.7 feet; triangles between 5504.0 and 5513.7 feet. A connection had been made between these two intervals.

Angles denoted by M designate multishot orientations of Table 4 converted into paleomagnetic directions using Eq.(1) of the text and assuming a late Cenozoic magnetization. Angles denoted by V are best estimates of the true paleomagnetic direction from each interval, using the new vector analysis method for eliminating drill press remanent magnetization, which points toward ~180°. Angles denoted by D represent the mode of observed paleomagnetic directions at the indicated demagnetization step (NRM = natural remanent magnetization; T100 and T107 indicate directions observed after thermal demagnetization at 100° and 107°C). Subscripts U and L refer to upper and lower Run 25 interval, respectively. The small circle is the inclination (+59°) of the Cenozoic reference magnetization at the MWX site. All directions are on the lower hemisphere and have normal polarity. All Run 25 plugs were drilled on the MOL's, which differ by 103° between the two intervals.

sets of plugs would fall within 90° of the biasing azimuth and hence would not be excessively distorted by the DPRM component.

APPLICATION OF THE NEW TECHNIQUE TO MWX CORE

The first intervals in which the new vector analysis technique was strictly applied are Runs 51, 56, and 57 of MWX-2. Paleomagnetic results from these intervals revealed the pervasiveness of the DPRM problem and suggested that even the vector analysis method is not able to completely eliminate this source of bias. Moreover, paleomagnetic results from two of these intervals demonstrated a serious error associated with the multishot technique.

In Run 51, the bias direction is essentially parallel to the observed paleomagnetic declinations (Table 5, Figure 5). The separation angle between average NRM directions from the two sets of plugs is 160°, which was the largest separation angle observed from the intervals in which the vector analysis technique was applied. This indicates that the Run 51 interval is least likely to have been biased by unremoved DPRM.

Comparison of the paleomagnetic, multishot, and stress analysis data from Run 51, however, revealed major discrepancies among the orientations derived from the three techniques (Table 6). The paleomagnetic orientation for this Run 51 interval is 176°E, using the vector analysis technique (Table 6). In contrast, 6 multishot photographs taken from this interval yielded values of 9°E (6482.5 feet), 15°E (6487.7 feet), 17°E (6493.8 feet), 19°E (6498.0 feet), 21°E (6504.9 feet), and 22°E (6508.0 feet). (Over this interval, there was no deviation between the PSL and the MOL, revealing that individual

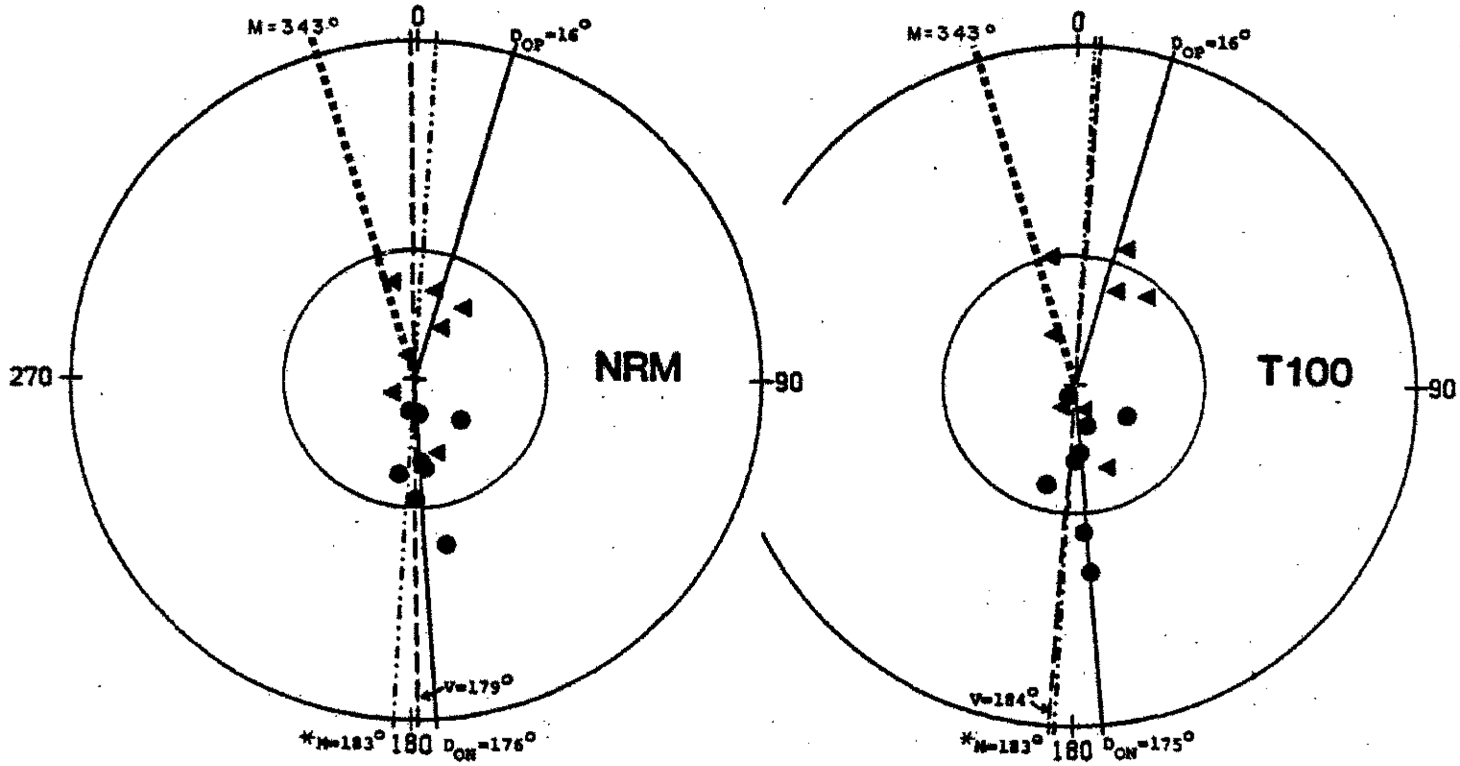

Figure 5: Paleomagnetic directions from mudstones of Run 51, MWX-2 at depths between 6482.5 and 6508.0 feet. Solid circles represent directions from plugs drilled on (D_{ON}) the MOL, and solid triangles represent plugs drilled opposite (D_{OP}) the MOL. Angles labeled M and depicted by the dotted line represent the uncorrected multishot values; angles labeled *M and depicted by the dashed-dot line represent the corrected multishot value (160°-addition), which is probably the correct orientation for this interval (see text). For comparison with the observed paleomagnetic directions, the multishot orientations have been converted into their corresponding paleomagnetic directions using Eq. (1) of the test and assuming a Cenozoic magnetization. Angles labeled V and depicted by the dashed line are derived by the new vector analysis method. Angles labeled D and depicted by solid lines are derived from the modes of the observed paleomagnetic directions.

TABLE 5: PALEOMAGNETIC DIRECTIONAL INFORMATION FOR MWX INTERVALS IN WHICH THE VECTOR ANALYSIS METHOD WAS APPLIED

Core Segment	(D_o)* Declination	$(I_o)^{\zeta}$ Inclination	(N_{mode}/N_{tot})† N	k**	β_{95} ++	ΔD_{95} δ
Run 51 (MWX-2)	175°	+76°	6 / 8	66	8.3°	36.6°
(6482.5-6508.0)	Z 16°	+68°	5 / 8	38	12.6°	35.6°
Run 56 (MWX-2)	76°	+70°	6 / 8	306	3.8°	11.2°
(7897.6-7901.2)	Z 207°	+67°	8 / 8	141	4.7°	12.1°
Run 46 (MWX-1)	147°	+66°	4 / 4	1459	2.4°	5.9°
(7901.7-7908.9	Z 292°	+76	5 / 5	401	3.8°	15.9°
Run 57 (MWX-2)	81°	+73°	5 / 8	274	4.6°	15.9°
(8130.2-8138.4)	Z 227°	+75°	6 / 8	243	4.3°	16.8°

NOTES:

Values for Runs 51, 56, and 57 are derived from the 100°C thermal demag. step; Values for Run 46 are derived from the 107°C thermal demag. step.

* Declination of the mode of specimen directions, in the specimen coordinate system. Values preceded by Z (not preceded by Z) are from plugs drilled opposite the MOL (on the MOL), respectively.

ζ 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 concentration parameter (Fisher, 1953) for the N_{mode} samples

++ β_{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. $\Delta D_{95} = \arcsin(\sin \beta_{95}/\cos I_o)$

TABLE 6: COMPARISON BETWEEN PALEOMAGNETIC AND MULTI-SHOT CORE ORIENTATIONS FOR MWX INTERVALS IN WHICH THE VECTOR ANALYSIS METHOD WAS APPLIED

Core	Run #/Interval	Pmag. Orientation† vs. Mag. Age Cret.	Cenoz.	Multishot†† Orientation	Discrepancy§
MWX-2	Run 51 (Mudstone) (6482.5-6508.0)	146° (155°)	176° (185°)	17° (6)	-159° (-168°)
MWX-2	Run 56 (Mudstone) (7897.6-7901.2)	288° (254°)	318° (284°)	182° (2)	-136° (-102°)
MWX-2	Run 57 (Mudstone) (8130.2-8138.4)	264° (248°)	294° (279°)	298° (5)	+4° (+19°)
MWX-1	Run 46 (Mudstone) (7901.7-7908.9)	195° (183°)	225° (213°)	235° (3) [8°L]	+10° (+22°)

NOTES:

† Paleomagnetic core orientations of the MOL as a function of late Cretaceous (left) or late Cenozoic (right) magnetization age. For each interval, the upper pair of numbers is based on the new vector analysis method for deriving paleomagnetic orientations (107°C thermal demag. data); the lower pair of numbers is based on the former method of deriving orientations from the mode of directions from plugs drilled on the MOL (Table 5 values).

†† Multishot orientations of the MOL, based on averaging the number of photographs indicated in parentheses and applying the PSL drift correction indicated in brackets.

§ Discrepancy between multishot and paleomagnetic core orientations of the MOL (multishot minus Cenozoic paleomagnetic value). For each interval, the upper number is based on the new vector analysis technique and the lower number (in parentheses) is based on the former technique of using the mode.

multishot values differed by up to 8° from the average value of 17°E.) Thus, the paleomagnetic and multishot orientations from this Run 51 interval differed by 176°E - 17°E = 159°. Moreover, the stress analysis orientations for this interval differed by ~20° from their expected value (D. C. Bleakly, J. A. Clark, personal communication). These angular discrepancies were probably caused by a multishot orientation error that was not discovered until Run 57, as discussed in more detail below.

The vector analysis method was even more essential in paleomagnetically orienting core from Run 56. In this interval, the separation angle between paleomagnetic directions from plugs drilled on and opposite the MOL is 117° for the NRM data, indicating appreciable drill press bias (Table 5, Figure 6). By this separation-angle criterion, Run 56 was the interval that was demonstrably most biased by DPRM. Even after thermal demagnetization to 107°C, the separation angle is only 134°, rather than the 180° angle that would be observed if no bias were present. If a paleomagnetic orientation had been calculated by the procedure used by Van Alstine (1981) and in Table 4 of this study, this orientation would differ by 32° from the orientation calculated using the vector analysis method.

As in Run 51, the Run 56 multishot orientations diverged widely from the paleomagnetic orientations and from the stress analysis data (Table 6). Two multishot photographs were taken over the interval plugged for paleomagnetic analysis. These two photographs yielded orientations of 182°E (7900.3 feet) and 183°E (7904.8 feet). In contrast, the calculated paleomagnetic orientation (derived from the 107°C data and using the vector analysis method) is 318°E (Table 6). Thus, the paleomagnetic and multishot orientations for this Run 56 interval differed by 318°E - 182°E = 136°.

