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Tectonic Rotations in the Cascade Mountains of Southern Washington

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TECTONIC ROTATIONS IN THE CASCADE MOUNTAINS OF SOUTHERN WASHINGTON

A Thesis Presented to the
Faculty of Western
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In Partial Fulfillment of
The Requirements for the
Master of Science Degree

by
Roger G. Bates
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Accepted in Partial Completion Of the Requirements for the Master of Science Degree

Dean, Graduate School

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ABSTRACT

Paleomagnetic directions from 34 widely distributed sampling sites in the Oligocene Ohanapecosh Formation in the Cascade Mountains of southern Washington are well grouped with a mean and confidence interval of: Dec. = 27^{o}, Inc. = 64^{o}, α_{95} = 4^{o}. When compared to the expected direction, computed from the Oligocene reference pole for stable North America, a clockwise rotation of $31^{o} \pm 12^{o}$ is apparently present. This result is not significantly different from other studies within the Cascades and Coast Range of southern Washington and suggests that the two Ranges have rotated as a single unit during late Eocene to mid-Oligocene time. Comparison with the results from rocks of similar age in Oregon suggests that at least two crustal blocks are involved in Pacific Northwest tectonics.

ACKNOWLEDGMENTS

I wish to thank Myrl Beck for suggesting this project to me and for the support and guidance he provided as it progressed. I also want to thank Russell Burmester and David Pevear for critically reviewing this paper and for their valuable suggestions.

Robert Simpson deserves special thanks for the help he was able to provide during the field and laboratory phases of my work.

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INTRODUCTION

In recent years the Pacific Northwest Coast Ranges have been the focus of a number of paleomagnetic investigations. Studies by Simpson and Cox (1977), and Cox and Magill (1977) on rocks of Eocene age, and by Beck and Plumley (personal communication, 1980) on Eocene, Oligocene and Miocene intrusive rocks, all within the Oregon Coast Range, show that the 350 km-long Range is a single allochthonous block which has rotated, relative to the North American interior, by as much as 60^{o} clockwise since Eocene time (Fig. 1).

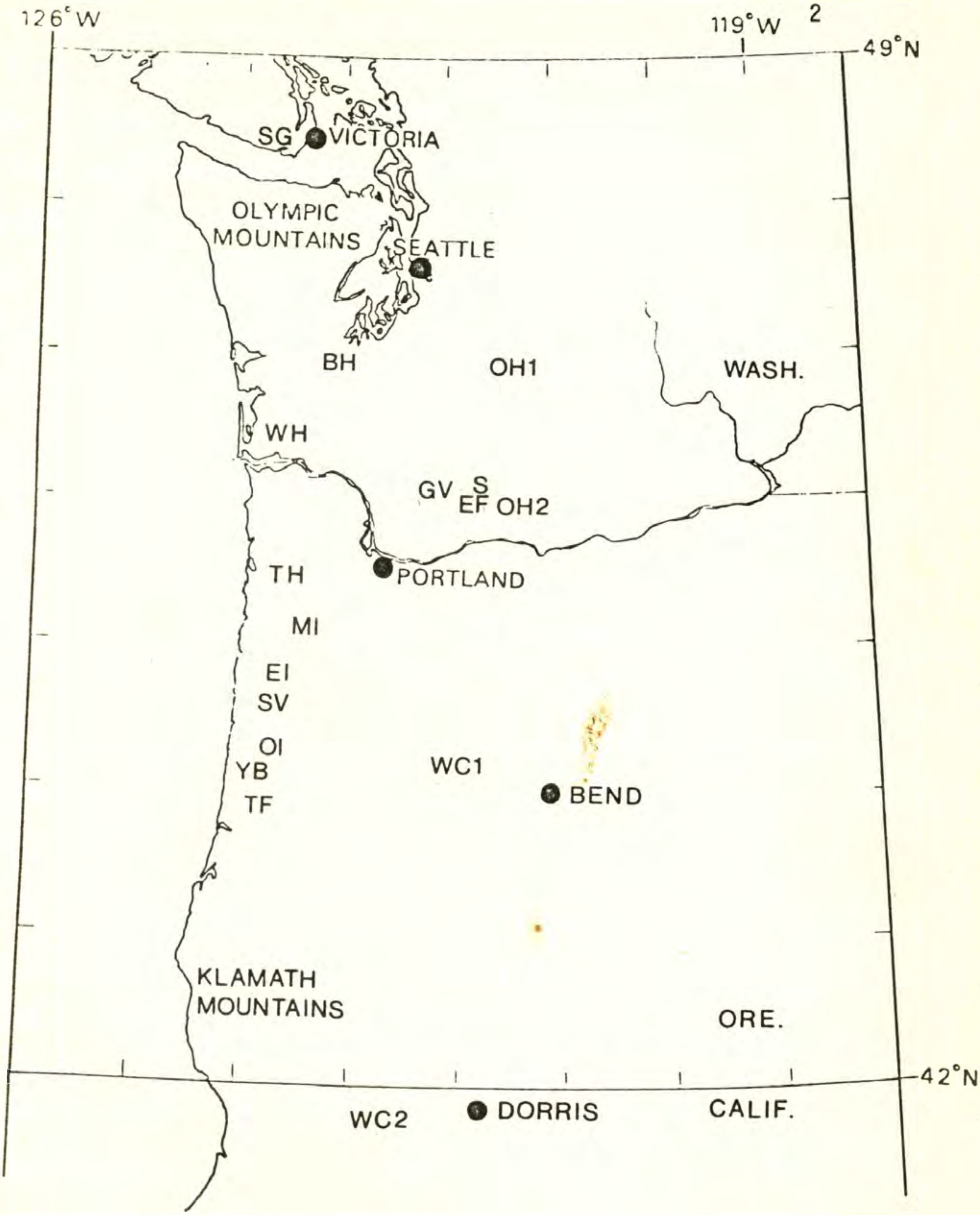
Work on Eocene rocks within the Washington Coast Range (Globerman and Beck, 1979; Wells and Coe, 1979) also shows a clockwise rotation, but apparently much less than in Oregon (Fig. 1). Globerman and Beck (1979) report approximately 36^{o} of rotation, whereas the Wells and Coe (1979) study shows at most 10^{o}. On the basis of these and other data Beck and Plumley (personal communication, 1980) suggest that there are at least two separate crustal blocks involved in the rotation. They also suggest that a portion of the boundary between the blocks may coincide with the present course of the Columbia River.

Considering the apparently allochthonous nature of the Coast Ranges, it seems appropriate to ask — what of the adjacent Cascade Range to the east? Could it be that it too has rotated, in whole or part, as the Coast Ranges seem to have done?

Paleomagnetic data reported by Beck (1962) indicates that the southern tip of the Cascade Range in northern California probably has rotated clockwise by about 13^{o}. Beck and Burr (1979) report approximately 25^{o} of clockwise rotation from the Goble Volcanic Series of mid-Eocene to mid-Oligocene age in southwestern Washington. The Goble Volcanics have been placed at

FIGURE 1. Location map showing areas of paleomagnetic studies in the Pacific Northwest, modified from Beck and Plumley (unpublished data).

SV = Siletz River Volcanic Series
YB = Yachats Basalts
TF = Tyee-Flournoy Formations (Simpson and Cox, 1977)
MI = Miocene intrusions
OI = Oligocene intrusions
EI = Eocene intrusions (Beck and Plumley, unpub. data)
TH = Tillamook Highlands (Cox and Magill, 1977)
WH = Willapa Hills (Wells and Coe, 1979)
BH = Black Hills (Globerman and Beck, 1979)
SG = Sooke Gabbro (Symons, 1978)
GV = Goble Volcanics (Beck and Burr, 1979)
WC1 = Western Cascades of Oregon (Cox and Magill, 1979)
WC2 = Western Cascades Series of California (Beck, 1962)
OH1 = Ohanapecosh Formation (type section)
OH2 = Ohanapecosh Formation (Wind River area)
S = Skamania Formation (Schriener, 1978)
EF = East Fork Formation (Schriener, 1978)


126°W
119°W
49°N
SG
VICTORIA
OLYMPIC
MOUNTAINS
SEATTLE
BH
OH1
WASH.
WH
GV
S
EF
OH2
TH
PORTLAND
MI
EI
SV
OI
YB
WC1
BEND
TF
KLAMATH
MOUNTAINS
ORE.
42°N
WC2
DORRIS
CALIF.

the base of the Lower Western Cascade Group of southern Washington by Hammond (1979, Fig. 4). Preliminary work by Cox and Magill (1979) in the Oregon Cascades also indicates a significant amount of clockwise rotation (Fig. 1). Hammond (1979) suggests that the Cascades and the Coast Ranges lay adjacent to one another during at least part of the time that the Coast Ranges were rotating; Hammond's conclusions are based on stratigraphic relationships reported by Hoover (1963) and Wells and Peck (1961) in Oregon and by Snavely and others (1958) and Roberts (1958) in southwestern Washington.

Although evidence for Cascade rotation is mounting, there is a significant gap in both space and time between the Goble Volcanics (Beck and Burr, 1979) and the mid-Tertiary Oregon Cascade study of Cox and Magill (1979). In an attempt to fill a part of this gap I instituted a paleomagnetic investigation of the Ohanapecosh Formation of southern Washington. The results of that study are presented in this paper.

GEOLOGIC SETTING

The Ohanapecosh Formation, described in detail by Fiske (1960) and Fiske and others (1963), is a thick sequence of subaerial and subaqueous volcaniclastic rocks, mudflows, and lava flows. It makes up part of the Lower Western Cascade Group (Hammond, 1979) and as such is among the oldest Cascade arc rocks exposed in southern Washington. Ohanapecosh rocks have been dated by plant fossils as late Eocene (Fiske and others, 1963) and, more recently, as early to mid-Oligocene (31-37 ma) by Joe Vance of the University of Washington (personal communication, 1979) by zircon fission-track dating.

The Ohanapecosh Formation can be traced from its type locality near

Mt. Rainier National Park, Washington, southward approximately 110 km to the Wind River area of Skamania County, Washington, where the bulk of this study was carried out. In the area between Mt. Adams and Mt. St. Helens the Ohanapecosh Formation crops out intermittently as it is covered by younger rocks from the two volcanoes (Wise, 1970; Simon, 1972). The Ohanapecosh in the Wind River area has been assigned an Oligocene age by Wise (1970) on the basis of floral remains.

Approximately 25 km to the west of the Wind River area Schriener (1978) has informally divided the Skamania Volcanic Series of Trimble (1963) into the East Fork Formation and the Skamania Formation. The informal terms Skamania Formation and East Fork Formation will be used throughout this paper. The East Fork Formation, cropping out mainly along the East Fork of the Lewis River, is a sequence of volcaniclastic rocks and basalt flows. The overlying Skamania Formation is a series of basalt flows with minor clastic units. The ages of the East Fork and Skamania Formations have not been determined precisely; however, lithologic and stratigraphic similarities and relationships allow tentative correlation with the Ohanapecosh Formation and the assignment of a probably Oligocene age (Schriener, 1978).

Two periods of folding are recognized by Hammond (1979) in the Lower Western Cascade Group. The older, northwest trending system is approximately contemporaneous with Ohanapecosh deposition, and is represented by broad, open folds whose limbs dip 10^{o} to 45^{o}. The younger pattern, which is the most prominent of the two in the Wind River area, is an extension of the Yakima fold system and trends east-west. Dips are generally less than 40^{o}.

All of the Ohanapecosh flows have undergone some alteration. In most places the alteration is slight, but in others, particularly where the deeper stratigraphic levels of the Ohanapecosh are exposed, alteration is extreme (Fiske, 1960; Wise, 1961; Fiske and others, 1963). In the East Fork Formation alteration has, in some places, resulted in near total replacement of the mafic minerals by chlorite, clay, opaques and epidote (Schriener, 1978). The alteration bears heavily on the magnetic stability as will be shown later.

PALEOMAGNETISM

Using portable core drilling equipment and 'in-situ' orienting devices similar to those described in Doell and Cox (1965) (but including a sun compass), a total of 336 samples were collected from lava flows at 40 sites in southern Skamania County, Washington, and five sites in the Ohanapecosh type section near Mt. Rainier, Washington (Fig. 2).

All samples were magnetically cleaned using the alternating field method. In general, the magnetic stability of the rock was good although one site gave a circle of 95% confidence of greater than 15^{o} and was rejected. Also, five sites were rejected on the basis that they showed very erratic and unstable behavior during A-F demagnetization (Fig. 3). As a group these rejected sited tended to be the most severly altered of all. A more complete discussion of the behavior of the rejected sites during demagnetization may be found in the appendices. One site whose mean direction gave a strong westerly declination and a shallow inclination was also rejected because it was clearly divergent from the tight grouping formed by the mean magnetic directions of the other sites (Fig. 4). This particular site was located in an isolated outcrop which may

Figure 2. Map of part of southern Washington (modified from Huntting and others, 1961) showing sampling locations in the Wind River area. Inset shows sampling locations near Mt. Rainier National Park. X = sample site. Map coordinates of the sampling sites can be found in Appendix A.

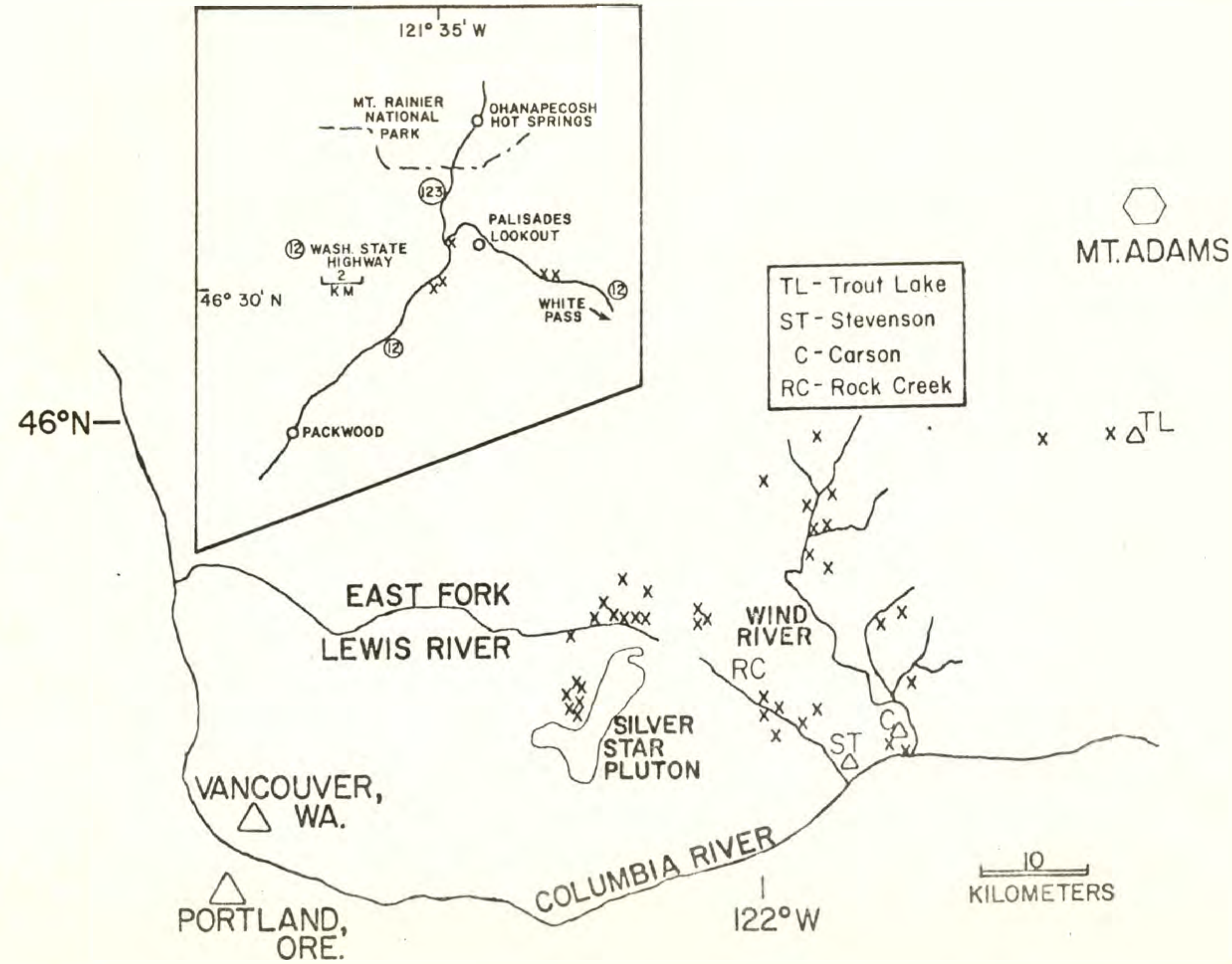
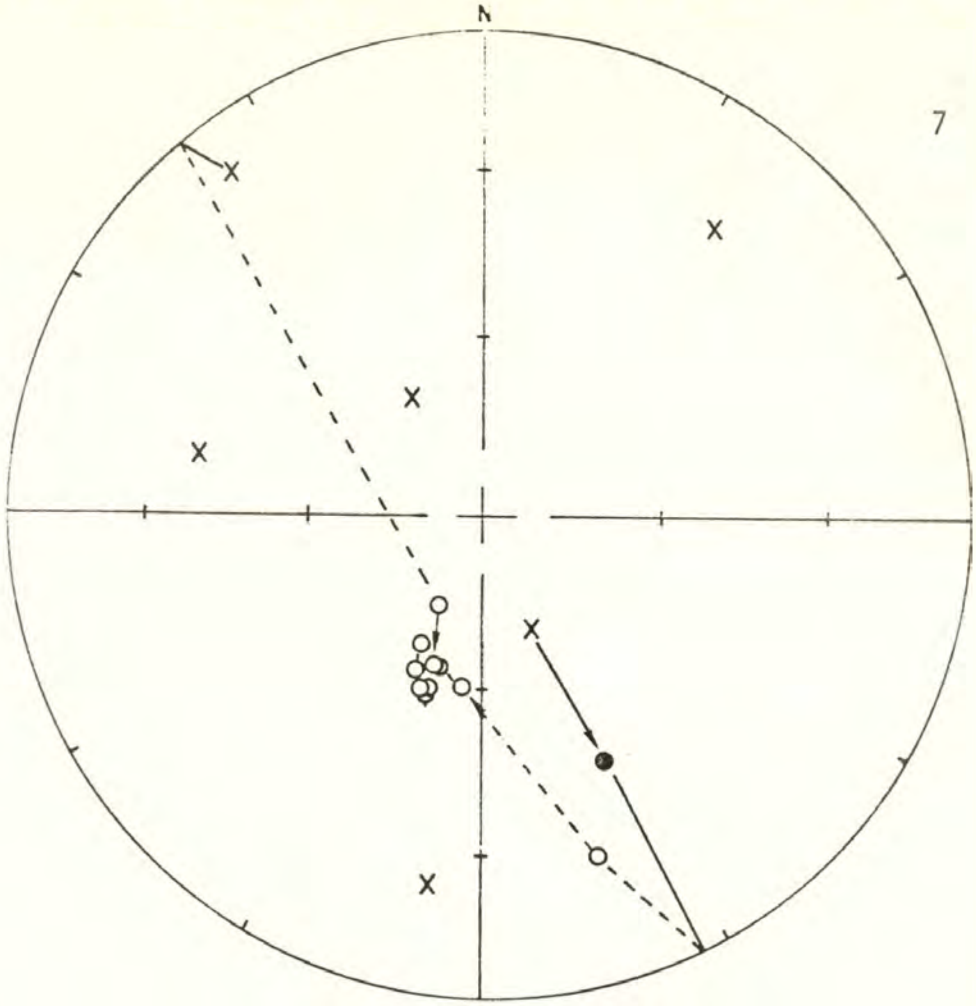