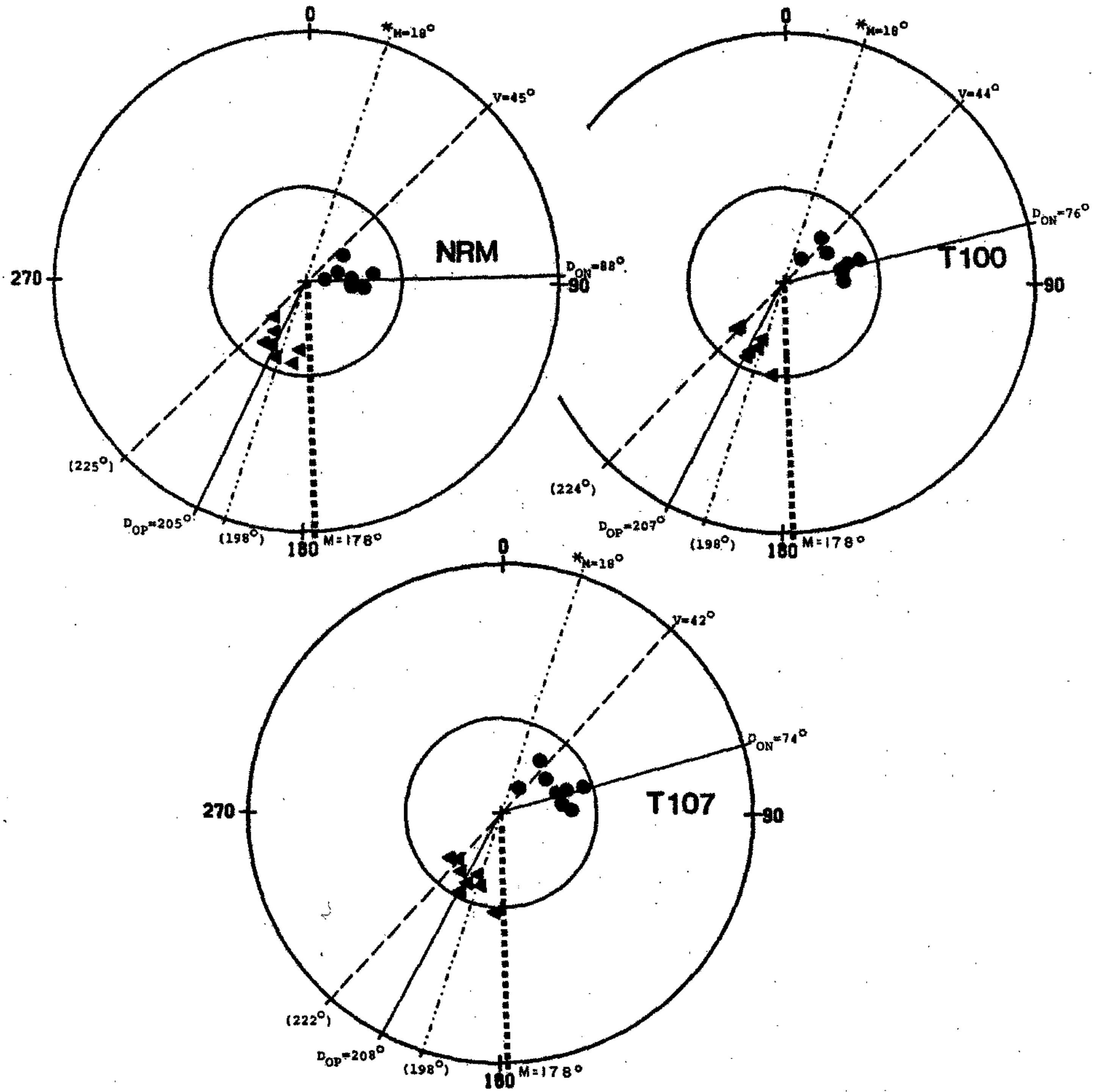

Figure 6: Paleomagnetic directions from mudstones of Run 56, MWX-2 at depths between 7897.6 and 7901.2 feet. Symbol conventions are as in Figure 5.

To check on the orientation discrepancy in Run 56 of MWX-2, the equivalent stratigraphic interval was resampled in Run 46 of MWX-1. The NRM data from the resampled core showed appreciable DPRM bias, as revealed by the 123° separation angle between plugs drilled on and opposite the MOL (Figure 7). This bias is significantly reduced by thermal demagnetization to 107°C, as evidenced by the increase in the separation angle to 145°. Applying the vector analysis method to the 107°C data reduces the discrepancy between the multishot and paleomagnetic core orientations from 22° (as calculated by the former technique of using the mode) to 10° (calculated by the vector method) (Table 6). Besides demonstrating the value of the vector analysis method, these paleomagnetic results from resampled Run 46 of MWX-1 confirm that the correct reference paleomagnetic declination at this depth is indeed ~0°; if the Cretaceous magnetization age were assumed, the discrepancy increases to 40°. Thus, the discrepancy between the paleomagnetic and multishot orientation data from Run 56 of MWX-2 must have some cause other than an anomaly in the recorded paleomagnetic field direction.

Several other important observations were made in resampling Run 46. For example, these results emphasize that the Fisherian k value is not a reliable guide to the accuracy of the paleomagnetic orientations. The distribution of paleomagnetic directions from the 4 plugs drilled on the MOL is 1,610, the highest value encountered in the MWX study; yet, the mode of paleomagnetic directions from these samples is biased by 12° from the vector analysis value and by 29° from the corresponding multishot value. Another important discovery is that the resampled plugs drilled on the MOL contain 7° more DPRM bias than the

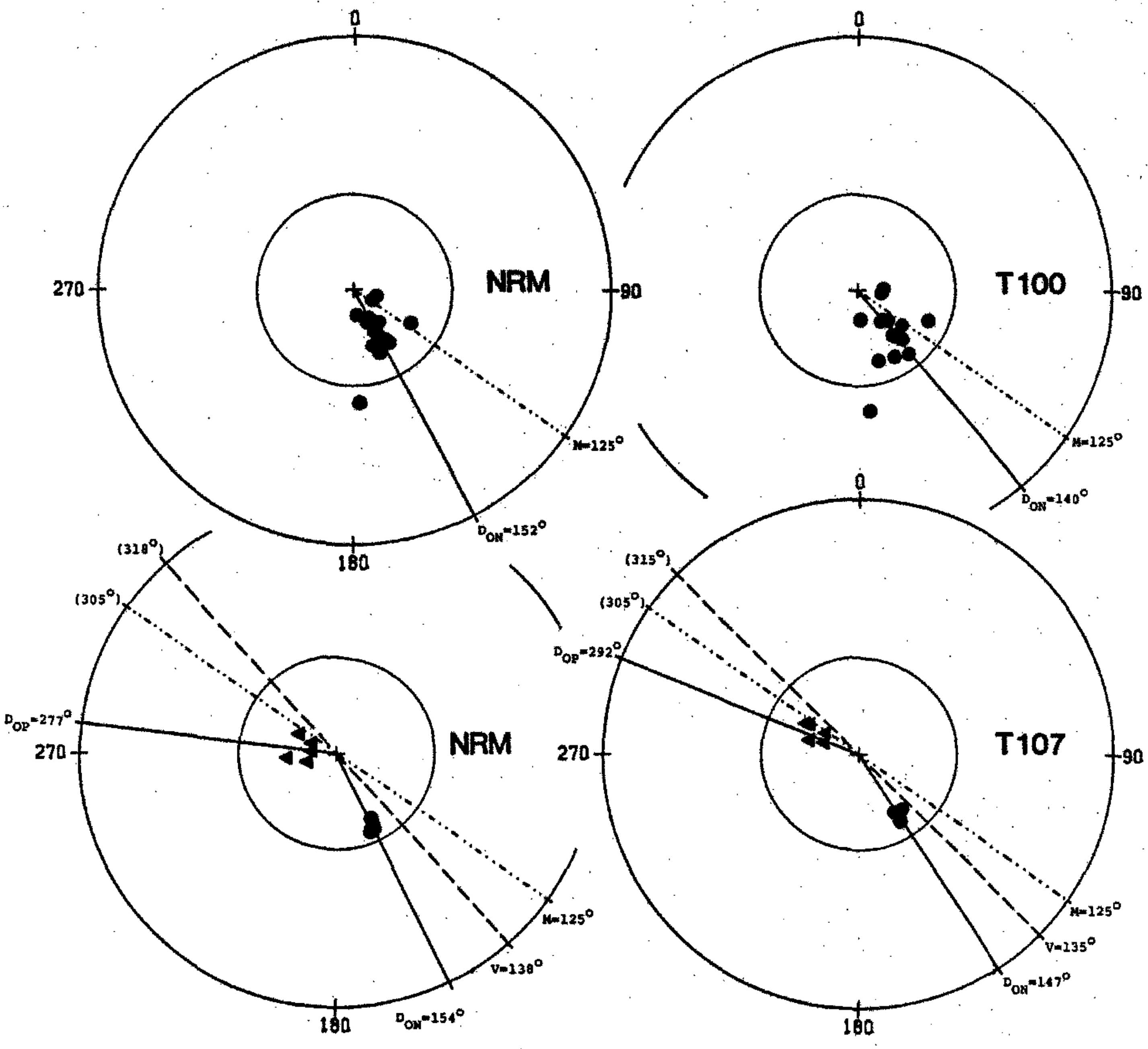

Figure 7: Paleomagnetic directions from mudstones of Run 46, MWX-1 at depths between 7901.7 and 7908.9 feet. Top row = original plugs of December, 1981; bottom row = resamples of May, 1982. Symbol conventions are as in Figure 5.

original plugs from Run 46. This difference probably reflects an increase in the intensity of magnetization of the drill-press bit between the initial sampling in December, 1981, and the resampling in May, 1982; in fact, a new bit had been installed just prior to the original plugging of Run 46, whereas at the time of replugging, the same bit had by then been used to collect several hundred plugs. This further implicates the magnetization of the drill-press bit as a source of bias in paleomagnetic core orientations and emphasizes the importance of collecting two sets of plugs (on and opposite the MOL) closely in time and using the same bit.

The value of the vector analysis method in paleomagnetic core orienting was also demonstrated in Run 57, where the drill-press bias direction is almost perpendicular to the VPTRM component (Figure 8). Even after thermal demagnetization at 107°C, the observed separation angle between paleomagnetic directions from plugs drilled on and opposite the MOL is 151°, rather than the unbiased 180°. Applying the vector analysis method to the 107°C data yields a paleomagnetic orientation of 294°E for this interval.

It was on Run 57 that a major source of error in the multishot orientations was discovered. Specifically, it was found on this run that the wrong scribing knife initially had been aligned with the multishot survey instrument. On MWX-2, an asymmetrical set of knives was used, having the geometry depicted in Figure 9. With this geometry, correcting the multishot values derived from erroneous knife alignment would require either adding 160° to, or subtracting 110° from, the reported multishot values, depending upon which knife was aligned with the survey instrument. On Run 57 the error in knife alignment was

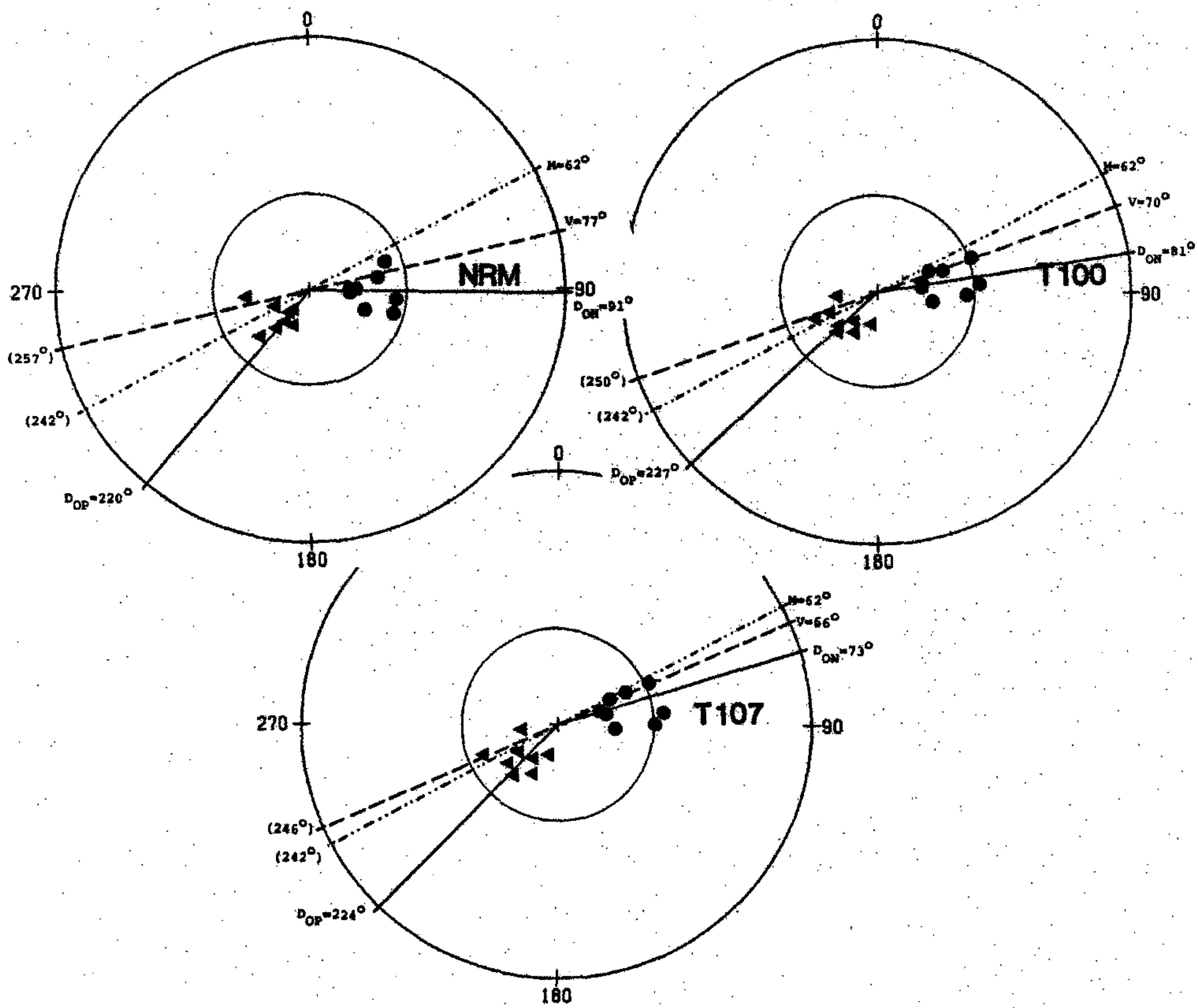

Figure 8: Paleomagnetic directions from mudstones of Run 57, MWX-2 at depths between 8130.2 and 8138.4 feet. Symbol conventions are as in Figure 5.