121° 35' W
MT. RAINIER NATIONAL PARK
OHANAPECOSH HOT SPRINGS
123
PALISADES LOOKOUT
12 WASH. STATE HIGHWAY
2 KM
46° 30' N
WHITE PASS
12
PACKWOOD
TL - Trout Lake
ST - Stevenson
C - Carson
RC - Rock Creek
MT. ADAMS
TL
46°N
EAST FORK
LEWIS RIVER
WIND RIVER
RC
C
ST
SILVER STAR PLUTON
VANCOUVER, WA.
PORTLAND, ORE.
COLUMBIA RIVER
122°W
10
KILOMETERS

Figure 3a. Site S-5; demagnetization level: NRM to 800 oe; α_{95} (NRM) = 11.1 α_{95} (cleaned) = 2.9

FIGURE 3. Both-hemisphere, equal area projections showing effects of A-F demagnetization on stable (3a) and unstable (3b) rock. Solid circles indicate lower hemisphere; open circles indicate upper hemisphere; x indicates NRM direction; arrows show path of step wise demagnetization.

Figure 3b. Site Ø-26; demagnetization level: NRM to 800 oe; α_{95} (NRM) = 15.5; α_{95} (cleaned) = 29.2


N

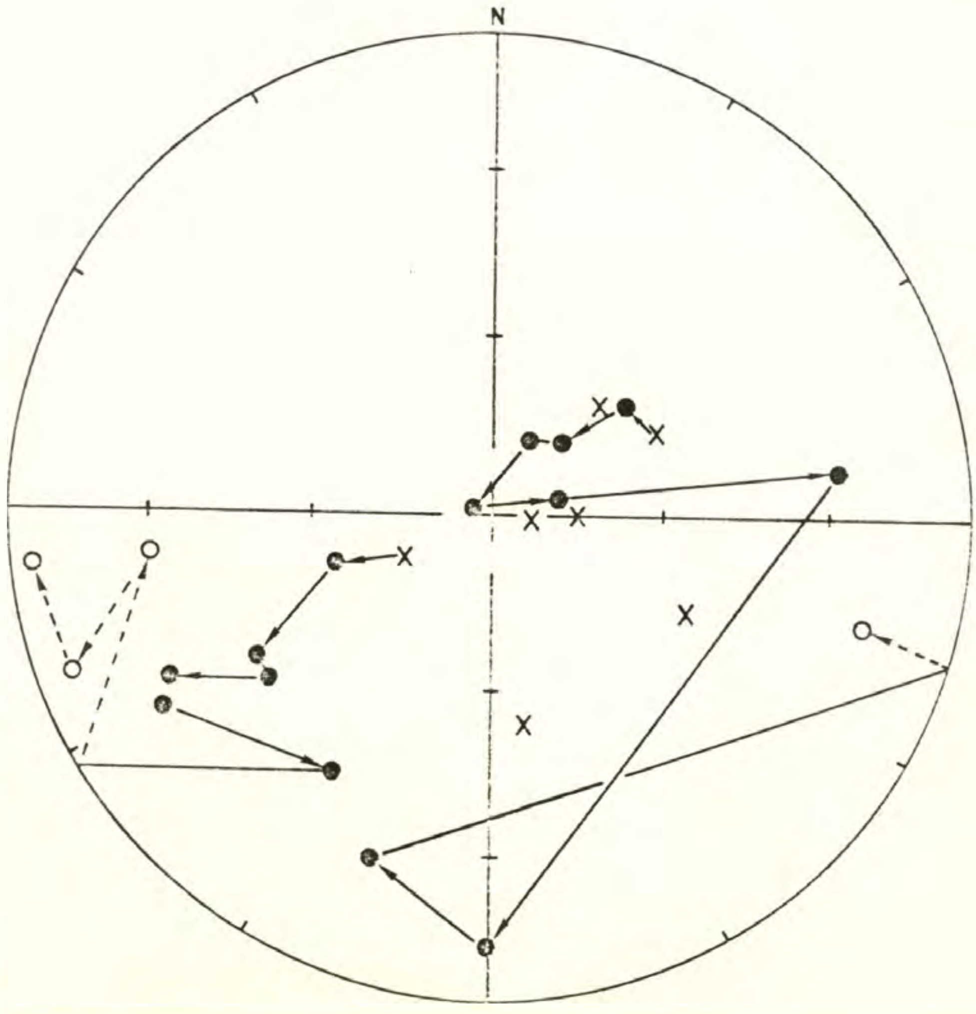
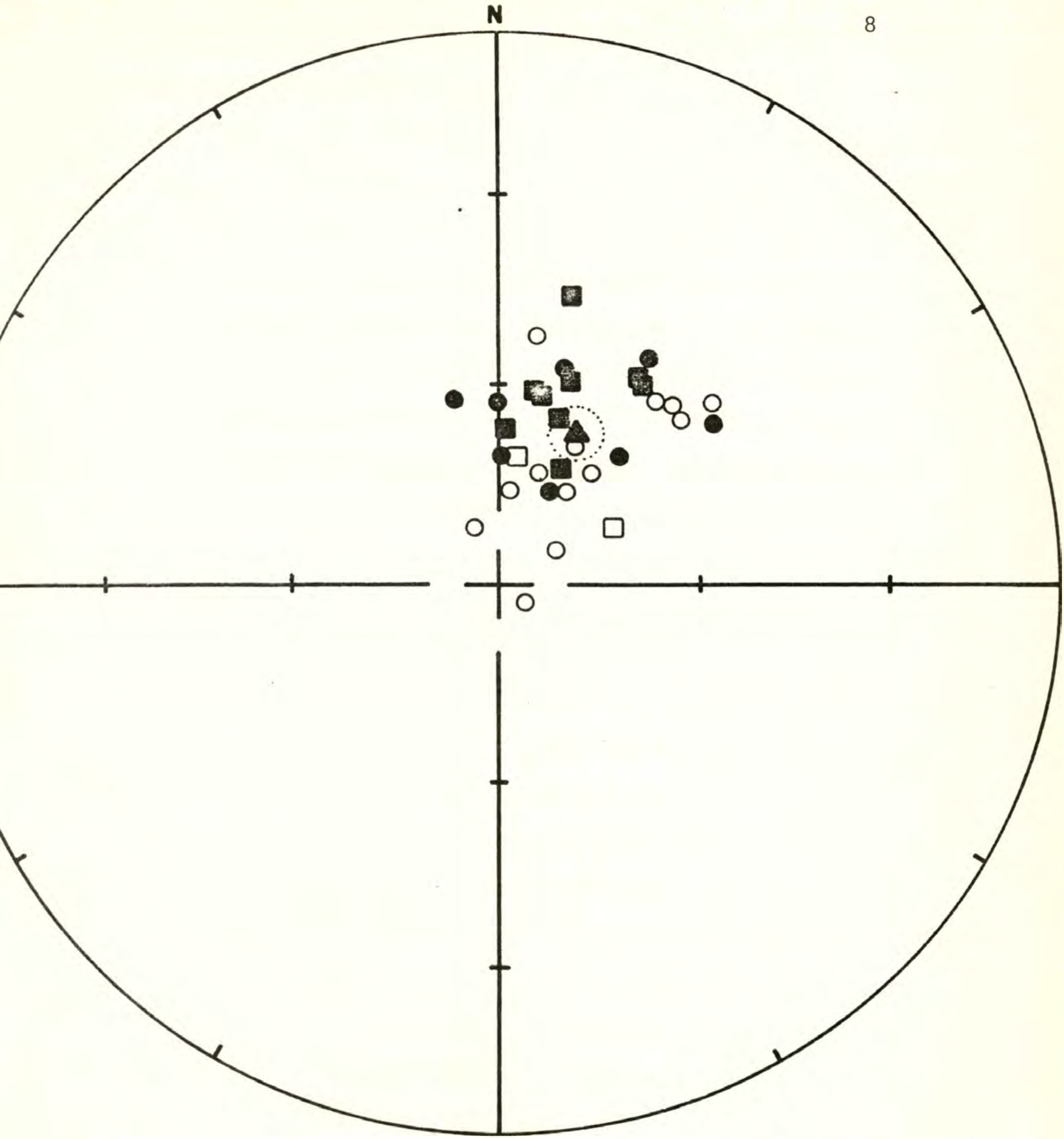

N

FIGURE 4. Site mean directions of remanent magnetization for Ohanapecosh, East Fork and Skamania Formations. Lower-hemisphere equal area plot. Solid symbols are normal polarity; open symbols are reversed polarity inverted through center of projection. Triangle indicates mean of site-means (with circle of 95% confidence). Circles indicate Ohanapecosh Formation. Squares indicate East Fork-Skamania Formation.


N

have been slumped or otherwise displaced. Three sites located in dikes intruding the Ohanapecosh were rejected as their age, other than being post-Ohanapecosh, could not be determined and their directions of remanent magnetization were not statistically different from that of the present dipole field. Individual samples which diverged from the site-mean by more than twice the angular standard deviation also were rejected. Thirty-two samples were rejected for this reason.

Both normal and reversed polarities of magnetization are present within the Ohanapecosh and East Fork-Skamania Formations. The mean directions of magnetization of the 16 sites showing reversed polarity and the 18 sites of normal polarity are antiparallel at the 95% confidence level, indicating that secondary magnetization has been substantially reduced, or eliminated.

The mean direction of remanent magnetization for the Ohanapecosh Formation has been determined from the remaining 228 samples representing 34 sites (Fig. 4). The 34 sites are distributed as follows: four sites at the Ohanapecosh type section, 19 sites in the Ohanapecosh Formation-Wind River area, and 11 sites in the East Fork-Skamania Formations (Fig. 1).

All sites were corrected for a tilt (dip) observed in the field in order to recover the original direction of magnetization. However, owing to the tendency for lava flows to conform to the land surface, in principle a distinction should be made between original dip and post-magnetization tilting. Unfortunately, this distinction is, in most places, very difficult, if not impossible, to make. "Correcting" for original dip undoubtedly introduces scatter into the data set, but because this "correction" presumably is small and random the mean direction is unlikely to be affected significantly. In fact, the scatter of mean directions was significantly reduced after application of tilt correction to all sites. The precision parameter of Fisher (1953) increased from 20.1 to 30.7, a statistically significant change (Cox, 1969; McElhinny, 1963), while the circle of 95% confidence decreased from 5.4° to 4.4°. This verifies the presence of important post-magnetization tectonic tilting and constitutes a positive fold test (McElhinny, 1973). It should be noted also that the blanket tilt correction made little difference in the overall mean. The mean directions of remanent magnetization, calculated with and without tilt correction, for the Ohanapecosh Formation are not statistically distinct at the 95% confidence level and differ by less than 7° of declination.

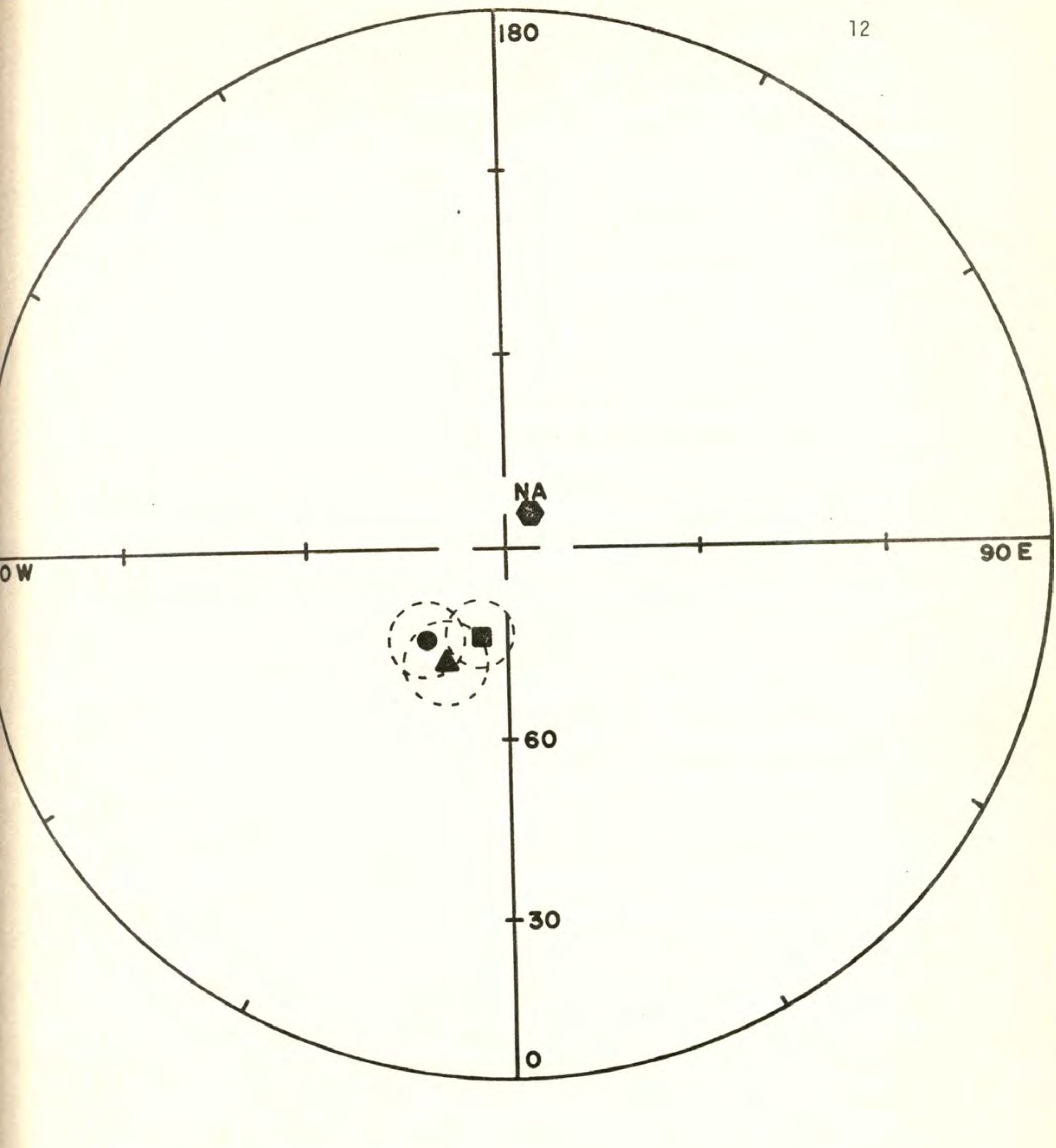
The mean direction of remanent magnetization for the Ohanapecosh (tilt corrected) is: dec. = 26.8° east, inc. = 63.6° down, $\alpha_{95} = 4.4^{\circ}$, k = 30.6 (Fig. 4). When compared to the expected direction of magnetization for the study area, calculated from the Oligocene pole of Irving (1979), a discordance in declination of $31^{\circ} \pm 12^{\circ}$ clockwise is noted. Because inclination is not significantly different from that calculated from the Oligocene pole, it appears that the Ohanapecosh did not move significantly north or south, relative to stable North America, but rather rotated more or less in place about a nearly vertical axis. It should be noted here, however, that movement or translations along latitude lines (rotations about the geographic pole) cannot be detected by paleomagnetic methods.

Further details of the laboratory methods and within-site statistics are available in the appendices.

INTERPRETATION

The results presented here suggest that at least the southernmost portion of the Cascade Mountains in Washington, and possibly all of the Washington Cascades south of Mt. Rainier, are displaced with respect to the stable North American interior. Additionally, the results reported by Beck and Burr (1979) from the Goble Volcanic Series, immediately west of the study area, and those of Globerman and Beck (1979) to the northwest in the Black Hills of the Washington Coast Range are statistically indistinguishable from my results, suggesting that the Washington Coast Range and the southern Cascades of Washington rotated together as a single unit (Fig. 5). This tends to support Hammond's (1979) suggestion that the Cascades and the Coast Ranges rotated as a single tectonic unit, at least in the area north of the Columbia River. This large crustal block appears to have rotated approximately 30^{0} in a clockwise direction during late Eocene to mid-Oligocene time. Whether or not rotation of the block continued beyond this time is a question which may be answered by paleomagnetic studies of upper Oligocene and Miocene age rocks in the southern Washington Cascades.

FIGURE 5. Paleomagnetic poles and 95% confidence intervale for the Goble Volcanic Series (square), Ohanapecosh, East Fork-Skamania Formations (circle), and Black Hills (triangle). NA = Late Eocene reference pole for North America (Irving, 1979).



180
NA
0 W
90 E
60
30
0

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APPENDICES

METHODS:

A minimum of five samples were taken from each site by drilling with a portable rock drill equipped with a stainless steel diamond bit. The individual samples were spaced from one to several meters apart in order to sample the outcrop uniformly. Each sample was oriented 'in-situ' using a Brunton compass and checked, whenever possible, by a sun compass, or back-sight. Use of the sun compass and back-sight made it possible to correct for local perturbations of the magnetic field, thereby maintaining a relatively small orientation error (less than 2^{o}).

In the lab the samples, measuring 2.5 cm in diameter, were cut into specimens 2.2 cm in length and natural remanent magnetizations (NRM) were measured on a Schonstedt Spinner Magnetometer model SSM1-A. Secondary components of magnetization were removed by alternating field (A-F) demagnetization in a Schonstedt model GSD-5, AC, tumbling demagnetizer.

The A-F demagnetizing level chosen for the magnetic cleaning of any particular site was determined from the behavior, during demagnetization, of two pilot specimens. The pilot specimens were demagnetized at progressively higher fields until very small divergence between the specimens was obtained or the changes in direction of magnetizations were essentially stopped. In general, intensities of magnetization decreased (see plot S-5, Appendix C). Failure of a site to satisfy either of these criteria, especially if combined with a low intensity of magnetization, was viewed as evidence of magnetic instability and grounds for rejection of the site from the data set. Sites E-2, E-4, S-2, Ø-12, Ø-26 were rejected for this reason. The NRM plots and pilot demagnetization paths for these rejected sites are given in Appendix C as equal-area projections. Included for comparison is the NRM plot and pilot demagnetization path of magnetically stable site S-5. One site (Ø-3), whose stability was only marginal as indicated by the criteria defined above, was retained but ultimately rejected as its α_{95} circle of confidence exceeded 15^{o}, a value used by Beck and Burr (1979) (Appendix C). The 15^{o} limit on α_{95} is dictated by a need to maximize data retention and at the same time insure a significantly meaningful result by eliminating sites with large amounts of scatter.

Site Ø-6 was rejected (Appendix C) because its mean direction was far west of the tight grouping formed by the other sites (Appendix B). Site Ø-6 is located in a relatively small and quite isolated outcrop and may have been dislocated in some manner. This would result in an inability to recover the original direction of magnetization. The problem also was compounded by the lack of structural control needed for proper tile correction.

Sites Ø-28, Ø-29, and Ø-30 are located in andesite dikes cutting the Ohanapecosh Formation. These sites gave very stable, well grouped directions (Appendix C) but were rejected because their ages could not be determined exactly. It was evident that they were post-Ohanapecosh but how much younger could not be determined independently. Their mean directions of magnetization are indistinguishable statistically from the present-day field. Thus, they probably are quite young and not representative of the Oligocene Ohanapecosh direction of magnetization.

The table and plots of Appendix A summarize the paleomagnetic data used in the calculation of the mean direction of magnetization for the Ohanapecosh and East-Fork-Skamania Formations. The plots are all equal area projections and show, for each site, the direction of magnetization for individual specimens, the site mean and the tilt corrected site mean.

The plots do not include those particular specimens, noted in the table of Appendix A, which have been rejected from various sites. These rejected specimens diverged from the site mean by more than twice the angular standard deviation and were rejected.

Every effort was made to obtain the attitude of the sample site from the confining beds and in most cases this was possible. In a few instances however, the tilt was obtained at some little distance from the site locality, due to lack of exposure and in one case (site Ø-6) it was very approximate and the site was rejected as mentioned earlier.

Diagrams showing the effect of the tilt correction applied to all sites appear in Appendix B. It can be seen that the net result of applying tilt corrections to all sites is a reduction in the amount of scatter. A small amount of scatter may have been introduced when the 'correction' was applied to original dip but these few cases do not significantly affect the results as original dip is probably small in magnitude and randomly oriented.

The mean direction of the sites exhibiting normal polarity and of those having reversed polarity are plotted in Appendix B. After magnetic cleaning the two groups are antiparallel at the 95% level indicating a negligible level of secondary magnetization.

APPENDIX A

Paleomagnetic results, map coordinates, and plots of individual sites

PALEOMAGNETIC RESULTS TABULATED AS SITE MEANS

SITE LOCALITY	NRM $\overline{D}$	$\overline{I}$	α_{95}	k	n
EAST FORK FORMATION					
E·1 E. Fk. Lewis R.					
E·2 "	7.7	49.7	19.7	8.4	11
E·3 "	30.4	66.9	25.7	3.7	8
E·4 "	320.7	58.9	28.1	3.1	8
E·5 "	334.4	54.5	19.3	7.4	8
E·6 "	351.8	63.0	7.3	35.9	10
SKAMANIA FORMATION					
S·1 Silver Star Mt.	26.5	48.9	22.0	5.0	8
S·2 "	18.3	1.8	28.9	3.9	6
S·3 "	0	63.0	14.7	11.2	8
S·4 Tatoosh Hills	256.3	84.1	19.4	6.4	8
S·5 Saturday Rock	313.9	62.2	30.5	2.6	8
S·6 Silver Star Mt.	325.2	85.2	33.6	1.9	8
S·7 "	3.6	57.7	2.9	284.0	8
S·8 "	78.3	74.1	26.5	3.4	8
S·9 Gumboot Mt.	275.2	-69.7	23.6	4.3	8
OHANAPECOSH FORMATION Wind River Area					
Ø·1 Trout Lake, Wa.	17.1	66.4	11.5	20.8	7
Ø·2 Carson, Wa.	191.5	-53.6	18.2	7.3	8
Ø·3 Rock Creek	271.2	73.0	6.8	6.8	7
Ø·4 "	97.4	87.0	32.8	2.5	7
Ø·5 Peterson Ridge	95.0	-42.0	39.9	1.8	7

			NRM		
OPANAPECOSH FORMATION Wind River Area (Cont.)	$\overline{D}$	$\overline{I}$	α_{95}	k	n
Ø·6 Bear Creek	351.7	47.8	12.8	14.7	8
Ø·7 Wind River	213.7	-71.5	19.6	7.2	7
Ø·8 "	158.3	-67.2	12.2	16.2	8
Ø·9 "	322.7	61.7	20.5	6.6	7
Ø·10 Paradise Hills	184.0	-26.1	39.2	1.8	7
Ø·11 Middle Butte	6.8	56.0	6.1	66.6	8
Ø·18 Green Knob	184.2	56.3	6.1	4.7	8
Ø·19 Greenleaf Peak	58.5	59.1	13.7	14.7	7
Ø·20 Rock Creek	175.9	-56.9	15.5	10.1	8
Ø·21 Paradise Creek	37.7	73.7	23.2	5.1	7
Ø·22 White Bluffs	233.5	82.9	15.8	9.7	8
Ø·23 Paradise Creek	16.3	57.0	4.7	112.2	8
Ø·24 Mouse Creek	23.1	63.8	6.4	11.5	7
Ø·25 12-mile Creek	105.3	58.9	32.5	2.6	7
Ø·26 8-mile Creek	104.9	75.7	15.5	11.5	7
Ø·27 Tatoosh Hills	300.5	43.2	38.6	1.6	8
Ø·28 Couger Rock	161.7	-73.2	33.6	2.1	8
Ø·29 "	122.7	-68.3	19.7	8.3	6
Ø·30 "	183.7	-60.1	6.7	105.3	7
Ø·31 Rock Creek	327.5	69.5	42.3	1.56	7
OHANAPECOSH FORMATION Type Section					
Ø·12 White Pass, Wa.	51.8	-21.8	46.8	1.2	8
Ø·13 "	122.1	64.9	19.8	7.2	7
Ø·14 "	39.1	50.8	11.1	26.6	6
Ø·15 "	228.5	-65.3	42.3	1.3	8
Ø·16 "	10.9	64.2	9.3	28.3	8
Ø·17 "					

PALEOMAGNETIC RESULTS TABULATED AS SITE MEANS

		CLEANED						TILT CORRECTED			
SITE	LOCALITY	$\overline{D}$	$\overline{I}$	α_{95}	k	field (oe)	n	Tilt Az./Dip	$\overline{D}$	$\overline{I}$	Remarks
EAST FORK FORMATION											
E·1	E. Fk. Lewis R.										Combined with site E·2
E·2	"										Unstable
E·3	"	18.6	69.9	9.9	28.6	100	7	355/10	11.2	60.5	
E·4	"										Unstable
E·5	"	3.9	56.4	8.6	52.8	250	5	175/10	3.5	66.4	
E·6	"	21.3	55.8	7.4	40.2	50	9	80/10	34.6	52.7	
SKAMANIA FORMATION											
S·1	Silver Star Mt.	3.3	59.6	5.9	46.7	400	6	120/10	20.6	62.8	
S·2	"										Unstable
S·3	"	12.0	56.8	5.6	87.4	300	7	100/5	19.5	56.5	
S·4	Tatoosh Hills	347.0	68.9	3.7	204.5	300	7	100/15	27.7	69.7	
S·5	Saturday Rock	198.7	-61.9	2.9	282.5	500	8	220/8	191.2	-69.2	
S·6	Silver Star Mt.	9.8	43.6	5.9	91.4	600	5	105/6	15.5	43.8	
S·7	"	0	57.4	1.7	815.7	400	8	115/8	12.8	60.0	
S·8	"	18.3	54.2	7.1	64.0	400	6	115/13	36.3	53.6	
S·9	Gumboot Mt.	270.3	-63.8	9.1	39.2	200	6	60/14	245.3	-74.5	
OHANAPECOSH FORMATION Wind River Area											
Ø·1	Trout Lake, Wa.	18.2	59.2	3.6	217.4	200	7	225/13	2.5	70.0	
Ø·2	Carson, Wa.	208.7	-67.1	3.0	346.2	400	6	240/10	189.7	-74.8	
Ø·3	Rock Creek	247.1	-40	25.3	10.2	1000	7	180/9			Rejected
Ø·4	"	205.9	-62.9	5.6	157.3	450	4	185/10	216.6	-71.9	

SITE LOCALITY	CLEANED $\overline{D}$	$\overline{I}$	α_{95}	k	field (oe)	n	TILT CORRECTED Tilt Az./Dip	$\overline{D}$	$\overline{I}$	Remarks
OHANAPECOSH FORMATION Wind River Area (cont.)										
Ø·5 Peterson Ridge	200.4	-86.1	4.6	152.7	400	6	170/10	333.4	-83.0	
Ø·6 Bear Creek	327.9	36.4	9.2	29.2	200	8	200/32	299.3	49.9	Rejected
Ø·7 Wind River	204.4	-67.6	4.0	172.7	200	7	180/15	238.6	-79.4	
Ø·8 "	162.0	-69.0	6.5	57.3	400	8	165/10	159.2	-79.3	
Ø·9 "	210.9	-41.7	12.4	18.1	500	7	145/20	230.1	-46.8	
Ø·10 Paradise Hills	182.3	-27.9	4.8	140.3	300	6	165/25	189.9	-51.3	
Ø·11 Middle Butte	8.6	50.6	4.6	116.0	300	8	127/10	18.6	57.5	
Ø·18 Green Knob	202.2	-66.6	2.4	545.7	400	6	240/8	220.7	-66.4	
Ø·19 Greenleaf Peak	37.4	24.5	5.8	84.1	300	7	185/32	53.5	49.4	
Ø·20 Rock Creek	183.1	-53.0	2.3	444.2	400	8	135/15	202.9	-61.1	
Ø·21 Paradise Creek	30.1	56.8	14.9	14.7	200	7	165/10	43.8	63.0	
Ø·22 White Bluffs	351.2	77.8	3.4	246.5	300	8	80/10	29.5	74.0	
Ø·23 Paradise Creek	15.5	59.9	5.6	77.6	400	8	75/18	34.7	48.1	
Ø·24 Mouse Creek	180.8	-71.1	4.9	138.9	200	5	—	180.8	-71.1	
Ø·25 12-mile Creek	234.1	-52.1	5.4	131.5	300	5	315/5	227.6	-52.9	
Ø·26 8-mile Creek										Unstable
Ø·27 Tatoosh Hills	207.6	-61.8	3.9	216.9	300	6	85/15	224.9	-51.8	
Ø·28 Couger Rock	170.6	-78.7	5.9	69.2	800	8	Dike	—	—	Rejected
Ø·29 "	158.2	-68.0	6.0	90.0	400	6	Dike	—	—	Rejected
Ø·30 "	168.6	-61.4	3.5	226.7	200	7	Dike	—	—	Rejected
Ø·31 Rock Creek	203.1	-54.7	10.5	25.4	200	7	180/10	210.7	-63.6	
OHANAPECOSH FORMATION Type Section										
Ø·12 White Pass, Wa.										Unstable
Ø·13 "	39.1	83.6	9.6	30.3	200	7	257/32	260.1	85.2	
Ø·14 "	23.2	47.8	5.9	219.1	300	6	257/32	341.7	57.0	

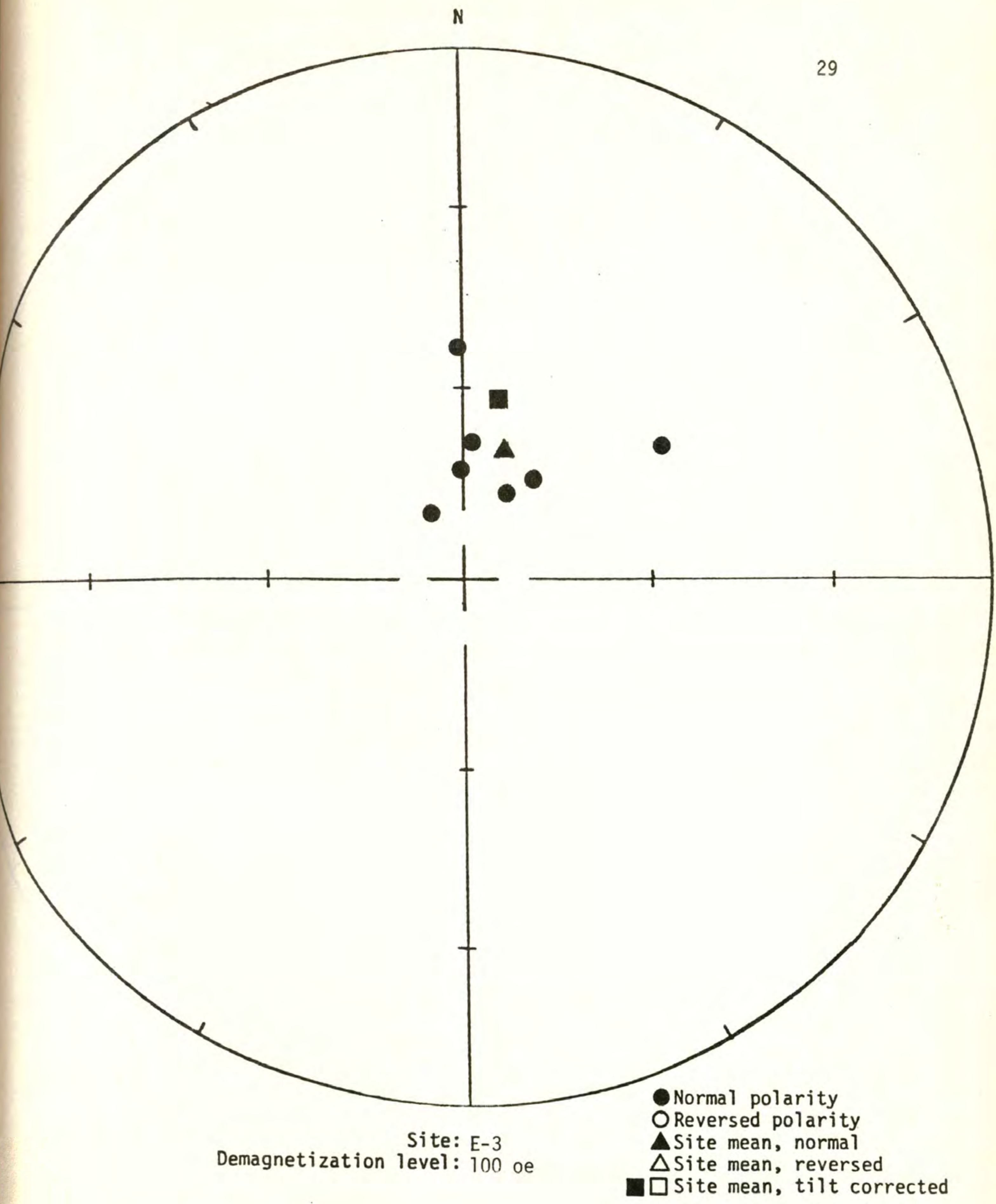
	CLEANED						TILT CORRECTED			
SITE LOCALITY	$\overline{D}$	$\overline{I}$	α_{95}	k	field (oe)	n	Tilt Az./Dip	$\overline{D}$	$\overline{I}$	Remarks
OHANAPECOSH FORMATION Type Section (cont.)										
Ø·15 White Pass, Wa.	225.7	-6.7	5.9	98.9	500	7	235/35	222.7	-41.1	
Ø·16 "	18.1	59.1	6.9	51.8	300	8	260/10	1.1	62.5	
Ø·17 "										Not Sampled