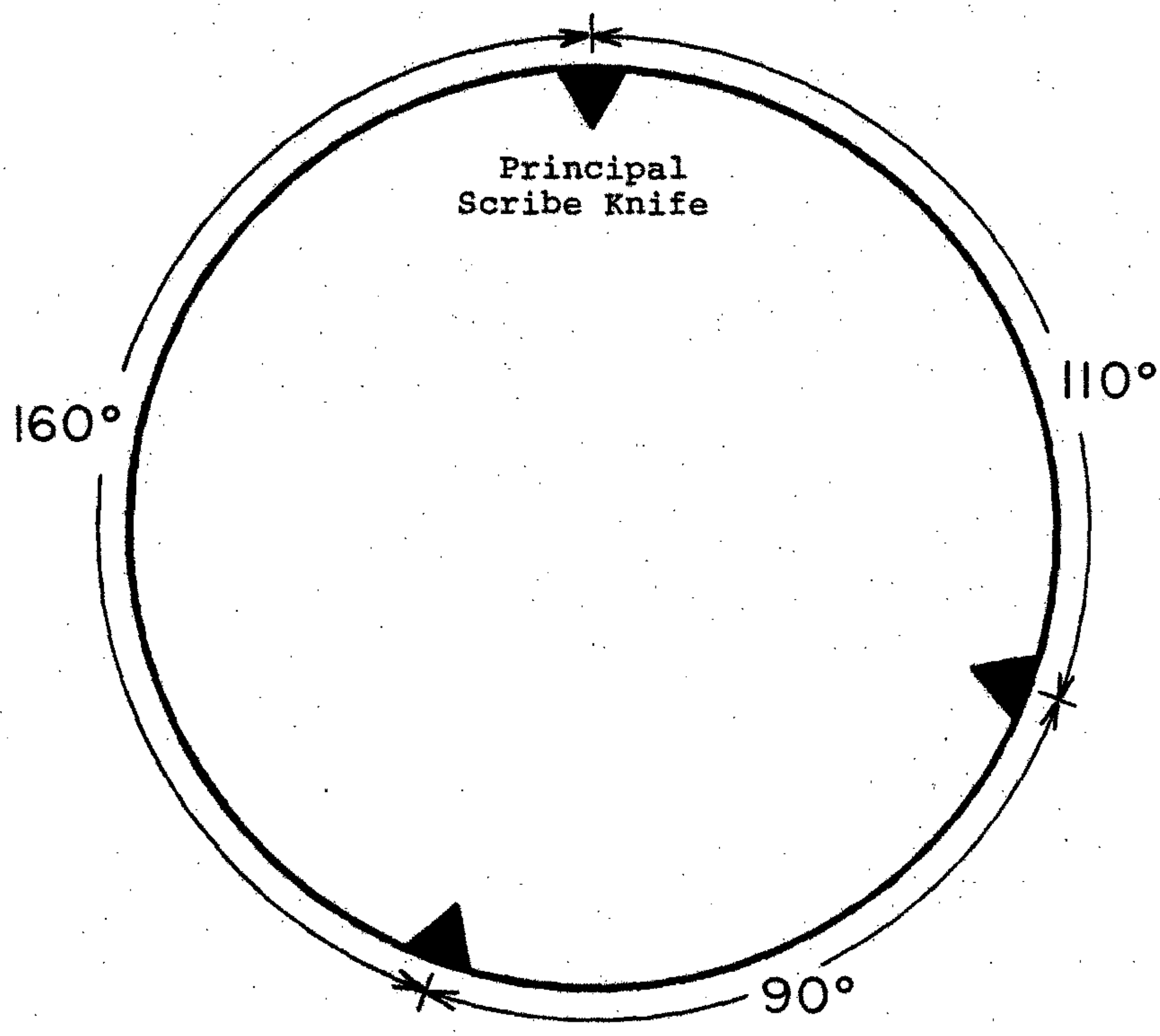

Figure 9: Configuration of the three multishot scribing knives (shown as solid triangles) used on MWX-2. View looking downhole.

found and corrected prior to tripping downhole. Thus, no additional corrections are required in evaluating the five multishot photographs from this Run 57 interval, which yielded orientations of 298°E (8122.4 feet), 298°E (8127.6 feet), 298°E (8132.3 feet), 297°E (8137.4 feet), and 297°E (8139.1 feet). There was no drift of the PSL with respect to the MOL over this interval, and the average multishot value of 298°E compares well with the paleomagnetic orientation of 294°E and with the stress analysis data.

A knife alignment error, like that discovered on Run 57, appears to be the best explanation of the discrepancy noted on Run 51 and best explains most of the discrepancy between the paleomagnetic and multishot orientations also for Run 56. For Run 51, if the 160° addition correction is made to the average multishot value, the corrected multishot orientation becomes 17°E + 160° = 177°E, which is concordant (within 1°) with the paleomagnetic orientation of 176°E and with the stress analysis data. In contrast, the 110° subtraction would yield a corrected multishot orientation of 267°E, which differs by 86° from the paleomagnetic orientation and which deviates widely from the stress analysis data. Thus, there is a clear indication from the Run 51 data that the 160°-addition correction is appropriate and that a knife alignment error had been made.

On Run 56 a 160°-addition correction also yields the best fit of the paleomagnetic, multishot, and stress analysis orientation data. When the 160°-addition correction is applied to the Run 56 data, the average multishot orientation becomes 182°E + 160° = 342°E. The reduces the discrepancy between the paleomagnetic and multishot orientations from 136° (318°E - 182°E) to 24° (342° - 318°E) and brings the stress analysis data within 10°-15° of the corrected multishot value. On the other hand, when the 110°-subtraction correction is applied, the corrected multishot orientation becomes 182° - 110° = 72°, which deviates by 246° (318°E - 72°E) from the paleomagnetic orientation. These results strongly suggest, therefore, that the same knife alignment error was made on Run 56 as was even more clearly indicated on Run 51. The significance of the apparent 24° residual discrepancy in the Run 56 paleomagnetic orientation is discussed in more detail below.

ACCURACY OF MWX PALEOMAGNETIC CORE ORIENTATIONS

This study has revealed a problem which if ignored can cause major errors in paleomagnetic core-orientations. This problem can be traced to a secondary magnetization acquired during plugging of the core. By applying a new method of taking plugs and of deriving paleomagnetic orientations, however, it is possible to correct for most of the bias imposed during plugging.

When the new paleomagnetic method was applied on four MWX intervals, a systematic discrepancy between the paleomagnetic and multishot orientations was reduced by about 60% (Figure 10). A residual, systematic discrepancy, however, suggests that the new technique does not perfectly compensate for drill press bias, perhaps owing to breakdown in one or more of the assumptions made in this method. The data acquired thus far suggest that core orientations derived by the vector method become less accurate as the magnitude of the DPRM component increases. One measure of the amount of drill press bias is the size of the separation angle between paleomagnetic directions from

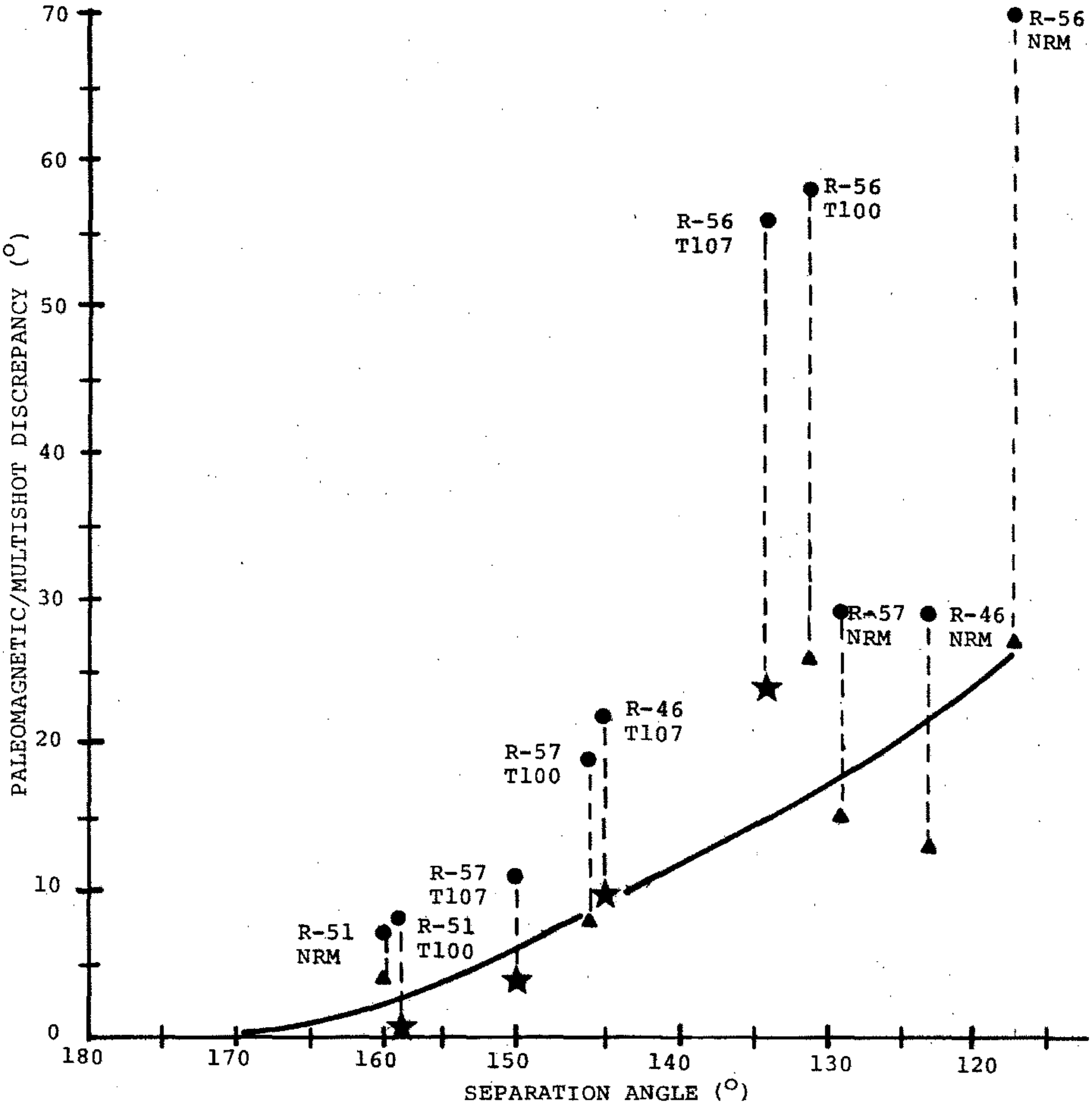

Figure 10: Comparison of the discrepancy between multishot/paleomagnetic core orientations (ordinate) versus observed separation angle between paleomagnetic directions from plugs drilled on and opposite the MOL (abscissa). Solid dots are based on paleomagnetic core orientations derived from the previous method of using the mode of plugs drilled on the MOL. Solid triangles and stars are based on paleomagnetic orientations using the new vector analysis technique. Stars are the final, best estimate of the paleomagnetic orientations for each of the 4 intervals. Data are from Runs 51, 56, and 57 of MWX-2 and Run 46 of MWX-1, measured at NRM and after thermal demagnetization at 100°C (T100) and 107°C (T107). Vertical dashed tie lines connect orientations based on the same data set but using the different paleomagnetic orientation techniques. Note that the vector analysis method reduces the discrepancy between the multishot and paleomagnetic orientations by about 60% and that the residual discrepancy increases for smaller separation angles, which reflect more pervasive drill press bias. This trend is represented by the solid curve, from which a correction factor could be derived.

plugs drilled on and opposite the MOL. The trend in Figure 10 suggests that there is a correspondence between decrease in this separation angle and increase in the discrepancy between multishot and paleomagnetic core orientations.