LOCATIONS OF PALEOMAGNETIC SAMPLING SITES

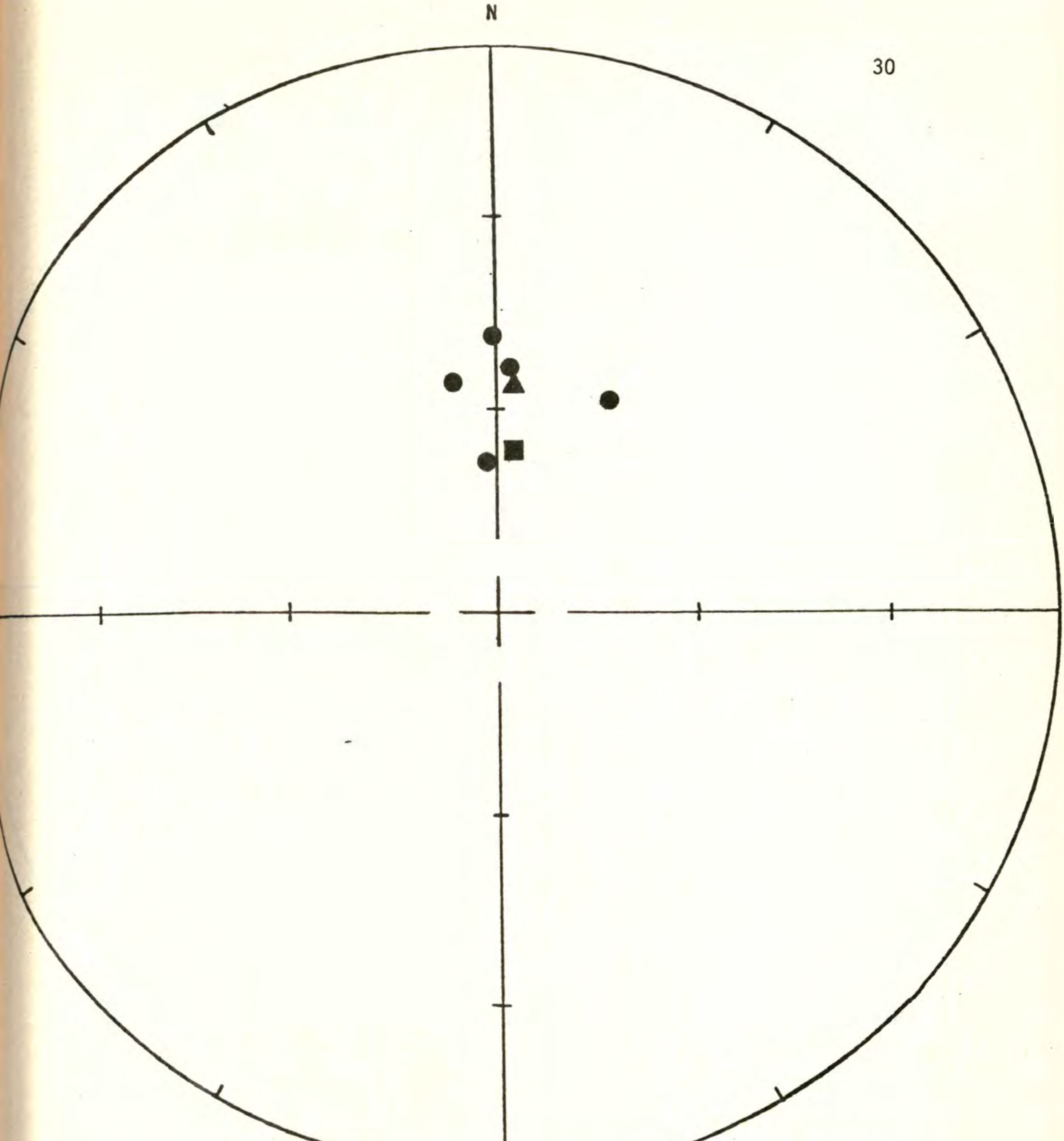
SITE			MAP LOCATION			MAP
E-1	T4N	R5E	SE1/4	SW1/4	Sec. 14	Lookout Mtn., Washington 15 min. quadrangle
E-2	same as E-1					
E-3	T4N	R5E	SW1/4	NW1/4	Sec. 15	Lookout Mtn., Washington 15 min. quadrangle
E-4	T4N	R5E	SW1/4	NE1/4	Sec. 14	"
E-5	T4N	R5E	NE1/4	NW1/4	Sec. 19	"
E-6	T4N	R5E	NE1/4	SE1/4	Sec. 17	"
S-1	T3N	R5E	SE1/4	NW1/4	Sec. 7	"
S-2	T3N	R5E	NE1/4	SW1/4	Sec. 7	"
S-3	T3N	R5E	NW1/4	NW1/4	Sec. 7	"
S-4	T4N	R5E	SE1/4	NW1/4	Sec. 9	"
S-5	T4N	R5E	NE1/4	NE1/4	Sec. 12	"
S-6	T3N	R5E	NW1/4	NE1/4	Sec. 7	"
S-7	T3N	R5E	SE1/4	NW1/4	Sec. 7	"
S-8	T3N	R5E	NW1/4	NE1/4	Sec. 18	"
S-9	T5N	R5E	SE1/4	SE1/4	Sec. 31	"
Ø-1	T5N	R9E	NW1/4	NE1/4	Sec. 21	Willard, Washington 15 min. quadrangle
Ø-2	T3N	R8E	NW1/4	SW1/4	Sec. 21	Bonneville Dam, Washington 15 min. quadrangle
Ø-3	T3N	R7E	NW1/4	SE1/4	Sec. 21	"
Ø-4	T3N	R7E	SW1/4	SW1/4	Sec. 7	"
Ø-5	T6N	R9E	SE1/4	SW1/4	Sec. 13	Sleeping Beauty, Washington 15 min. quadrangle
Ø-6	T3N	R8E	SW1/4	SW1/4	Sec. 4	Wind River, Washington 15 min. quadrangle
Ø-7	T3N	T8E	SW1/4	NE1/4	Sec. 21	Bonneville Dam, Washington 15 min. quadrangle

SITE	MAP LOCATION					MAP
Ø-8	T5N	R7E	NW1/4	SE1/4	Sec. 17	Wind River, Washington 15 min. quadrangle
Ø-9	T5N	R7E	NW1/4	SE1/4	Sec. 20	"
Ø-10	T6N	R6E	NE1/4	SW1/4	Sec. 25	Lookout Mtn., Washington 15 min. quadrangle
Ø-11	T5N	R7E	SE1/4	SE1/4	Sec. 16	Wind River, Washington 15 min. quadrangle
Ø-12	T14N	R10E	NW1/4	SE1/4	Sec. 20	Packwood, Washington 15 min. quadrangle
Ø-13	T14N	R10E	NW1/4	SE1/4	Sec. 29	Packwood, Washington 15 min. quadrangle
Ø-14	same as Ø-13					
Ø-15	T14N	R10E	SW1/4	NW1/4	Sec. 26	Packwood, Washington 15 min. quadrangle
Ø-16	T14N	R10E	SE1/4	NW1/4	Sec. 26	"
Ø-18	T4N	R7E	NE1/4	NW1/4	Sec. 32	Wind River, Washington 15 min. quadrangle
Ø-19	T3N	R7E	SW1/4	SE1/4	Sec. 20	Bonneville Dam, Washington 15 min. quadrangle
Ø-20	T3N	R7E	SW1/4	SW1/4	Sec. 10	Wind River, Washington 15 min. quadrangle
Ø-21	T5N	R7E	SW1/4	NW1/4	Sec. 4	"
Ø-22	T6N	R7E	SE1/4	SE1/4	Sec. 7	"
Ø-23	T6N	R7E	SW1/4	SE1/4	Sec. 23	"
Ø-24	T4N	R8E	NW1/4	SE1/4	Sec. 5	"
Ø-25	T4N	R8E	NW1/4	NE1/4	Sec. 7	"
Ø-26	T5N	R7E	NE1/4	NE1/4	Sec. 34	"
Ø-27	T5N	R5E	NW1/4	SE1/4	Sec. 34	Lookout Mtn., Washington 15 min. quadrangle
Ø-28	T4N	R6E	SW1/4	SE1/4	Sec. 8	"
Ø-29	T4N	R6E	SE1/4	NW1/4	Sec. 8	"

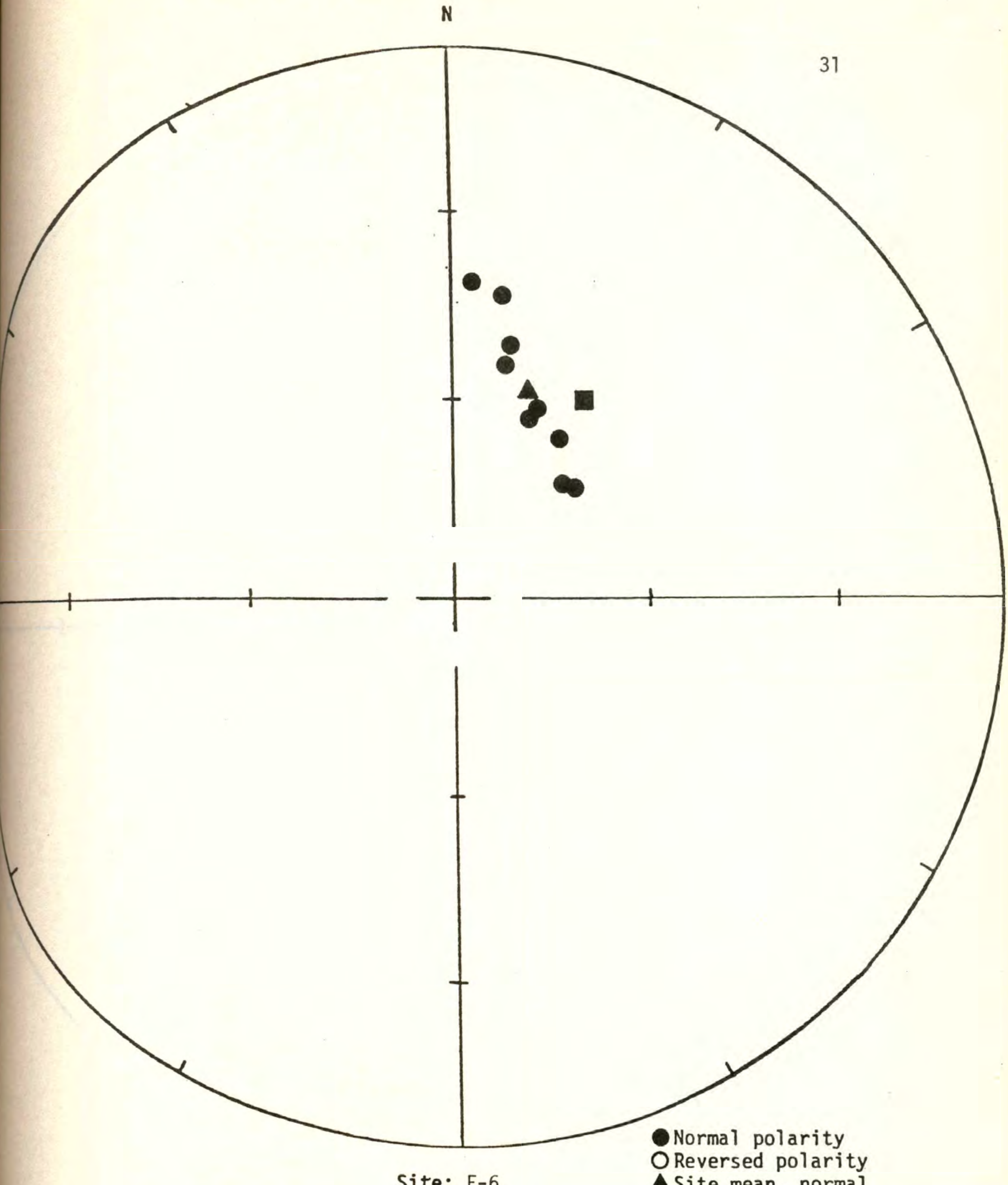
SITE	MAP LOCATION					MAP
Ø-30	T4N	R6E	NW1/4	SE1/4	Sec. 8	Lookout Mtn., Washington 15 min. quadrangle
Ø-31	T3N	R7E	SW1/4	NE1/4	Sec. 18	Bonneville Dam, Washington 15 min. quadrangle



Site: E-3
Demagnetization level: 100 oe

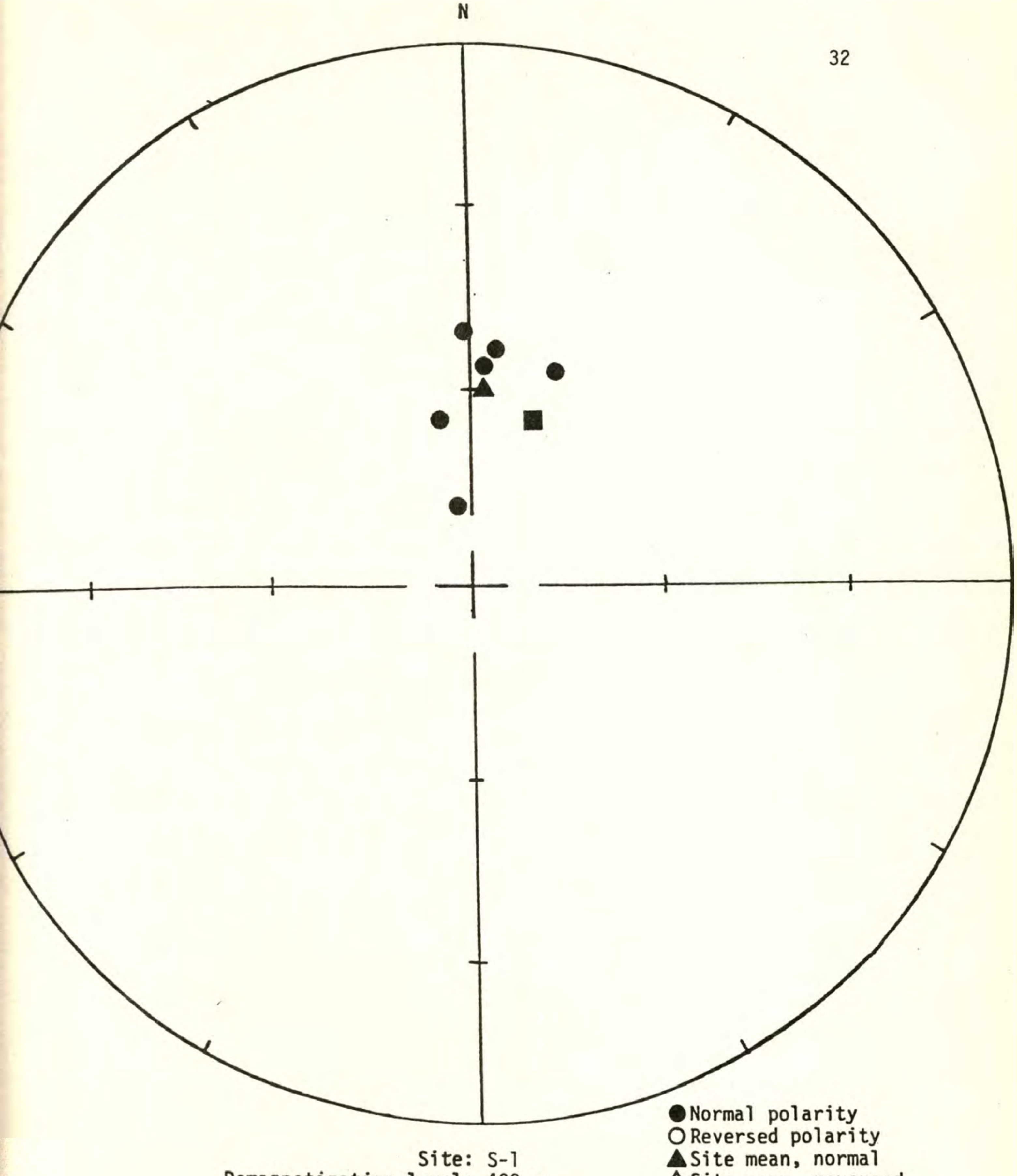


Site: E-5
Demagnetization level: 250 oe

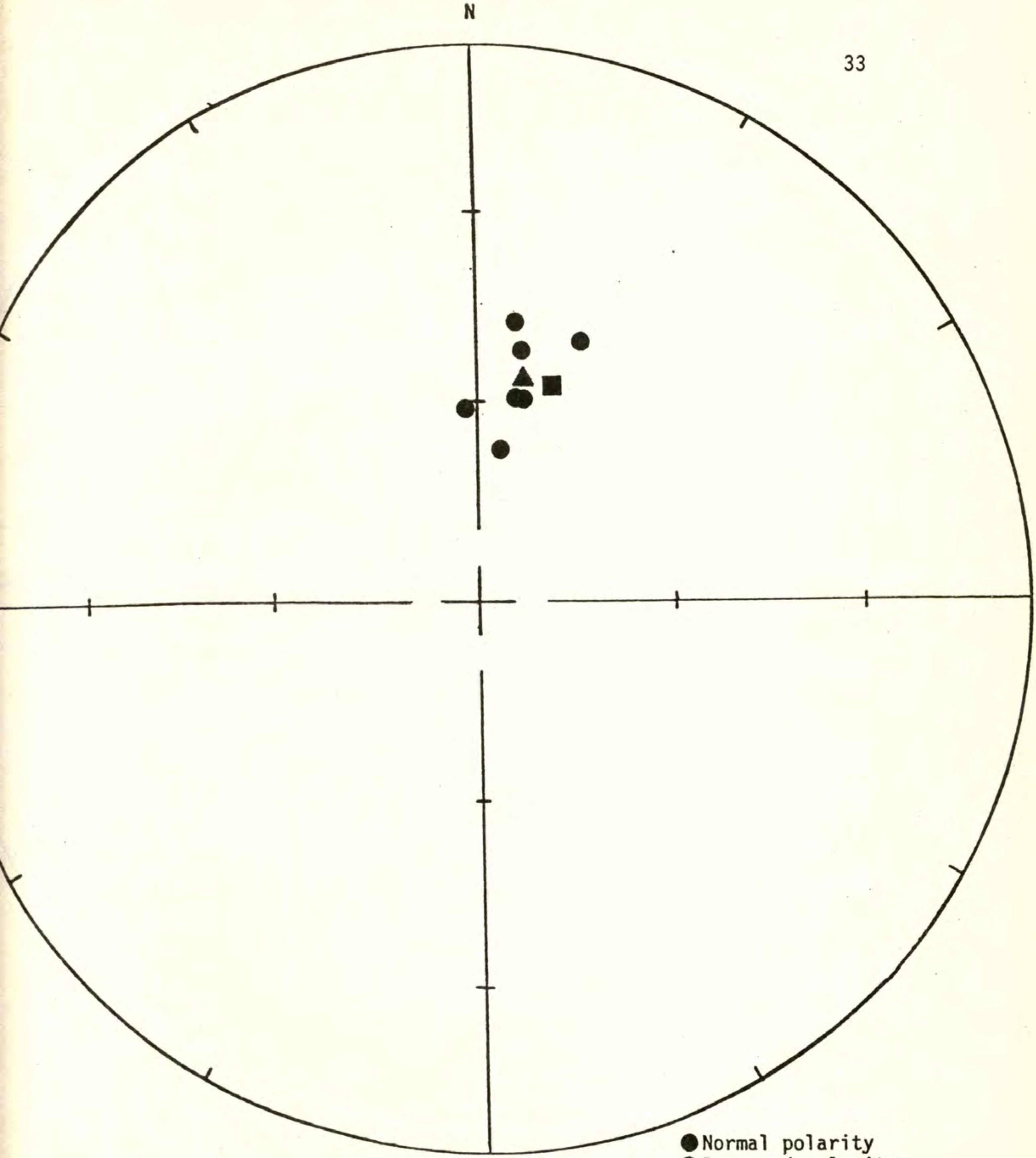


Normal polarity
Reversed polarity
Site mean, normal
Site mean, reversed
Site mean, tilt corrected

Site: E-6
Demagnetization level: 50 oe

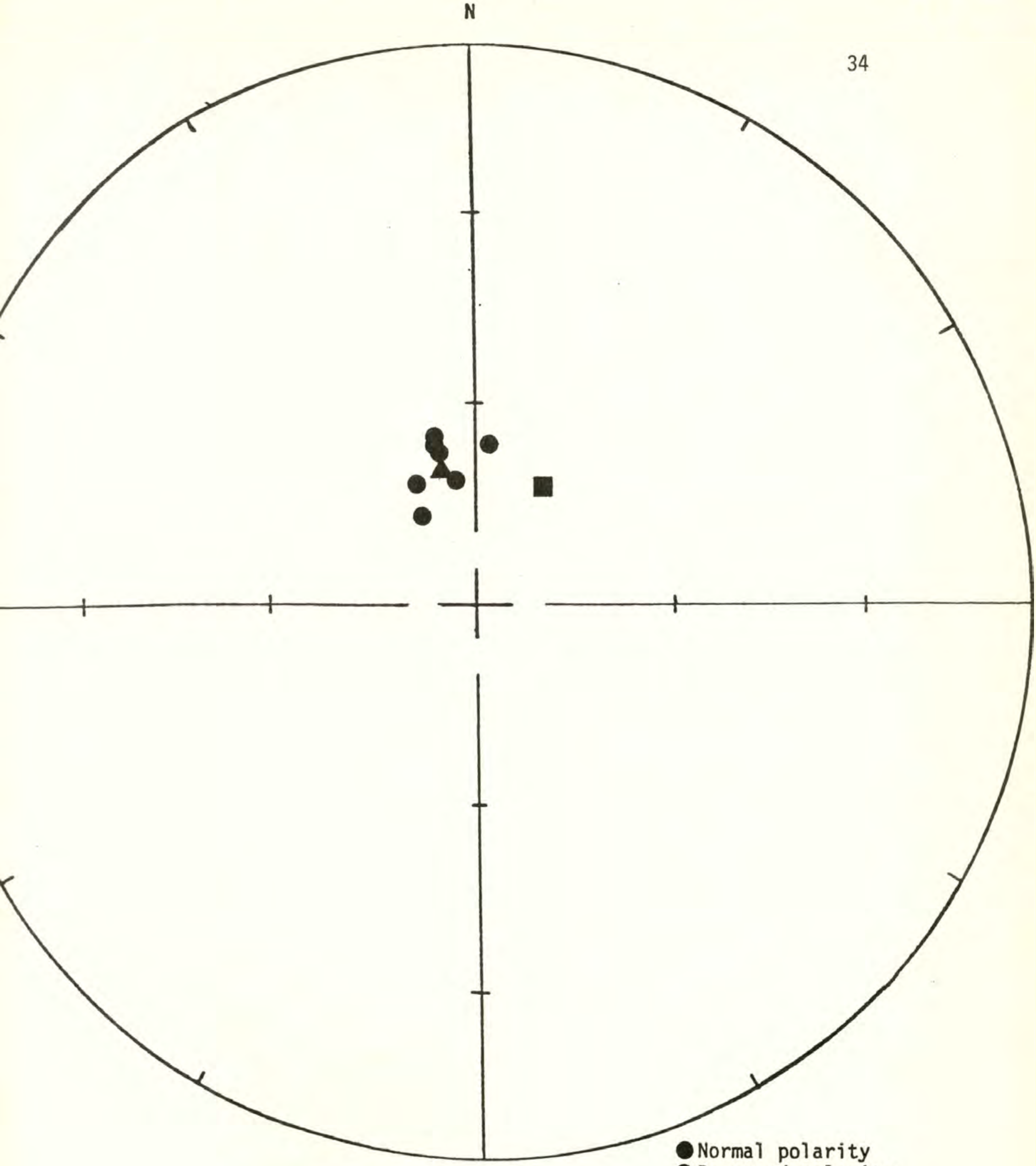


Site: S-1
Demagnetization level: 400 oe

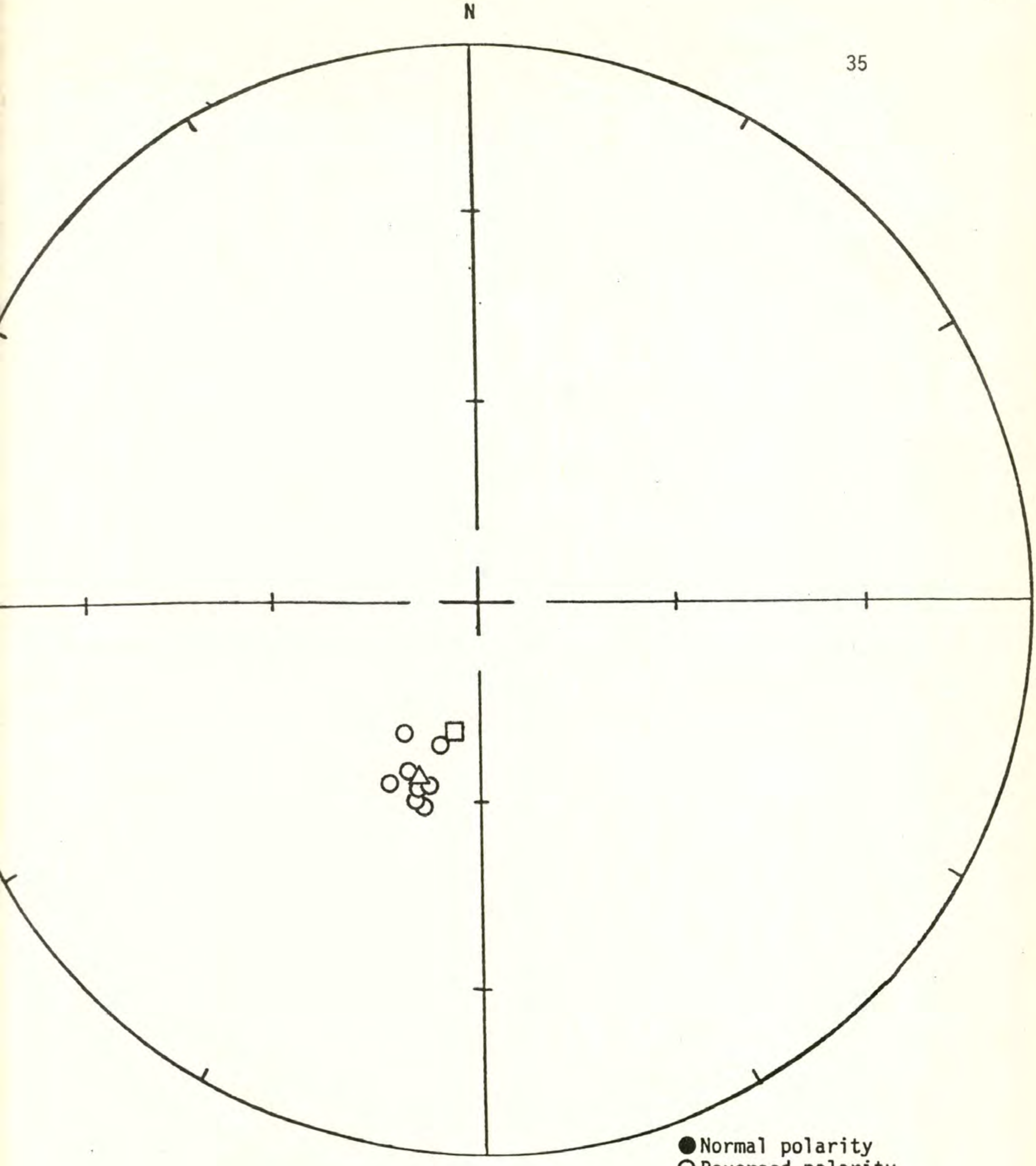


Site: S-3
Demagnetization level: 300 oe

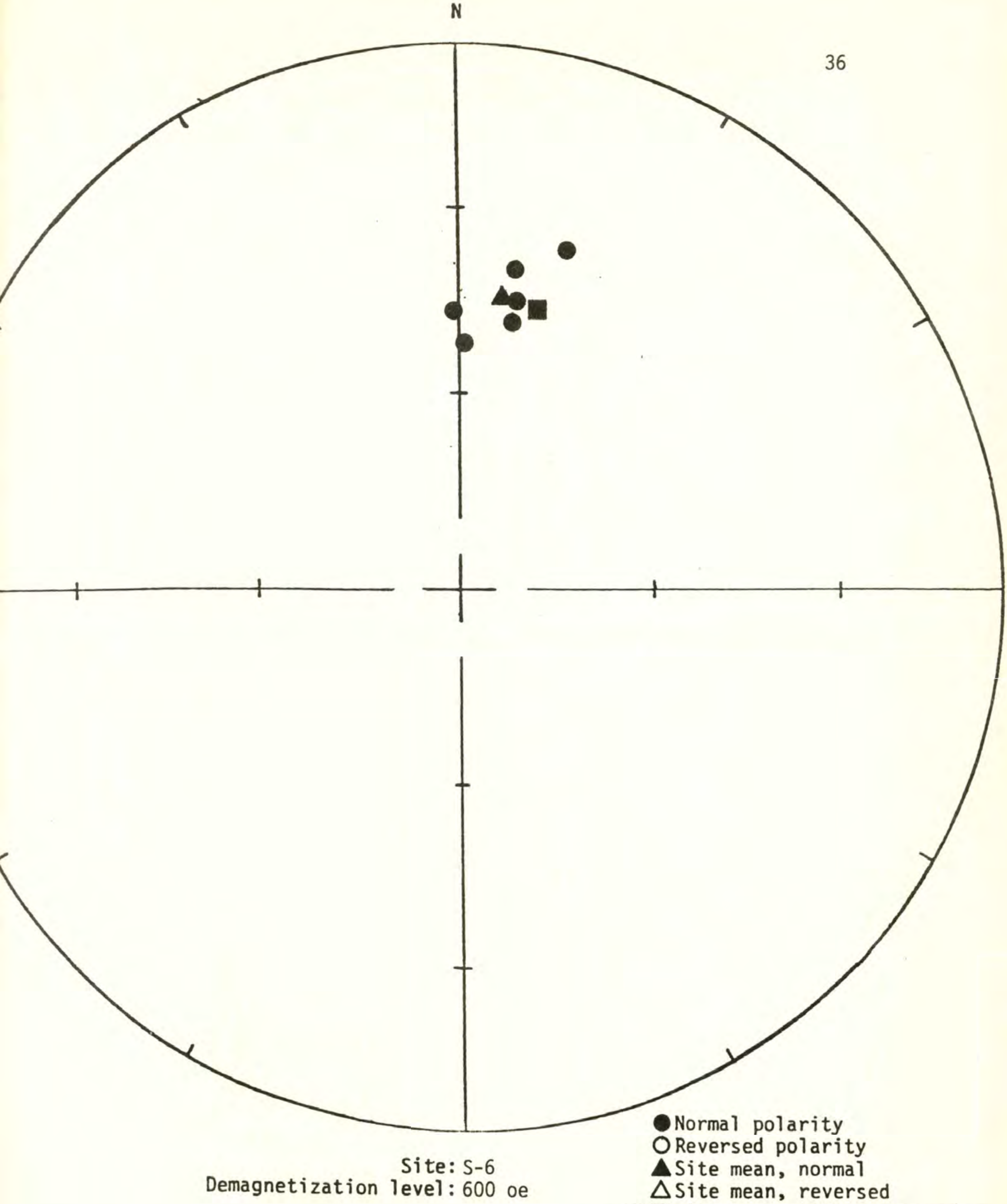
● Normal polarity
○ Reversed polarity
▲ Site mean, normal
△ Site mean, reversed
■ □ Site mean, tilt corrected