To some extent, the apparent relationship between multishot/paleomagnetic discrepancy versus paleomagnetic separation angle may be an artifact of a limited data base. The slight reduction (3°) in this discrepancy for Runs 56 and 46, despite a considerable increase (~20°) in separation angle upon thermal demagnetization, suggests that other sources of error may be responsible; for example, positioning of the MOL can be in error by up to 10°, as observed for Run 25. The reality of the trend suggested in Figure 10, however, is supported by the data from Run 57, in which the discrepancy between the multishot and paleomagnetic orientations is reduced from 15° (at NRM) to 8° (after 100°C) to 4° (after 107°C) as the separation angle increases from 129° to 146° to 151°.

The apparent relationship between a systematic error in the paleomagnetic orientations and the amount of drill press bias is important for two reasons. First, this relationship allows the accuracy of any given paleomagnetic orientation to be estimated; for example, if the observed separation angle between mean paleomagnetic directions from sets of oppositely-directed plugs is ≦160°, the multishot/paleomagnetic discrepancy is ≦5°, and for separation angles of ≦140°, the discrepancy is ≦10°. Upon thermal demagnetization, three of four sampled intervals yielded separation angles <140°, suggesting that most of the MWX core can be paleomagnetically oriented with an accuracy of better than 10° even when using magnetic drill-press bits. Intervals yielding smaller separation angles could be resampled in such an orientation that the bias direction lies closer to the VPTRM direction, as in Run 51 of this study. Second, the systematic relationship implied by Figure 10 indicates that the residual discrepancy between multishot and paleomagnetic orientations could be reduced even further by reading a correction factor off the trend line in the figure.

CONCLUSIONS AND RECOMMENDATIONS

A final comparison of the paleomagnetic and multishot core orientations is made in Table 7, which lists the current best estimates of the paleomagnetic and multishot orientations from each interval. It should be emphasized that in only a few intervals was the more accurate vector analysis method employed as a means of revealing and removing bias caused by the drill press (DPRM); yet, knowledge of the direction of this bias in other intervals allows a prediction as to whether the discrepancy between the paleomagnetic and multishot orientations can be explained by DPRM. In 9 out of 10 intervals in which the discrepancy between paleomagnetic and multishot orientations was ≧5°, this discrepancy would indeed be reduced by subtracting a magnetization pointing down the barrel of the drill-press bit.

Comparison of multishot and paleomagnetic core-orienting techniques during the Multiwell Experiment has revealed several problems associated with each technology. Successful application of the multishot technique depends on several factors, including absence of downhole equipment failures, correct alignment of the scribing knives, precise correspondence between individual pictures and actual core depths, low rates of angular rotation of the Principal Scribe Line, and accuracy of

TABLE 7: FINAL COMPARISON BETWEEN PALEOMAGNETIC AND MULTI-SHOT ORIENTATIONS FOR MWX CORES

Interval	Pmag.[†]	Method*	Multishot[††]	Discrepancy[§]	Comment[ζ]
Run 11 (MWX-1) (4704.3-4712.0)	323°E	D	19°E	(<56°?)	Data inadequate
Run 12 (MWX-1) (4803.1-4815.3)	213°	D	243°	(<30°?)	Data inadequate
Run 24 (MWX-1) (5431.7-5440.7)	140°	D	140°	0°	Good agreement
Run 24 (MWX-1) (5441.8-5448.0)	236°+	D	271°	+35°	Residual DPRM(?)
Run 25 (MWX-1) (5495.7-5503.7)	113°-	V	108°	-5°	Residual DPRM
Run 25 (MWX-1) (5504.0-5513.7)	216°	V	215°	-1°	Good agreement
Run 41 (MWX-1) (6442.3-6463.2)	202°±	D	350°	+148°	Severe residual DPRM (?) Coarse-grained (Med ss)
Run 41 (MWX-1) (6503.3-6514.5)	139°-	D	182°	+43°	Unexplained discrepancy
Run 46 (MWX-1) (7870.5-7886.8)	116°-	~V	90°	-26°	Small k, small N, residual DPRM
Run 46 (MWX-1) (7901.7-7908.9)	225°+	~V	235°	+10°	Small N, residual DPRM
Run 46 (MWX-1) (7951.0-7959.6)	185°+	~V	194°	+9°	Small k, small N, residual DPRM
Run 47 (MWX-2) (4879.7-4886.3)	197°+	D	233°	+36°	Residual DPRM(?)
Run 47 (MWX-2) (4893.4-4907.5)	34°±	D	42°	+8°	Small k, residual DPRM(?)
Run 51 (MWX-2) (6482.5-6508.0)	176°	V	177°	+1°	Multishot knife error (corrected 160°)
Run 56 (MWX-2) (7897.6-7901.2)	318°+	V	342°	+24°	Residual DPRM, multishot knife error (corrected 160°)
Run 57 (MWX-2) (8130.2-8138.4)	294°	V	298°	+4°	Good agreement

Table 7. (Continued)

NOTES:

† Best estimate of paleomagnetic orientation for each interval, followed by the sign of residual drill press remanent magnetization (DPRM) bias. The ± symbol for Runs 41 and 47 indicates that the paleomagnetic inclination is so steep (≥82°) that accurate orientations cannot be derived.

* Method used in deriving paleomagnetic orientations

D = former technique of using the mode of plugs taken on the MOL (Van Alstine, 1980).

V = new vector analysis technique, 16 plugs per interval (recommended)

∿V = new vector analysis technique, 8 plugs per interval (probably too few plugs for accurate orientation).

†† Multishot orientations (Tables 4 and 6). Values for Runs 51 and 56 have been corrected by adding 160° to compensate for probable knife alignment error (see text).

§ Angular discrepancy between paleomagnetic and multishot orientations. (Multishot - Pmag.)

ζ Probable cause of discrepancy

"Residual DPRM" indicates a reduction in discrepancy if a magnetization pointing down the barrel of the drill-press bit is removed. The presence of DPRM is known if the V method was applied, and is assumed if the D method was applied.

"Small k" indicates scattered directions (small Fisherian k parameter).

"Small N" indicates fewer than recommended number of plugs taken.

compass readings. During the Multiwell Experiment, problems with each of these factors were encountered. On the other hand, the accuracy of the paleomagnetic orienting technique depends on knowledge of the reference magnetization direction, on correctly aligning each core segment prior to plugging, on removing steel particle contamination, on the presence of fine-grained sediments, and, as dramatically revealed in this study, on avoiding imparting a magnetization bias during plugging.

In many respects, the Mesaverde Formation posed a formidable challenge to the technology of paleomagnetic core-orienting. The formation is very weakly magnetized, so that magnetic contamination by steel particles acquired during plugging and sample preparation can be a serious problem, if untreated. Moreover, the horizontal component of the magnetization, which is the only part of the paleomagnetic signal actually used in core orienting, constitutes only about 50% of the signal in the Mesaverde because of the steep reference inclination of +60°. In addition, the Mesaverde readily acquires secondary magnetizations both during subsurface drilling and during plugging. Most perversely, these secondary magnetizations are more resistant to both alternating-field and thermal demagnetization than is the reference paleomagnetic signal; hence, the traditional paleomagnetic "cleaning" techniques actually decrease the signal-to-noise ratio in the Mesaverde.

Despite these problems, application of new methods developed during this study have enhanced the accuracy with which Mesaverde drillcore can be oriented using paleomagnetism. In particular, results from Runs 25, 46, 51, 56, and 57 demonstrate not only the viability of the new vector analysis technique in paleomagnetically orienting drillcore but also the value of using paleomagnetism as a check on multishot orientations. Moreover, results from this investigation further document that the strongest magnetization in the Mesaverde has a declination near 0°; this corroborates results from our previous study, in which it was concluded that the dominant paleomagnetic signal in the Mesaverde is a viscous partial thermoremanent magnetization (VPTRM) probably acquired during mid to late Tertiary uplift. Another major finding of this study is that, using new paleomagnetic sampling and statistical techniques, the magnitude and sign of biases imposed during plugging can be determined (i.e., from the separation angle between paleomagnetic vectors from two oppositely-directed sets of plugs).

Finally, it seems certain that the accuracy of paleomagnetic core orientations can be improved by collecting plugs with non-magnetic drill-press bits. Comparison of paleomagnetic orientations derived by plugging with magnetic steel bits (e.g., this study) versus non-magnetic stainless steel bits (e.g., Van Alstine, 1981) indicates that non-magnetic bits yield far more accurate orientations in the Mesaverde, even without employing the vector analysis method. Thus, in future paleomagnetic core-orienting, the vector analysis method should be used in conjunction with non-magnetic drill-press bits. By applying both of these improvements in the paleomagnetic core-orienting technique, we are confident that Mesaverde drillcore can be routinely oriented paleomagnetically with an accuracy of ~5°.