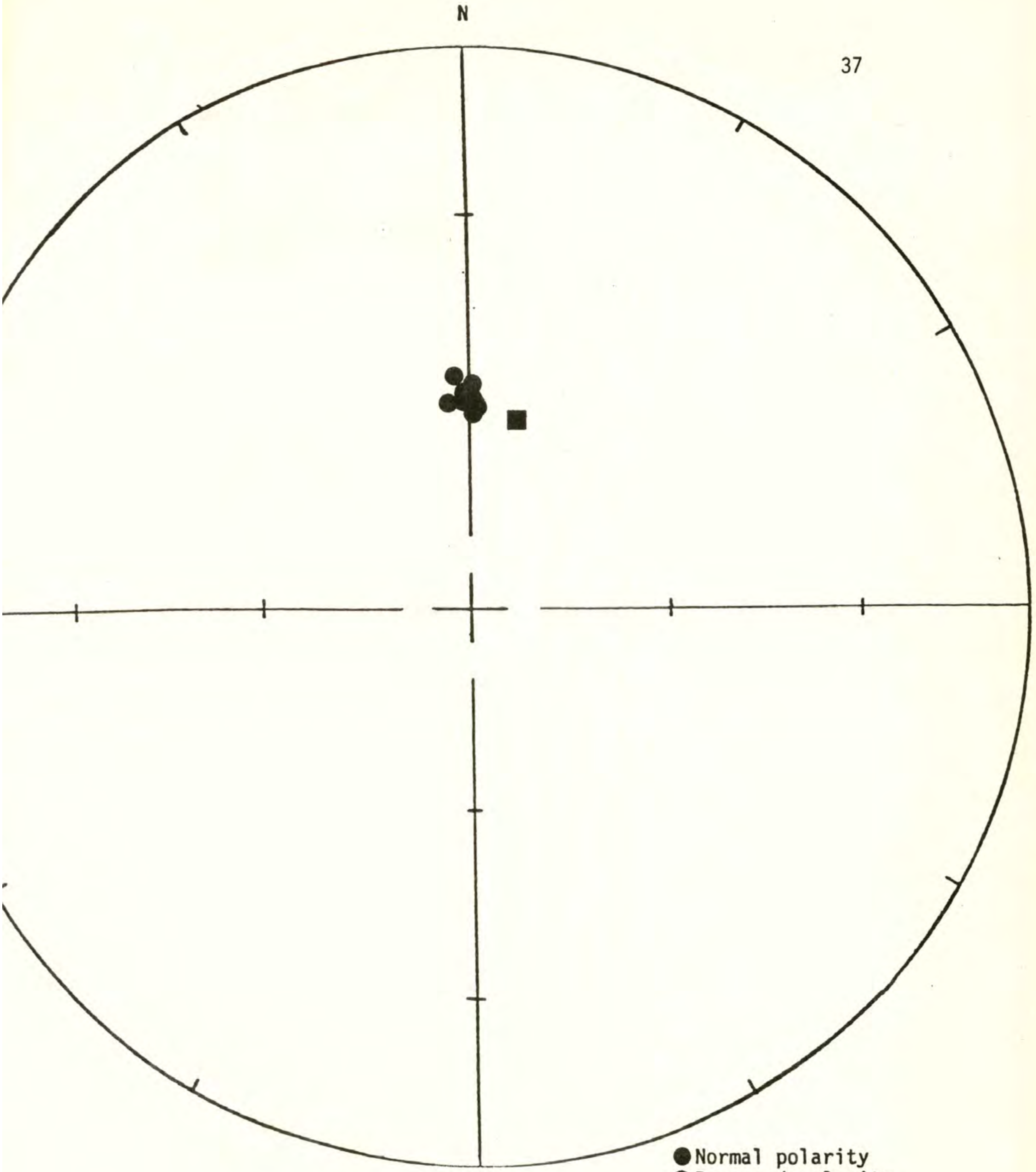
Site: S-4
Demagnetization level: 400 oe



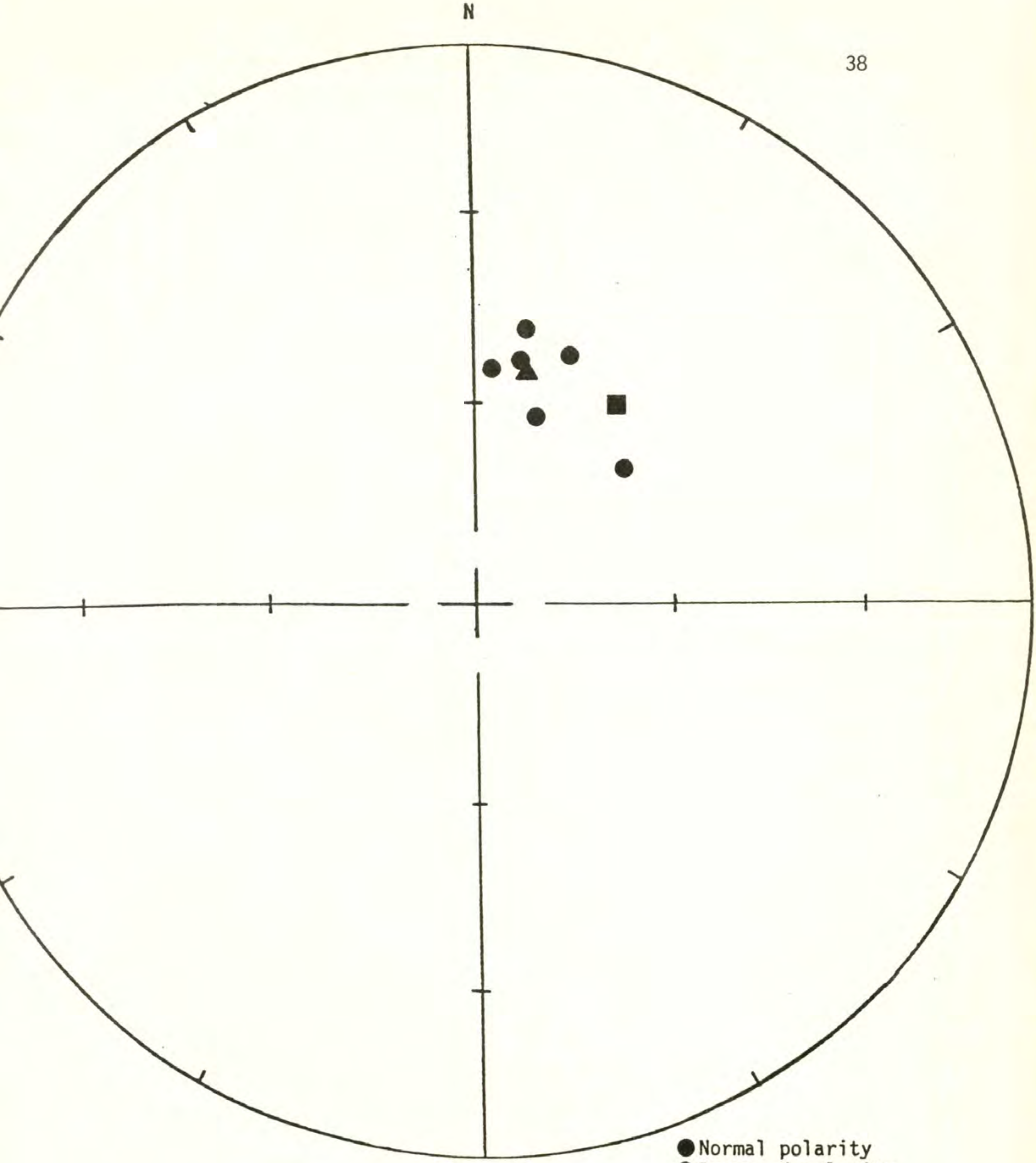
Site: S-5
Demagnetization level: 500 oe



Site: S-6
Demagnetization level: 600 oe

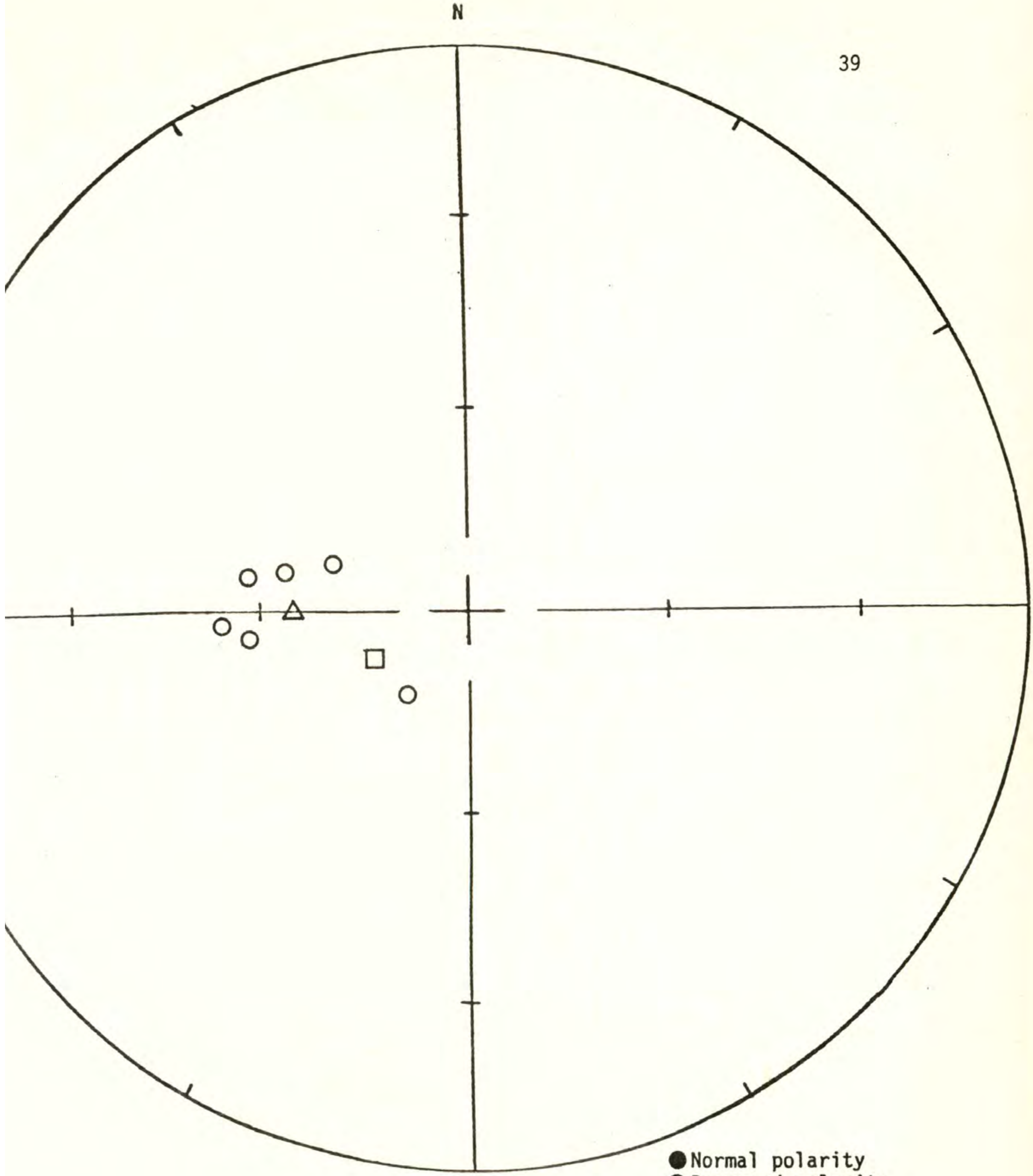


Site: S-7
Demagnetization level: 400 oe



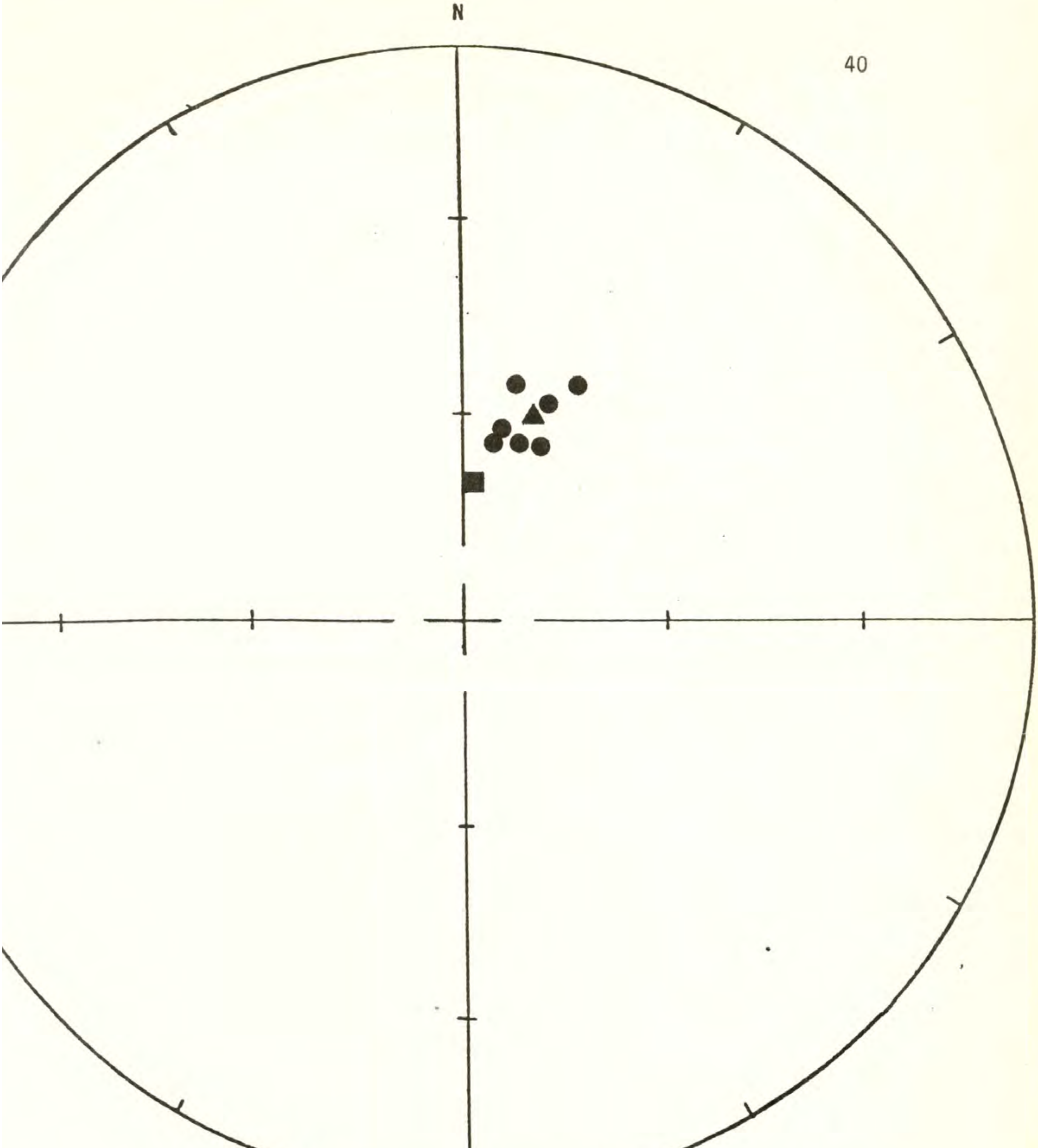
Site: S-8
Demagnetization level: 400 oe

● Normal polarity
○ Reversed polarity
▲ Site mean, normal
△ Site mean, reversed
■ □ Site mean, tilt corrected

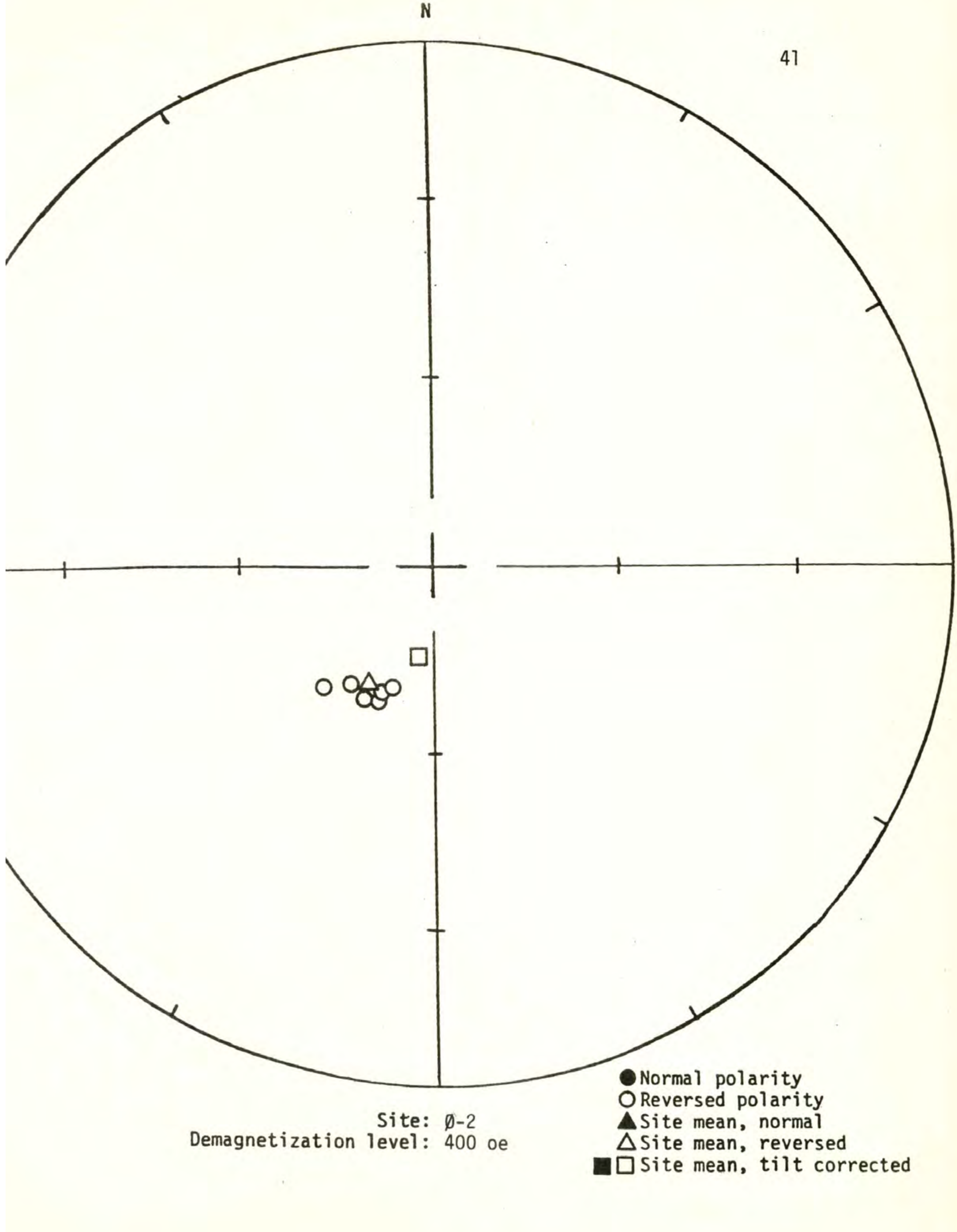


Site: S-9
Demagnetization level: 200 oe

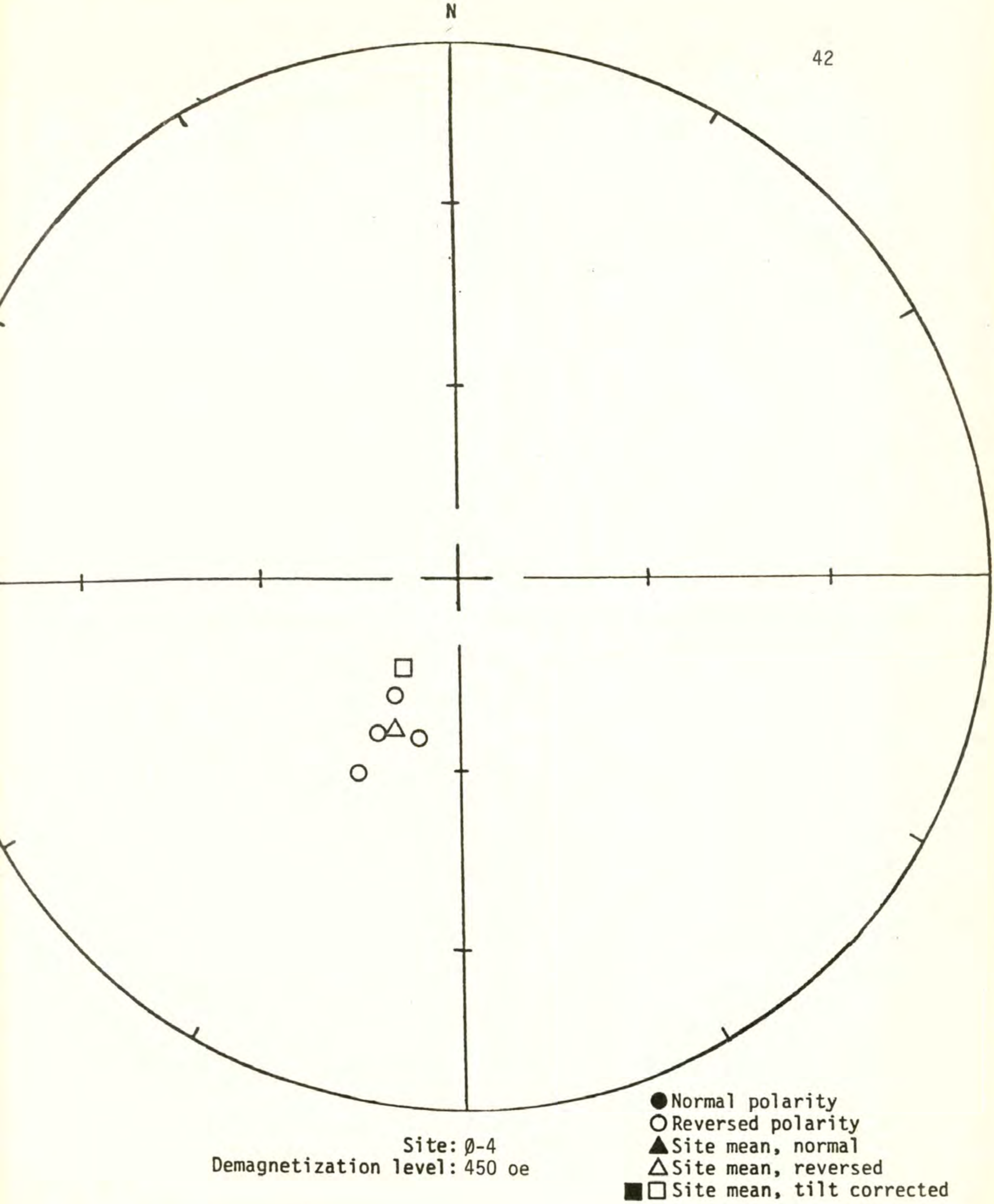
●Normal polarity
○Reversed polarity
▲Site mean, normal
△Site mean, reversed
■□Site mean, tilt corrected



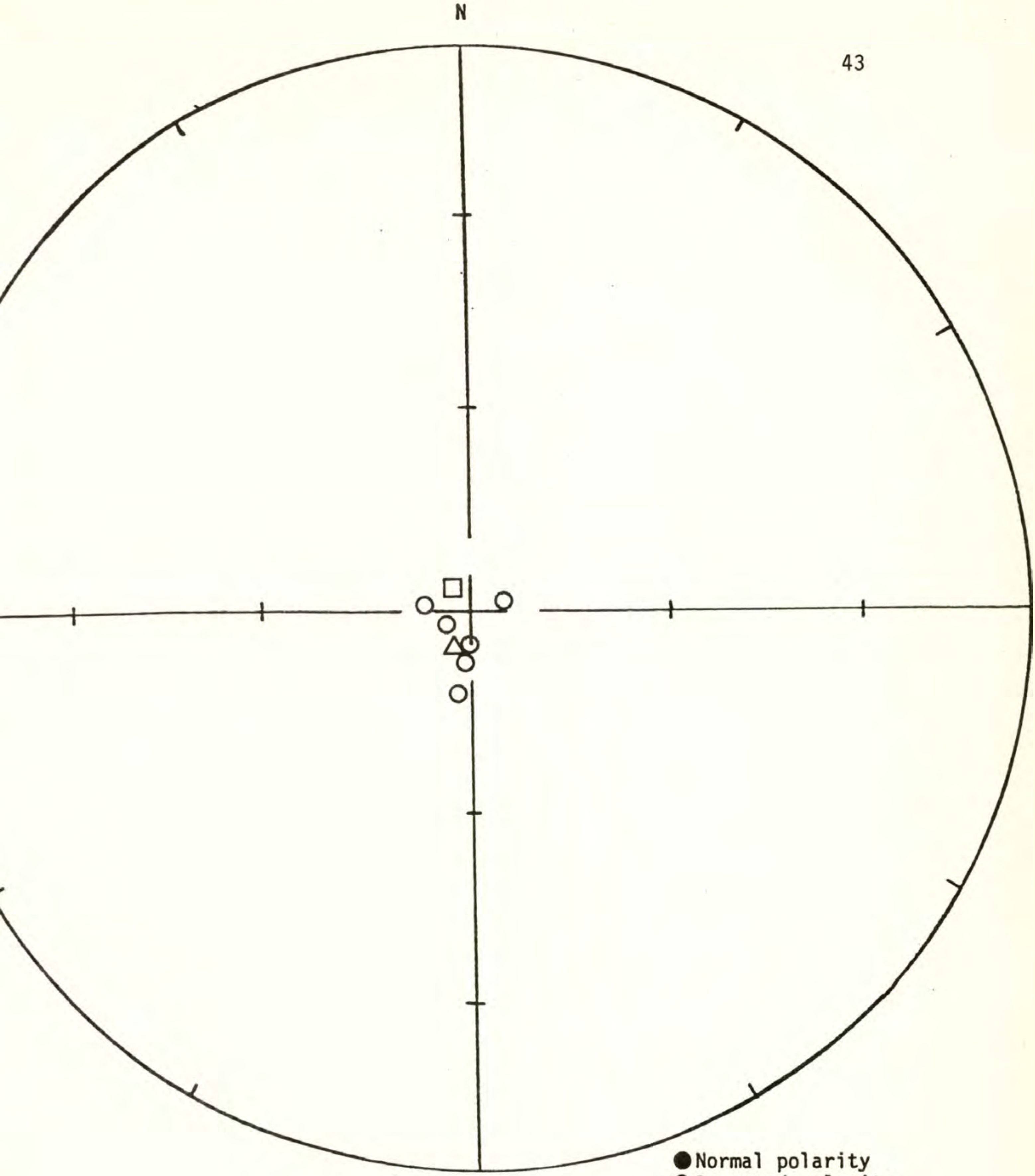
Site: Ø-1
Demagnetization level: 200 oe



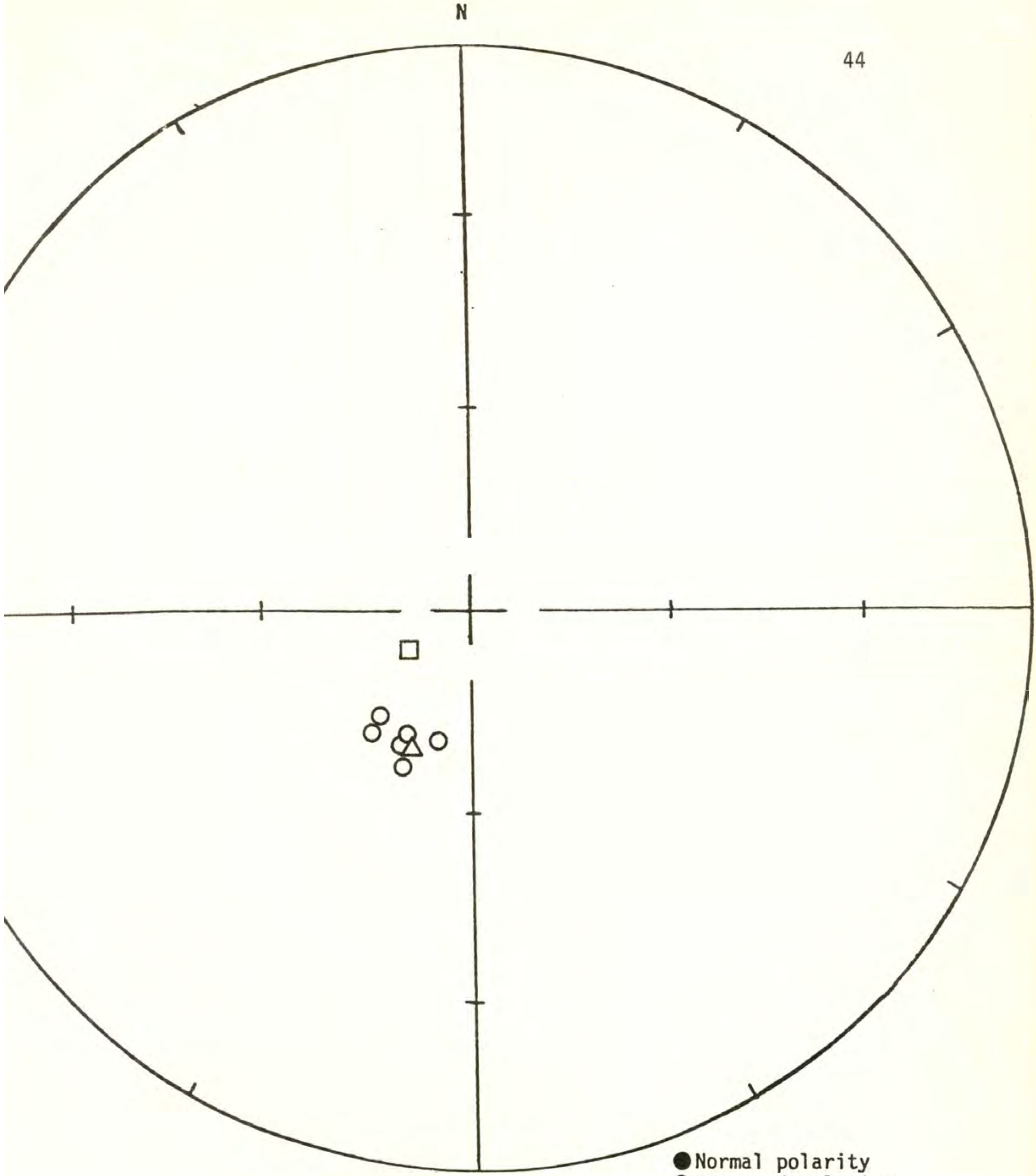
Site: Ø-2
Demagnetization level: 400 oe



Site: Ø-4
Demagnetization level: 450 oe

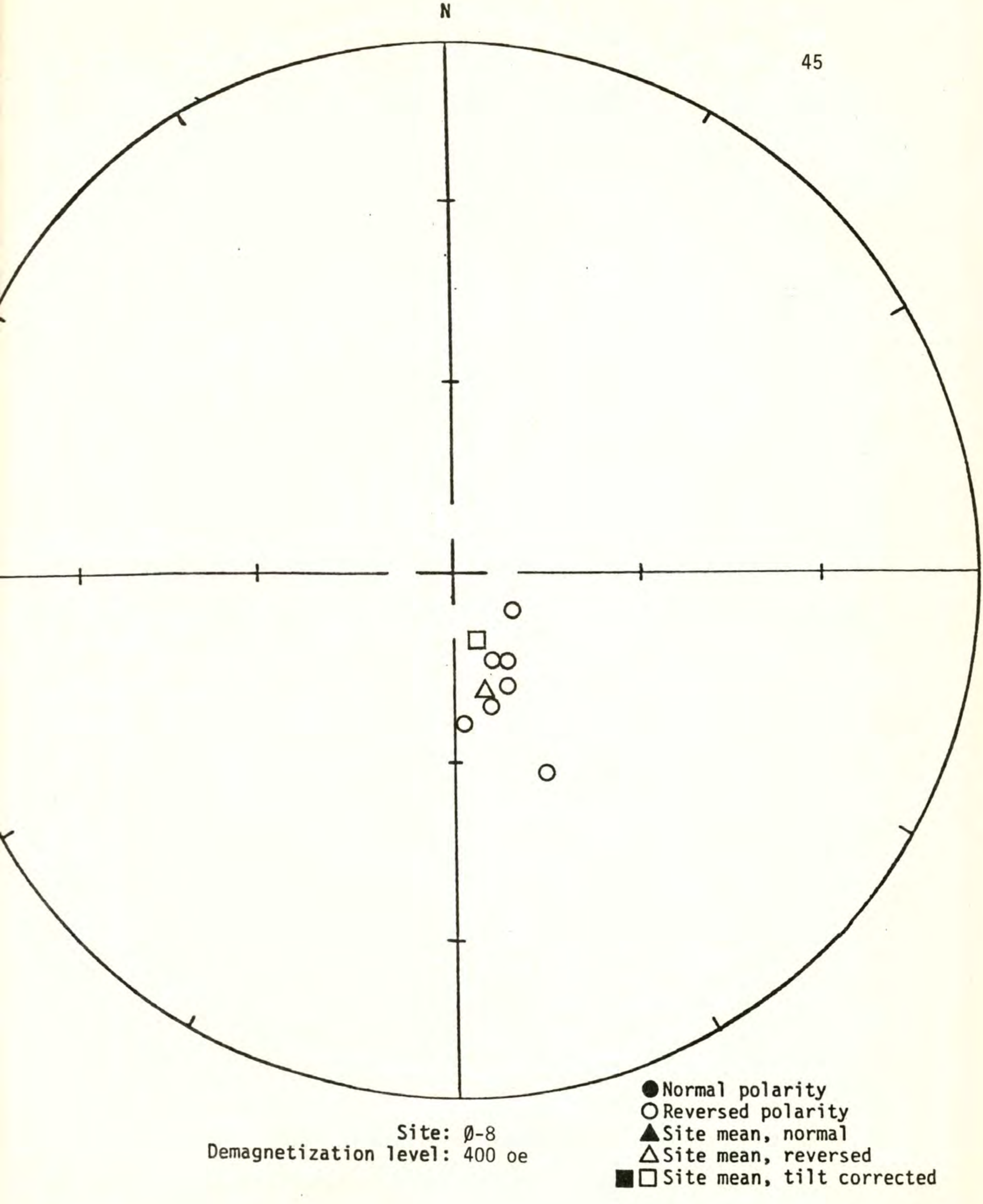


Site: Ø-5
Demagnetization level: 400 oe

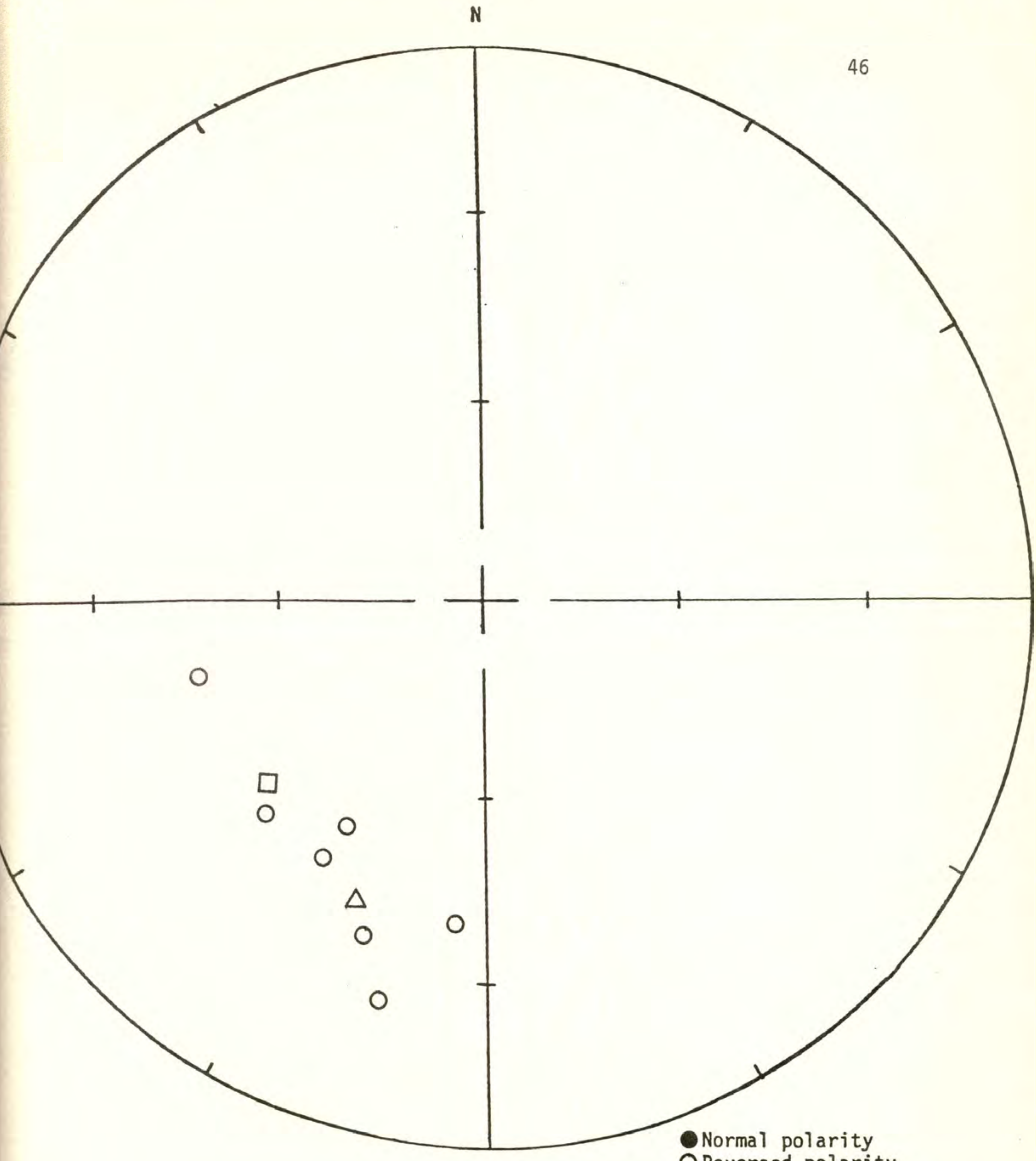


Site: Ø-7
Demagnetization level: 200 oe

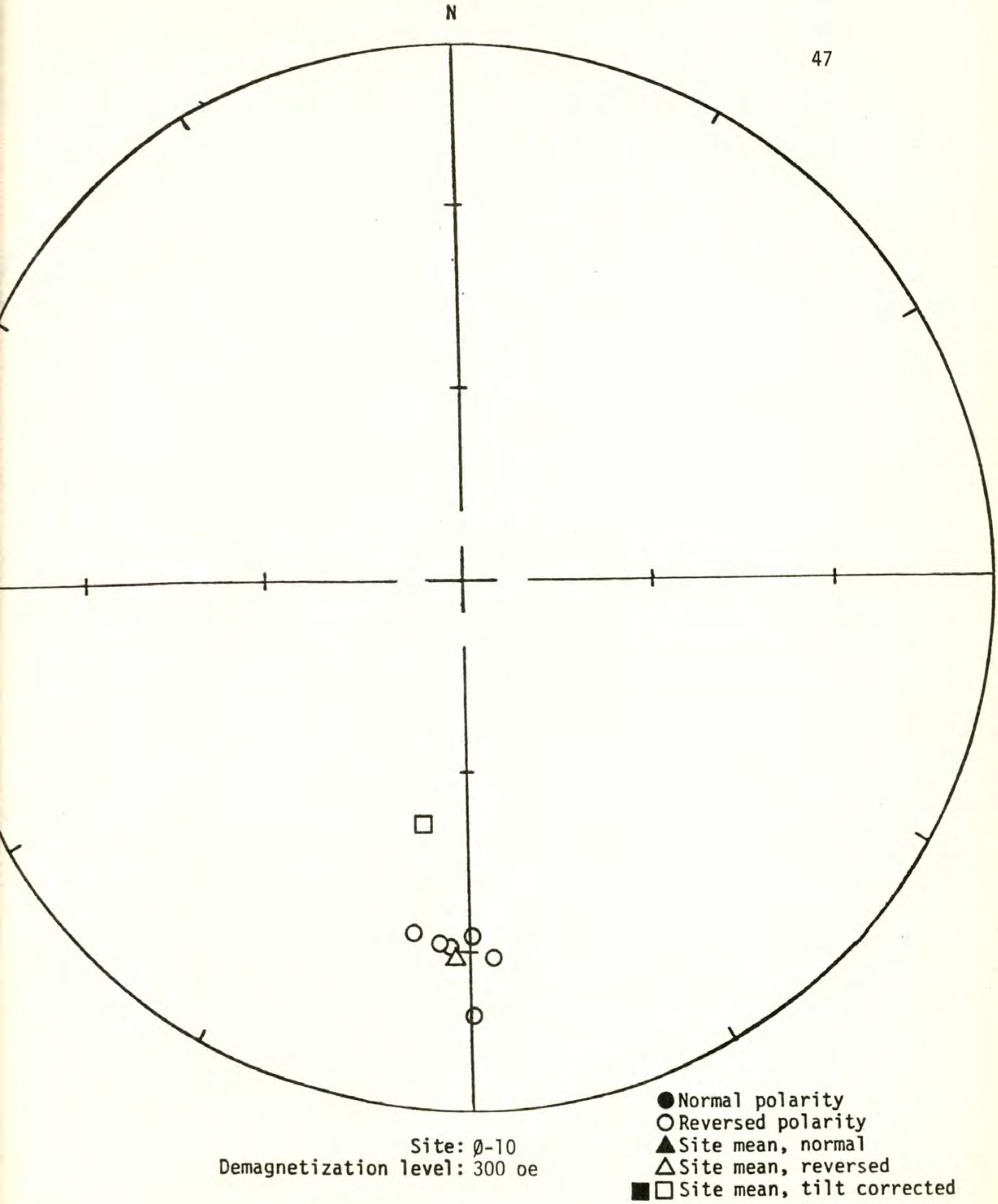
● Normal polarity
○ Reversed polarity
▲ Site mean, normal
△ Site mean, reversed
■ □ Site mean, tilt corrected