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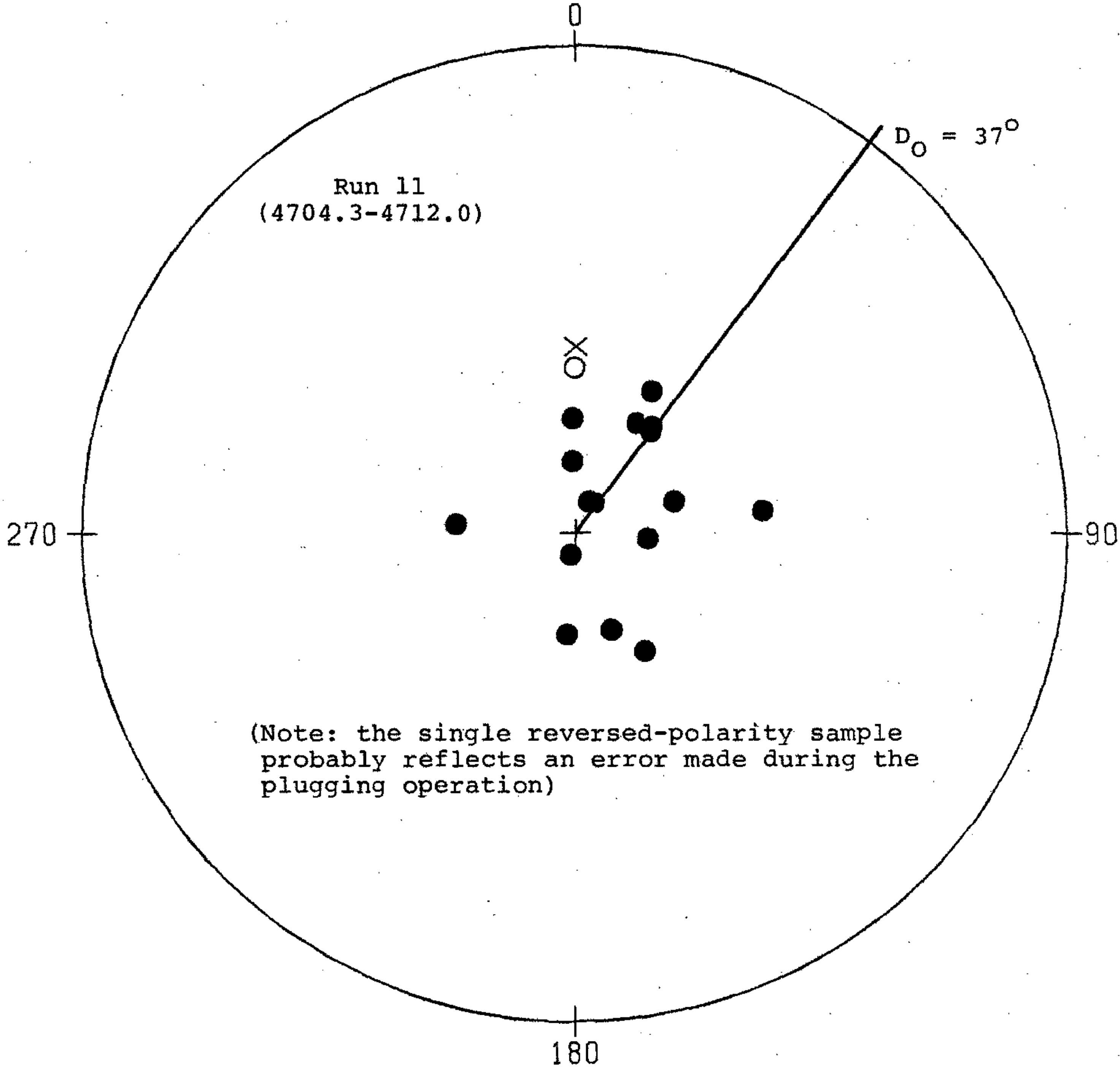
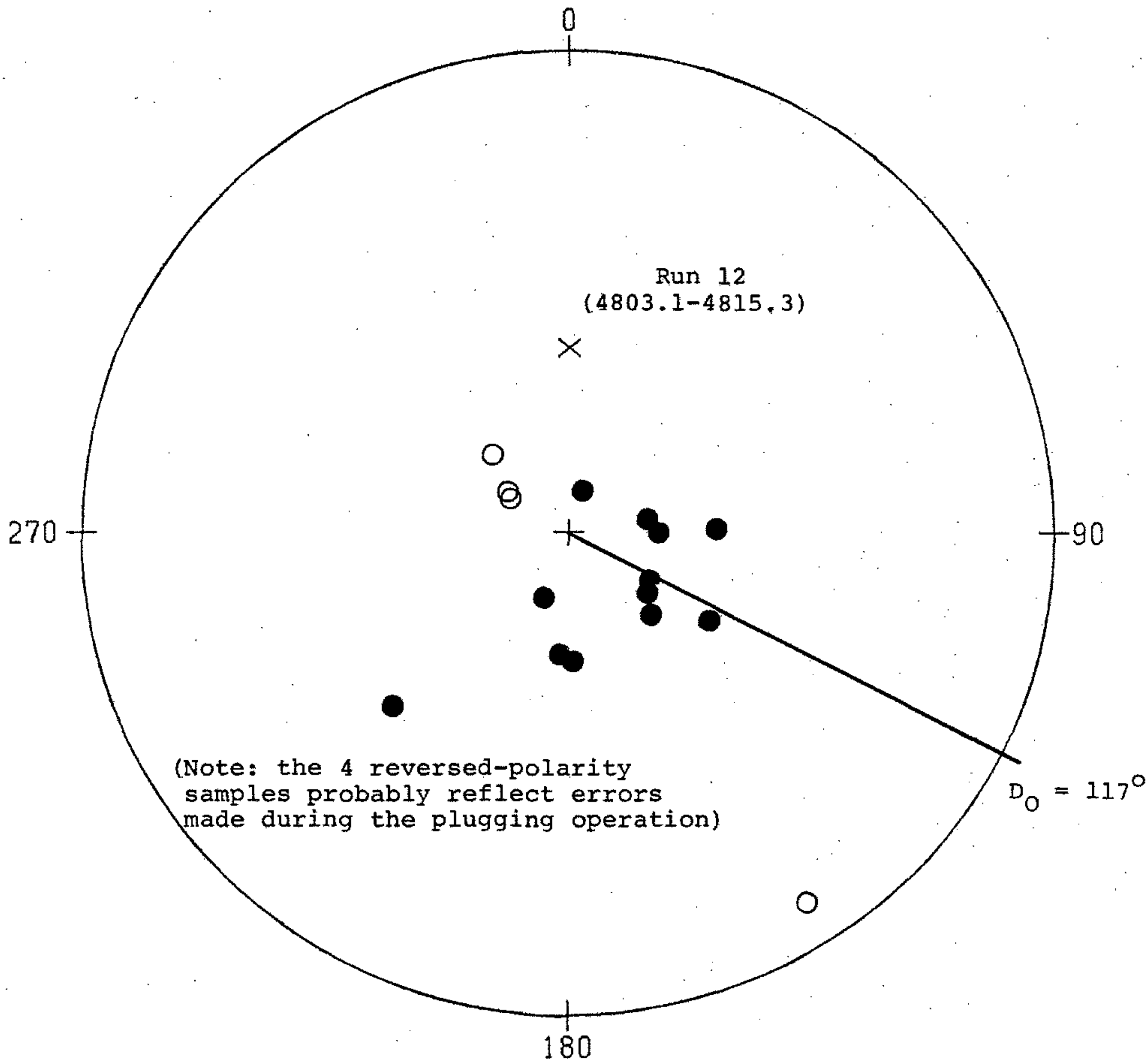
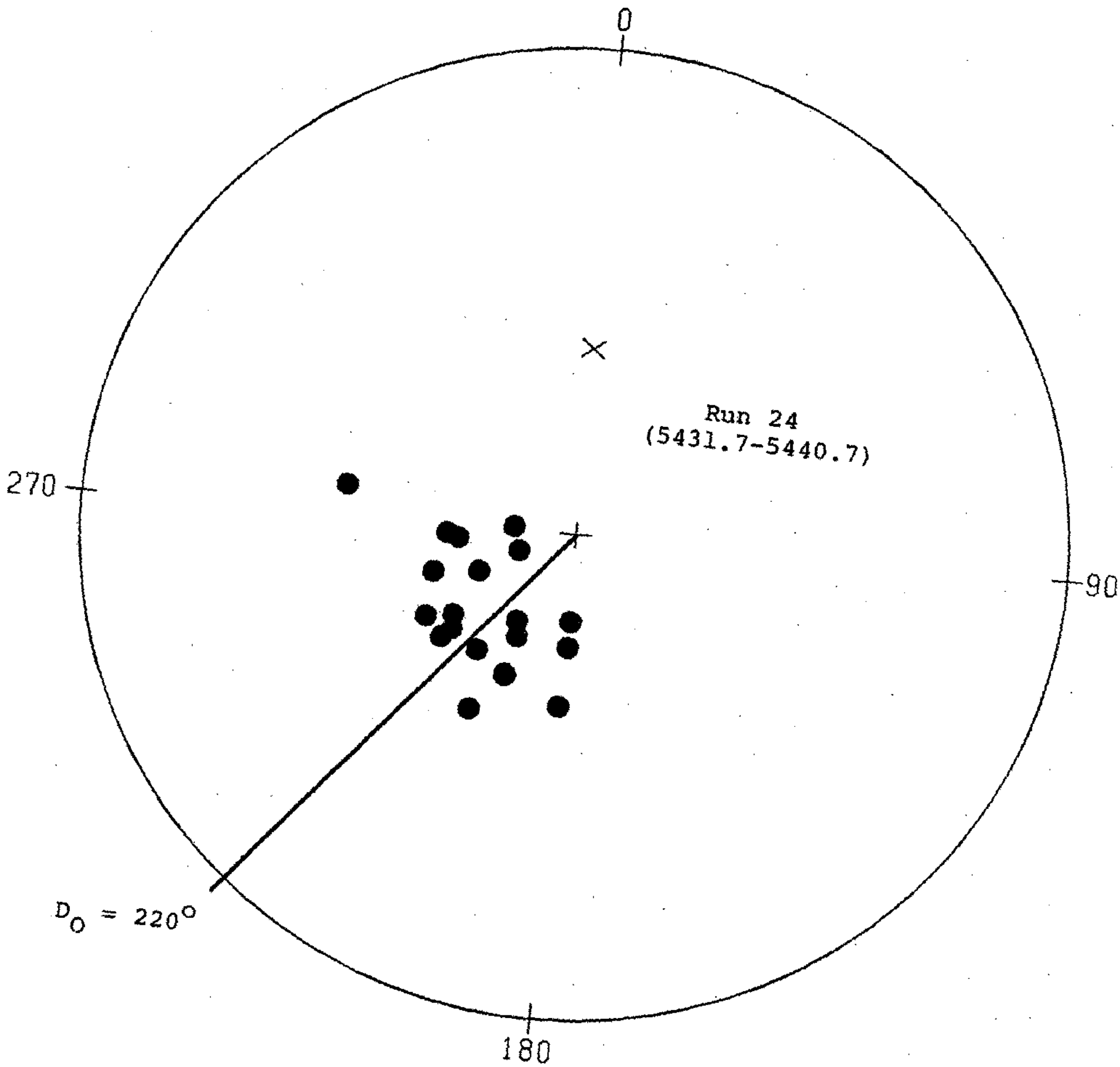
APPENDIX

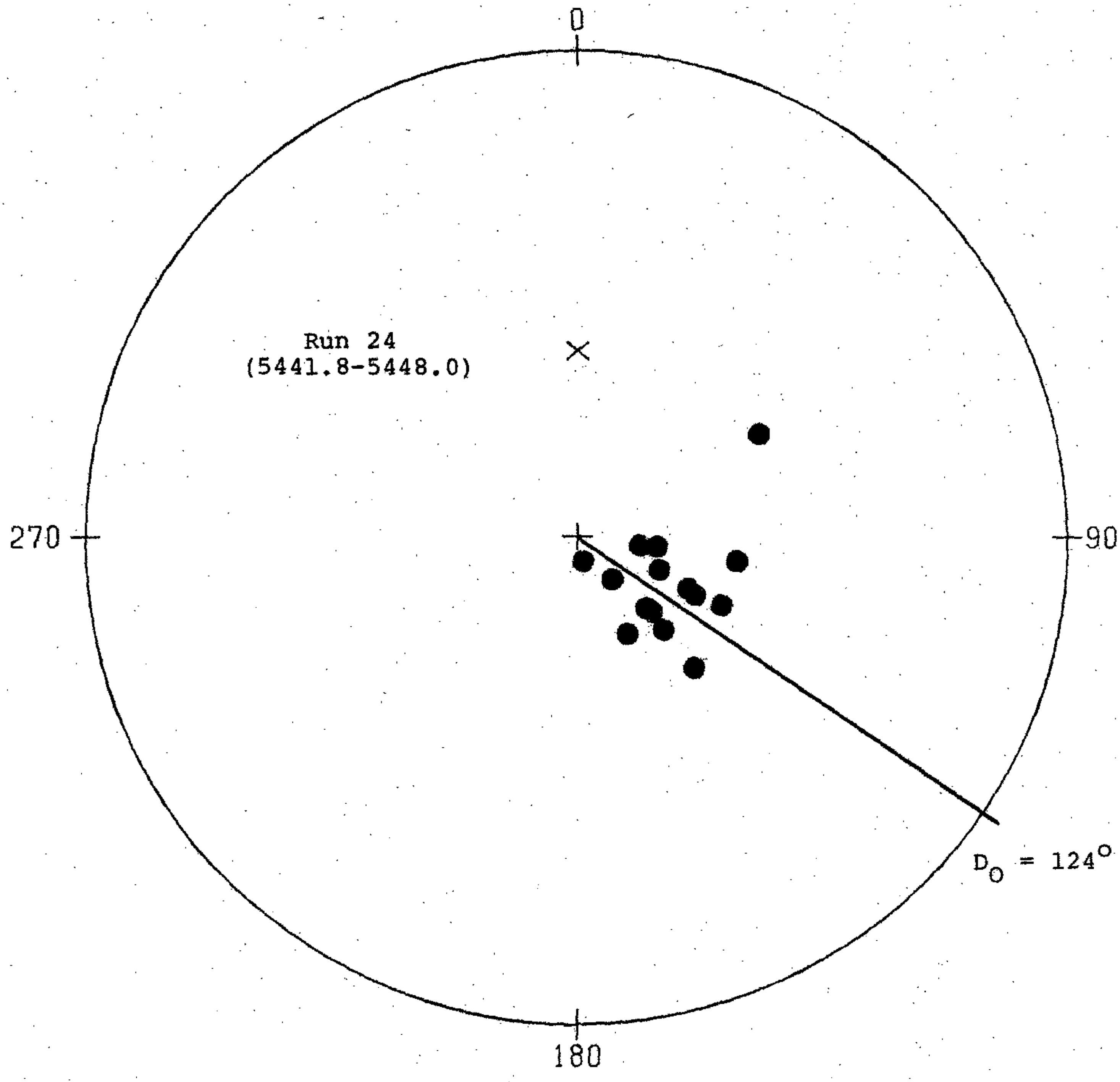
This Appendix contains supplementary stereographic projections of paleomagnetic data from MWX cores; only those data are shown that do not appear in figures in the main body of the text. The figures show Lambert equal-area projections of paleomagnetic data from Runs 11, 12, 24, 41, and 46 of MWX-1 and from Run 47 of MWX-2. Solid (open) symbols are on the lower (upper) hemisphere, respectively. The X marks the inclination of the present-axial-dipole (= late Cenozoic) geomagnetic field at the MWX site. All directions are plotted in the specimen coordinate system, which is fixed with respect to the Master Orientation Line (MOL). For most intervals, only the observed declination (D_O) of the mode of specimen directions from plugs drilled on the MOL was obtained.

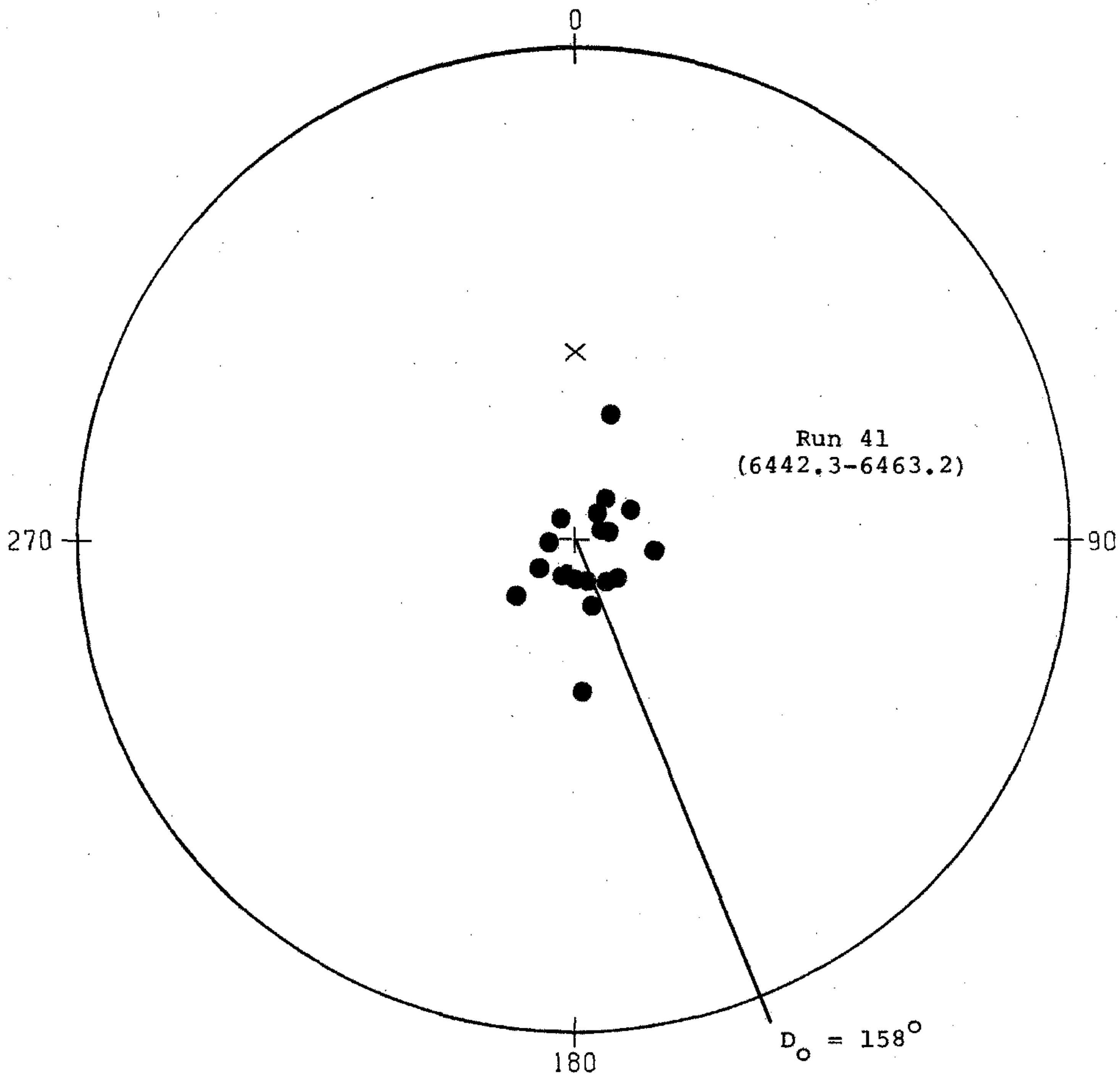


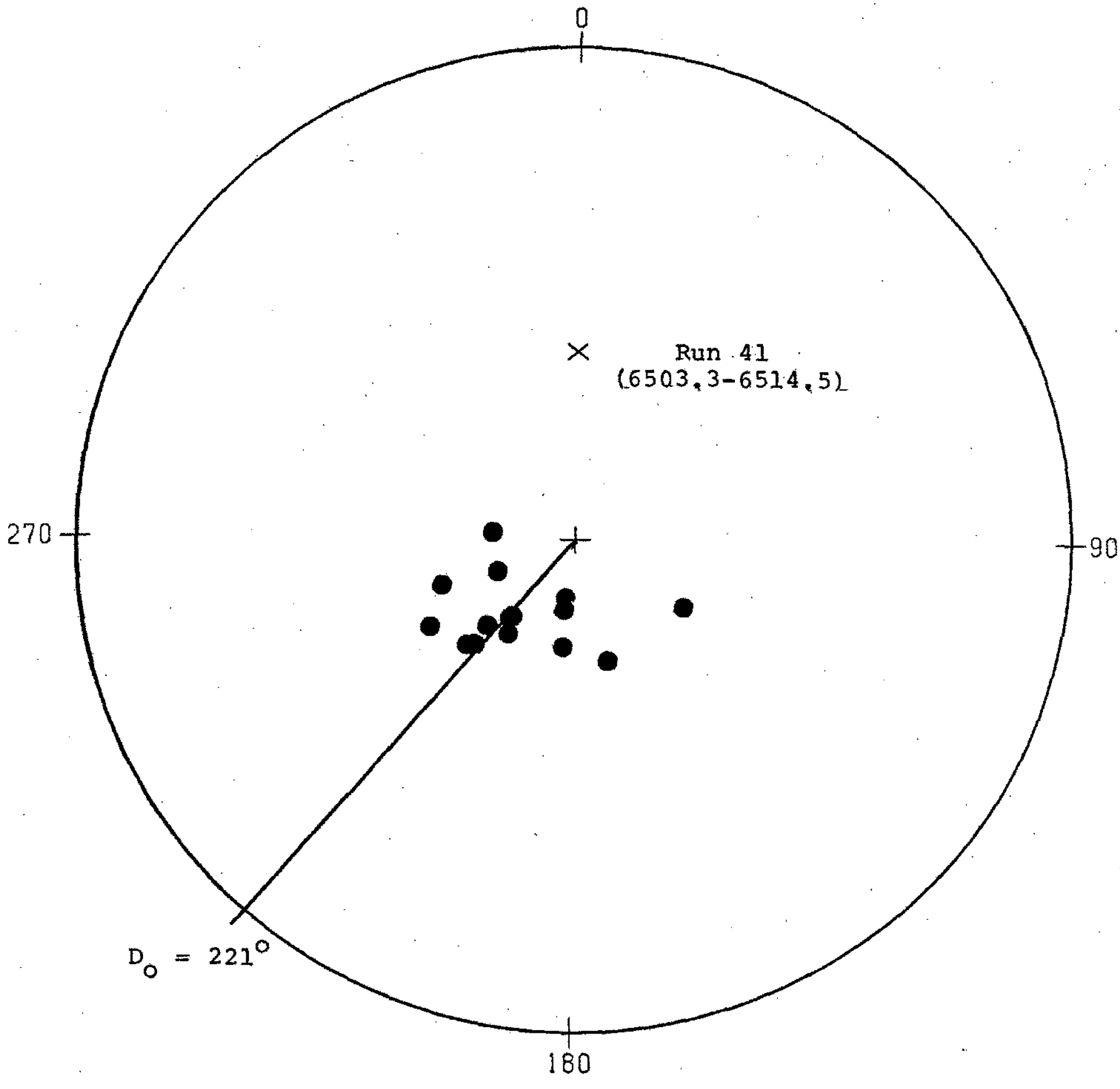
(Note: the single reversed-polarity sample probably reflects an error made during the plugging operation)

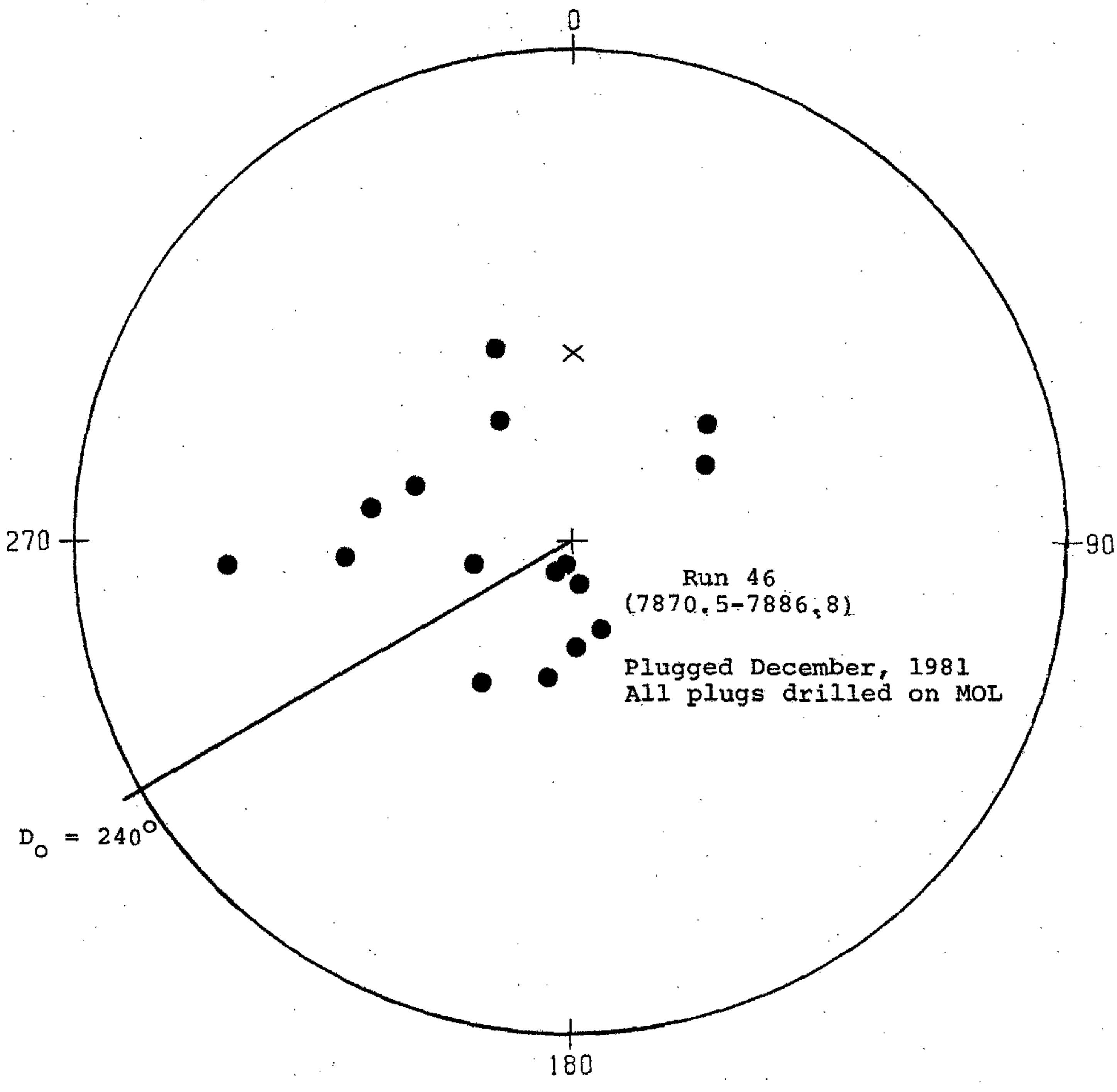

0
90
180
270
Run 12
(4803.1-4815.3)
(Note: the 4 reversed-polarity
samples probably reflect errors
made during the plugging operation)
$D_o = 117^o$

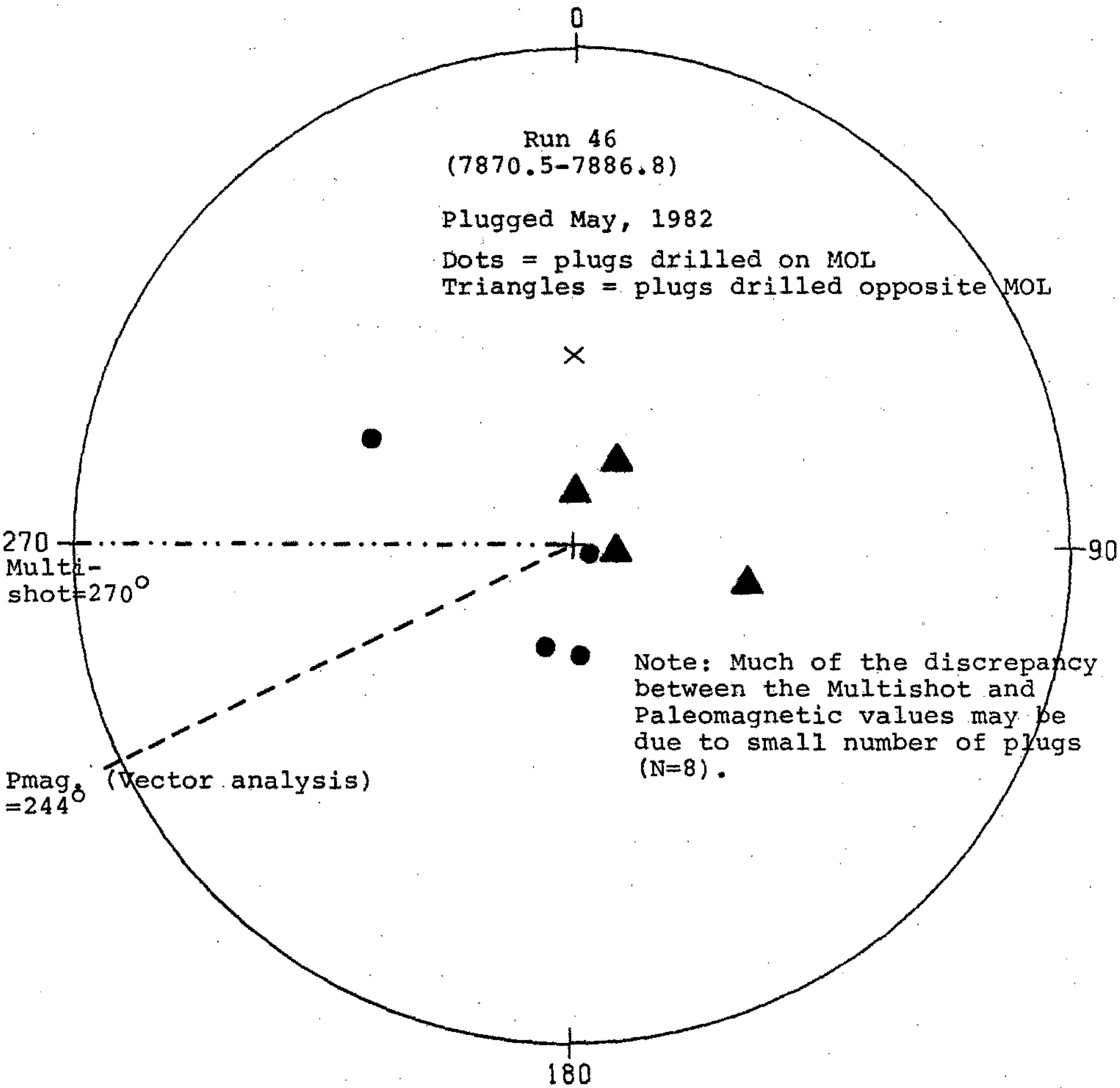

0
90
180
270
Run 24
(5431.7-5440.7)
$D_O = 220^o$

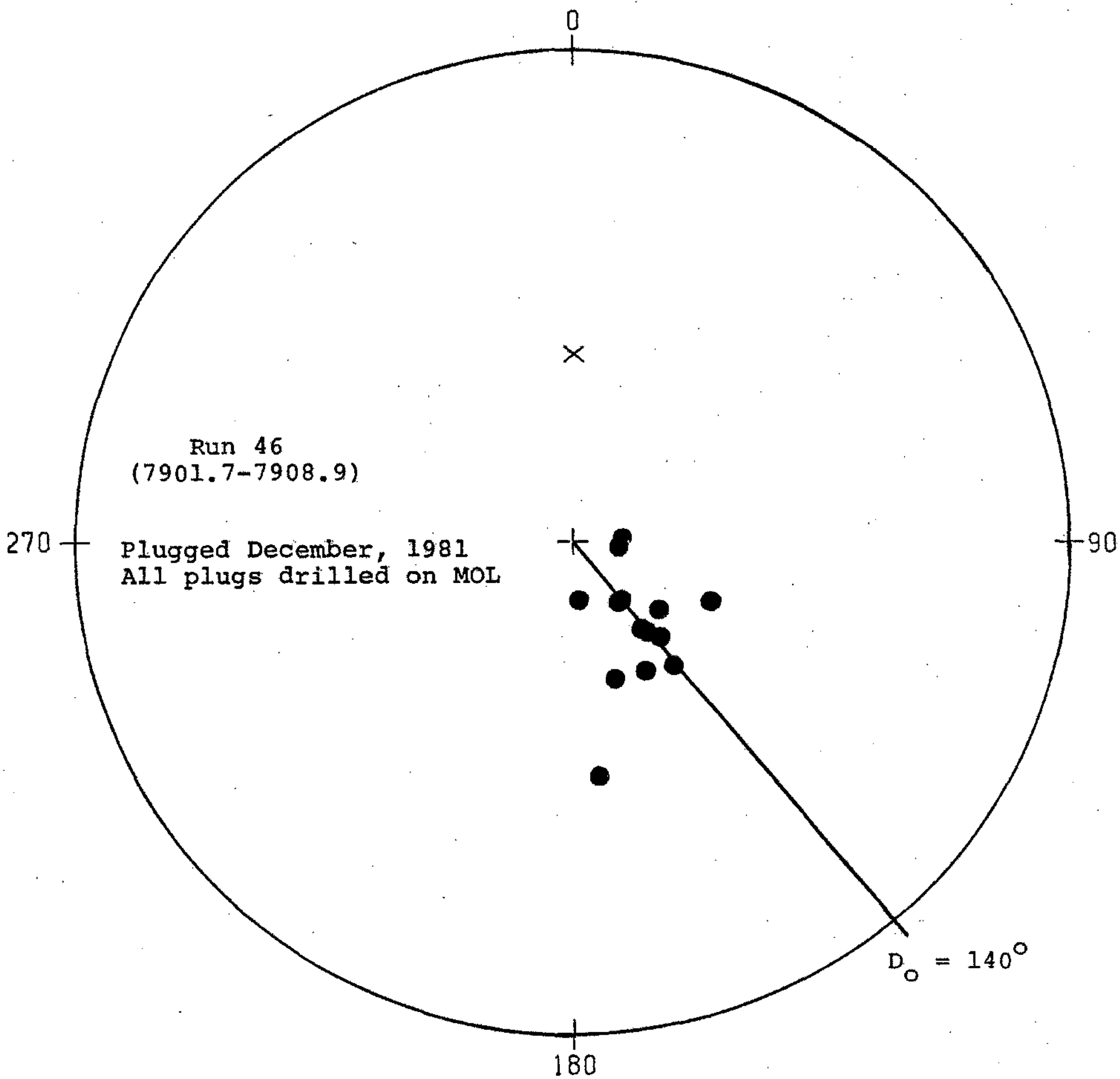

0
90
180
270
Run 24
(5441.8-5448.0)
D_O = 124°

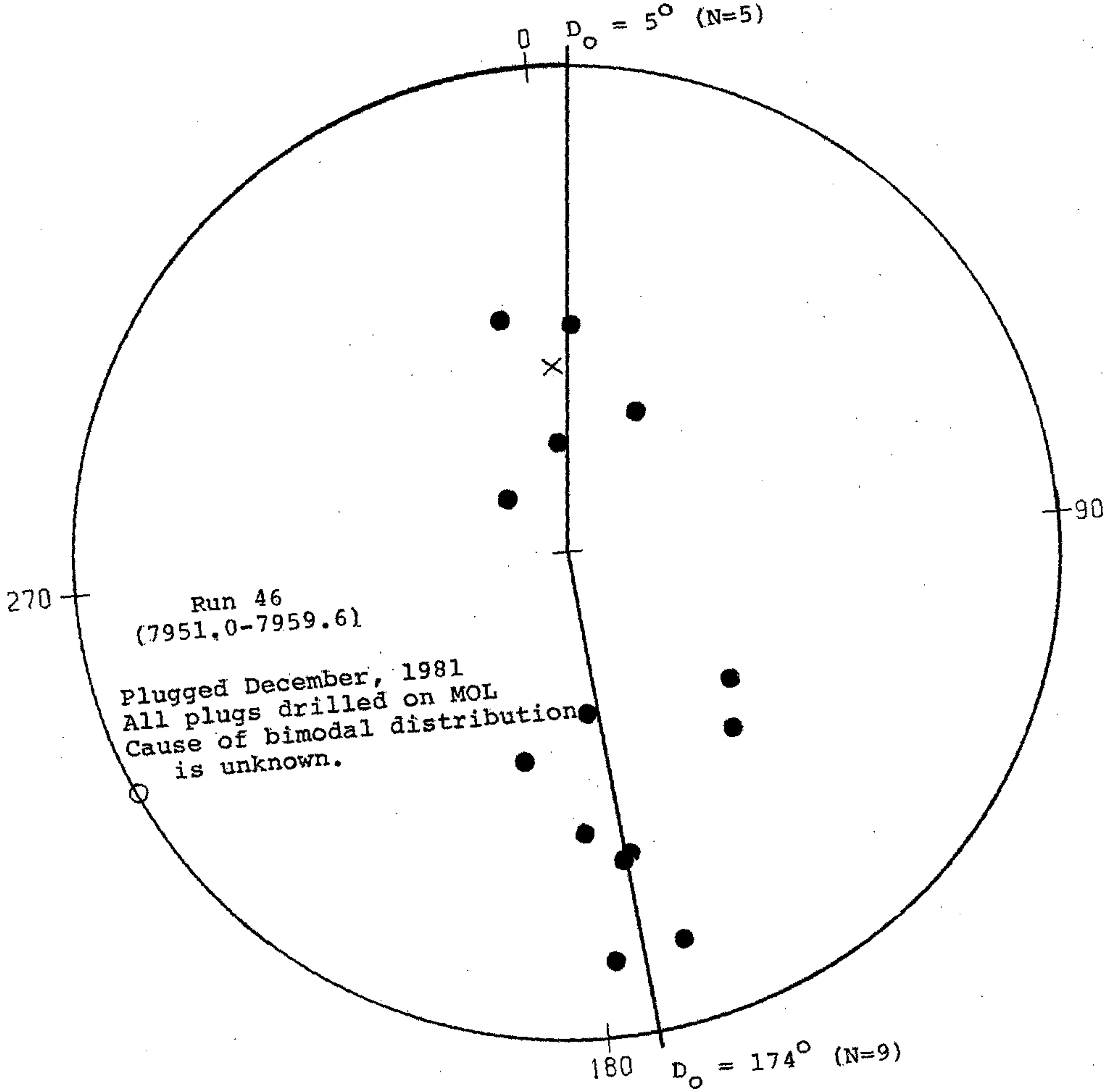

0
270
90
180
Run 41
(6442.3-6463.2)
$D_o = 158^\circ$

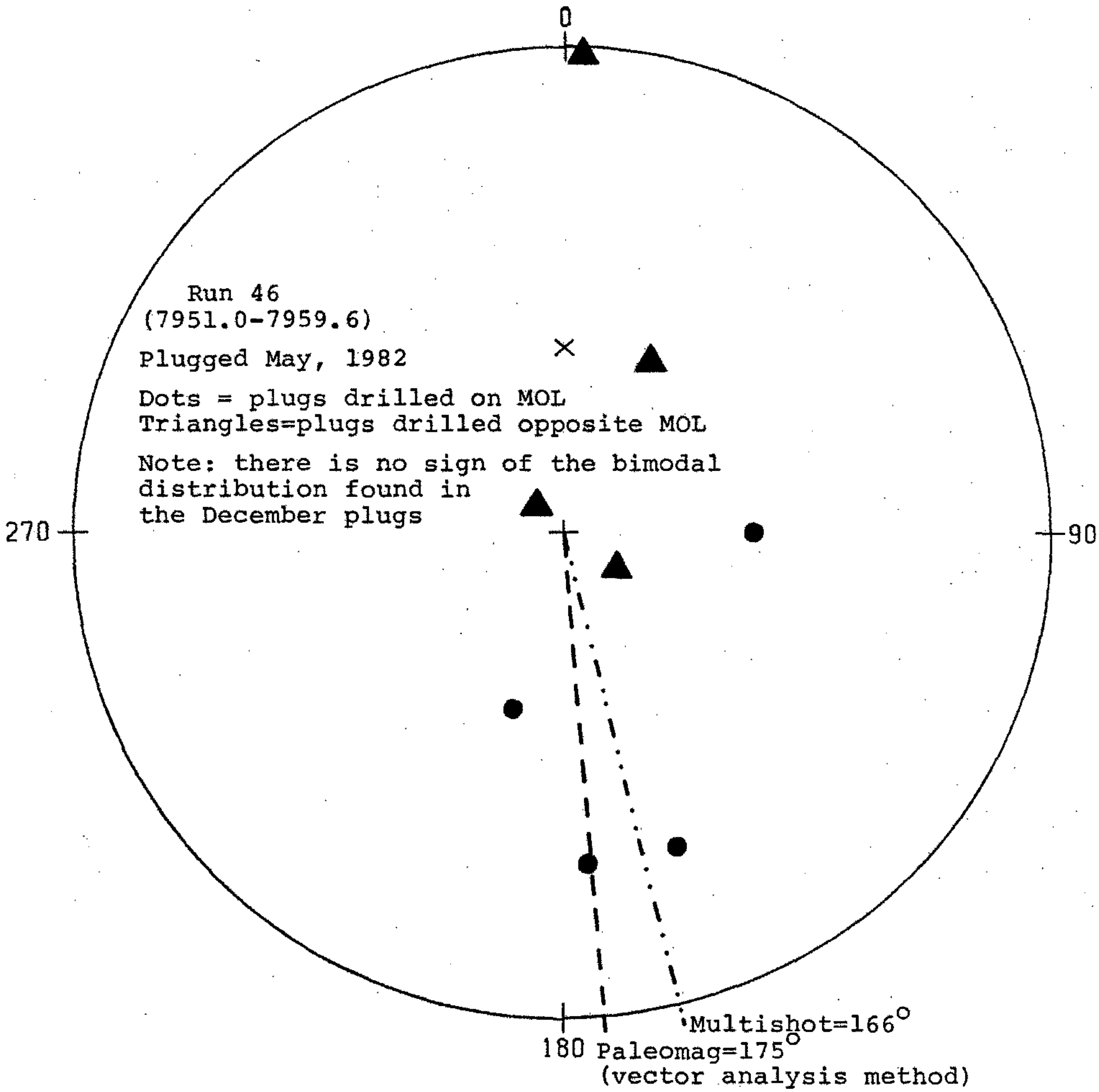

0
90
180
270
Run 41
(6503.3-6514.5)
D_o = 221°

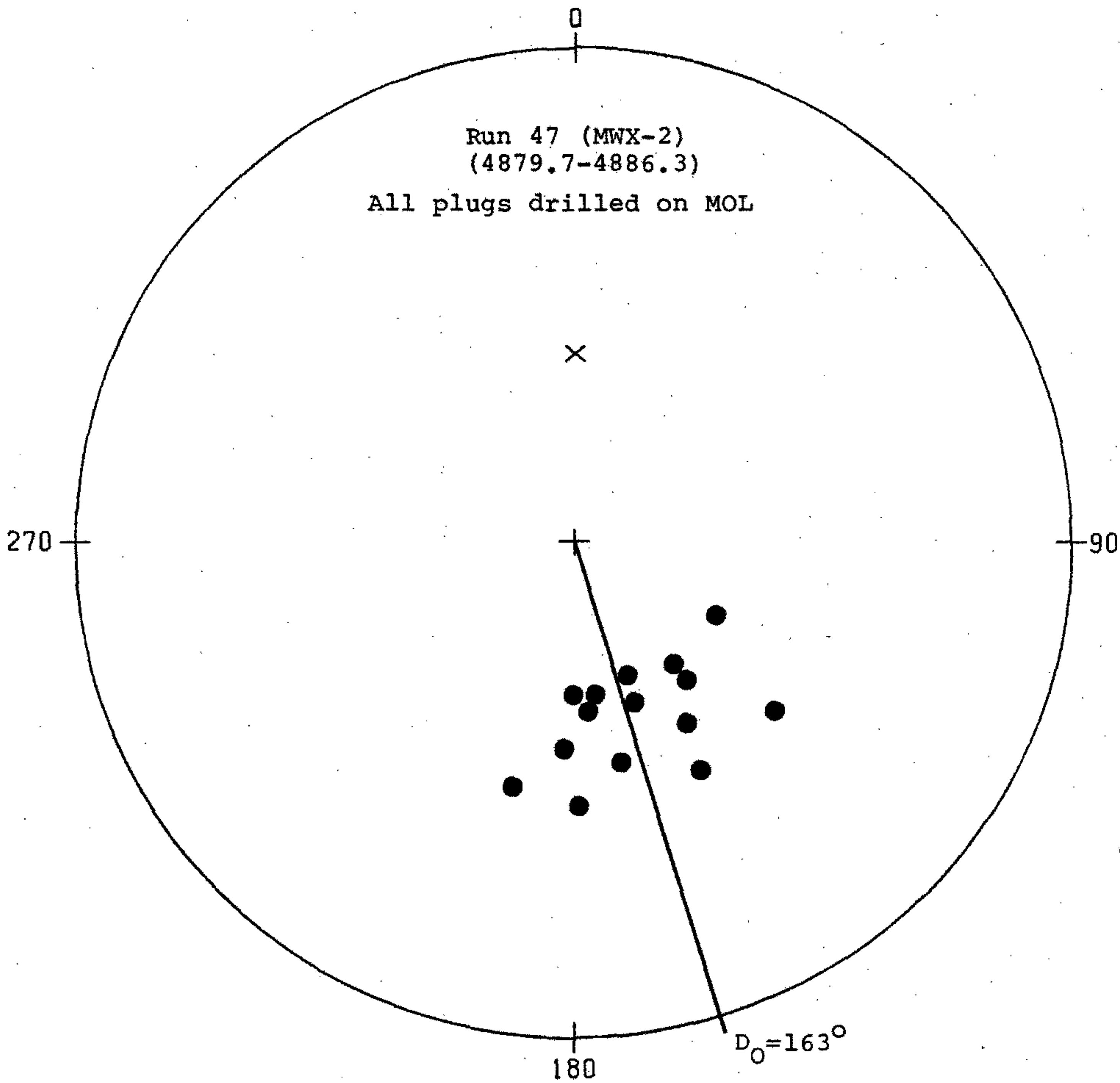

0
270
90
180
Run 46
(7870.5-7886.8)
Plugged December, 1981
All plugs drilled on MOL
D_o = 240°

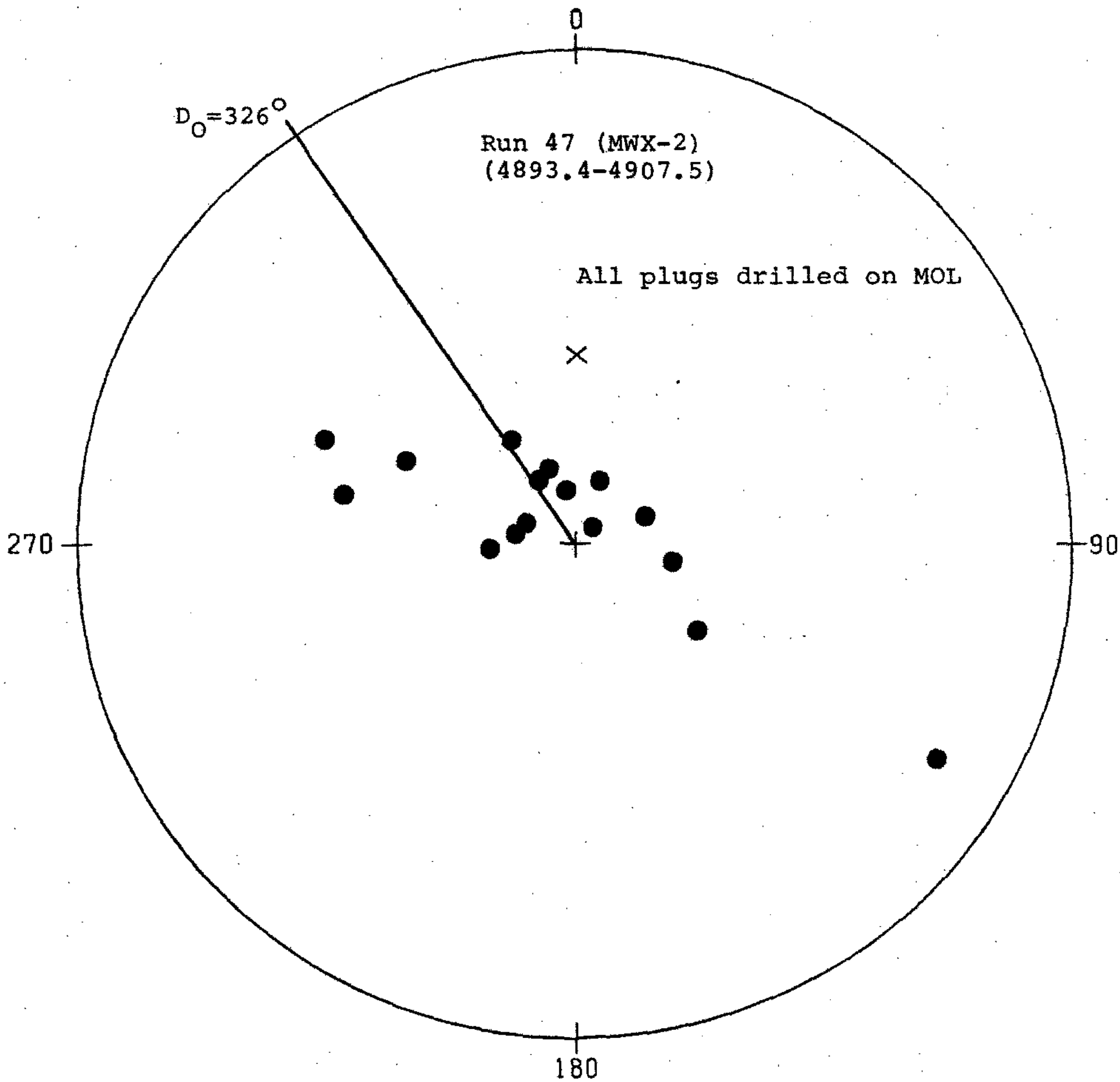

0
Run 46
(7870.5-7886.8)
Plugged May, 1982
Dots = plugs drilled on MOL
Triangles = plugs drilled opposite MOL
270
Multi-
shot=270°
90
Note: Much of the discrepancy between the Multishot and Paleomagnetic values may be due to small number of plugs (N=8).
Pmag. (Vector analysis)
=244°
180


0
270
90
180
Run 46
(7901.7-7908.9)
Plugged December, 1981
All plugs drilled on MOL
$D_o = 140^\circ$


0
$D_o = 5^o$ (N=5)
90
270
Run 46
(7951.0-7959.6)
Plugged December, 1981
All plugs drilled on MOL
Cause of bimodal distribution
is unknown.
180
$D_o = 174^o$ (N=9)


0
Run 46
(7951.0-7959.6)
Plugged May, 1982
Dots = plugs drilled on MOL
Triangles=plugs drilled opposite MOL
Note: there is no sign of the bimodal
distribution found in
the December plugs
270
90
180
Multishot=166°
Paleomag=175°
(vector analysis method)


0
Run 47 (MWX-2)
(4879.7-4886.3)
All plugs drilled on MOL
270
90
180
D_O=163°


0
D_O=326°
Run 47 (MWX-2)
(4893.4-4907.5)
All plugs drilled on MOL
270
90
180