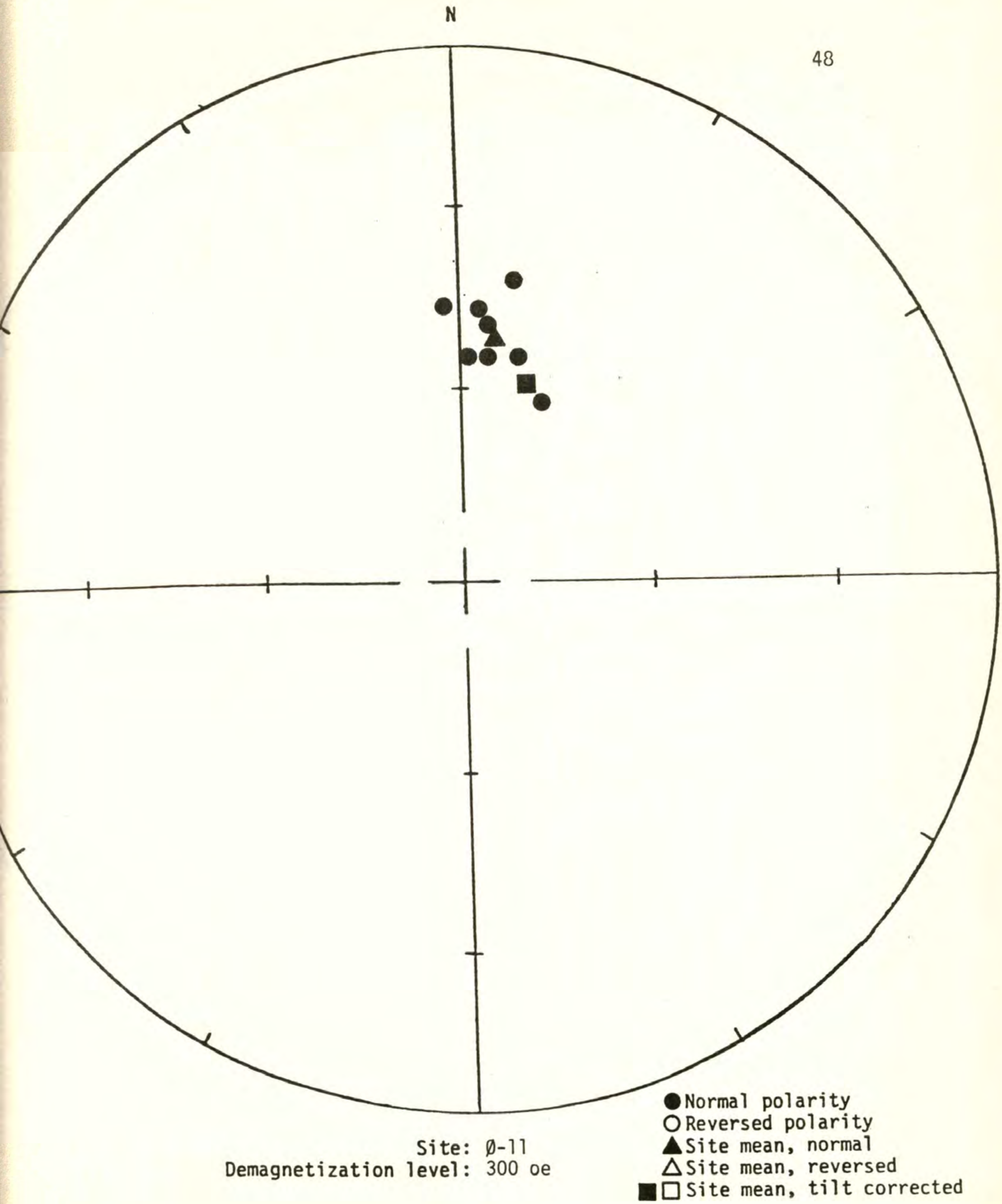
Site: Ø-8
Demagnetization level: 400 oe



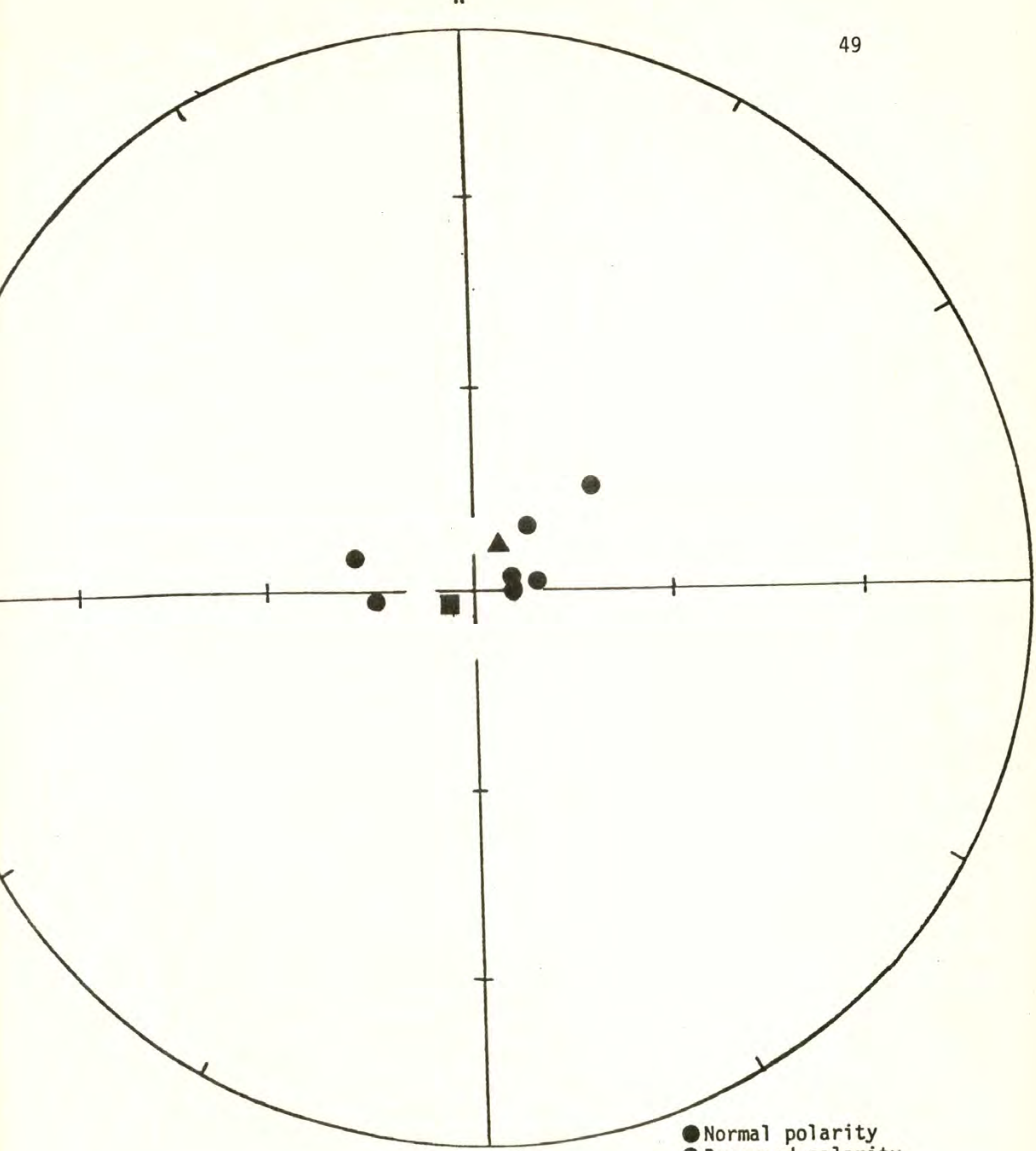
Site: Ø-9
Demagnetization level: 500 oe



Site: Ø-10
Demagnetization level: 300 oe

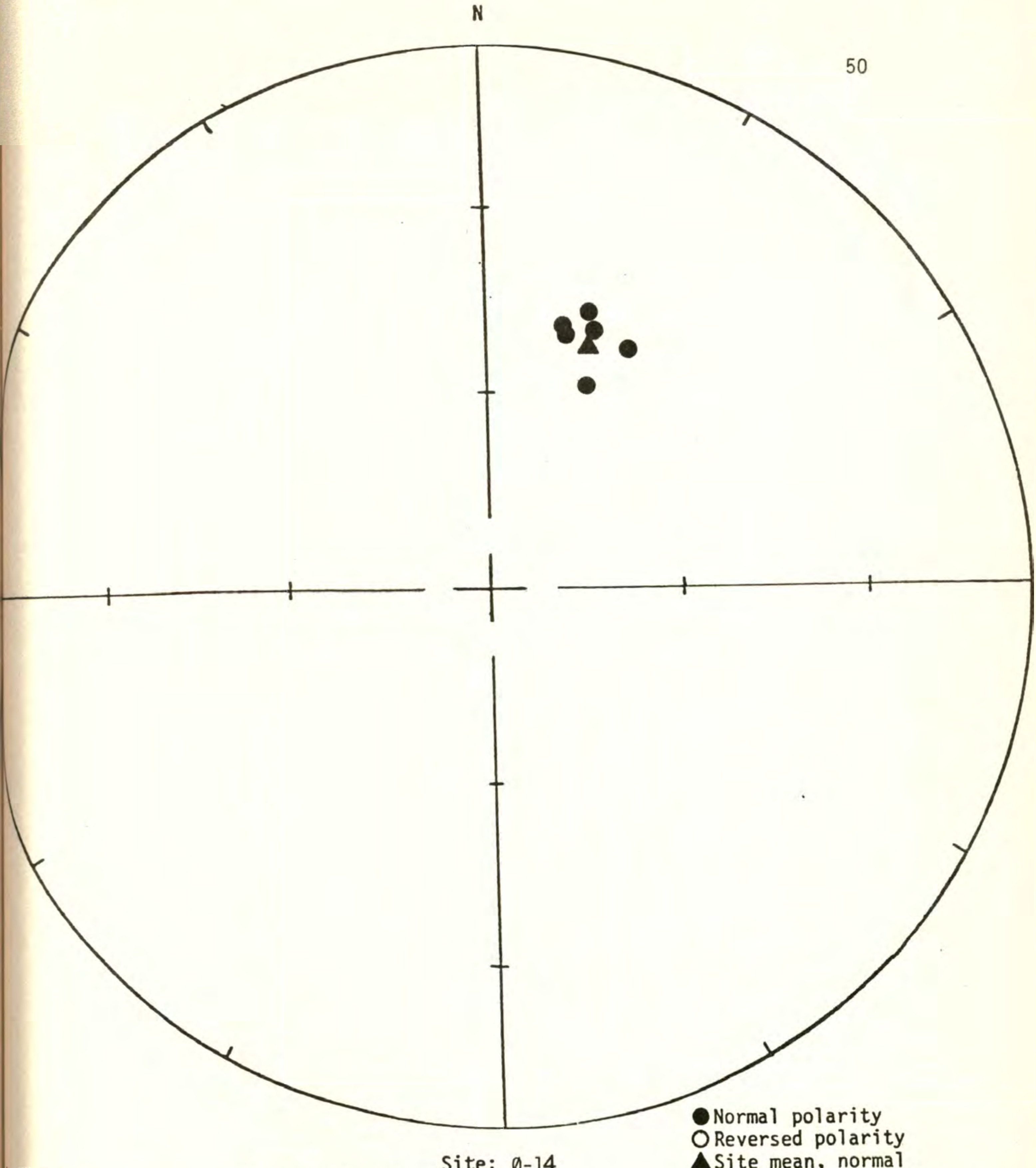


Site: Ø-11
Demagnetization level: 300 oe

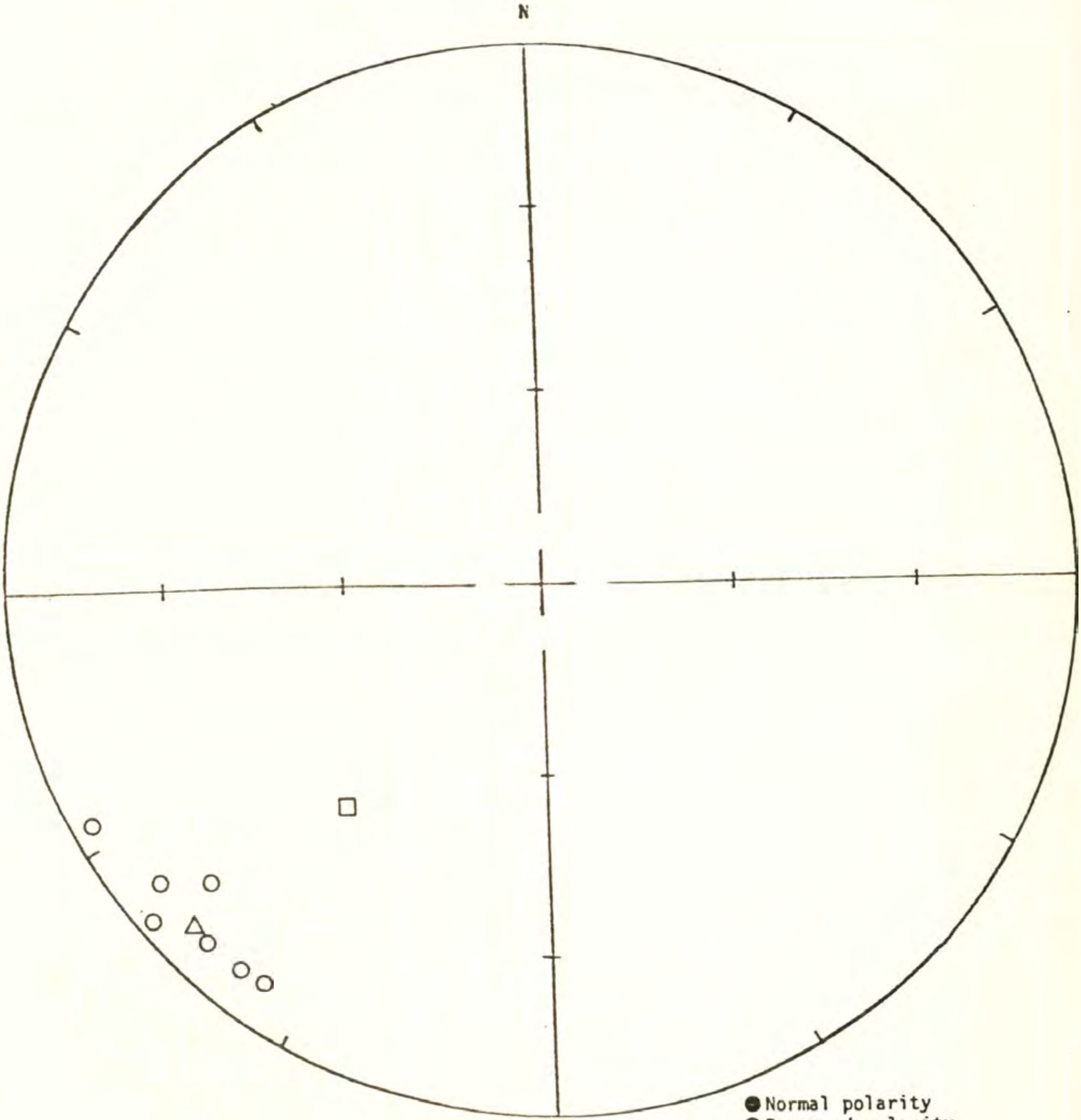


Site:Ø-12
Demagnetization level:200 oe

●Normal polarity
○Reversed polarity
▲Site mean, normal
△Site mean, reversed
■□Site mean, tilt corrected

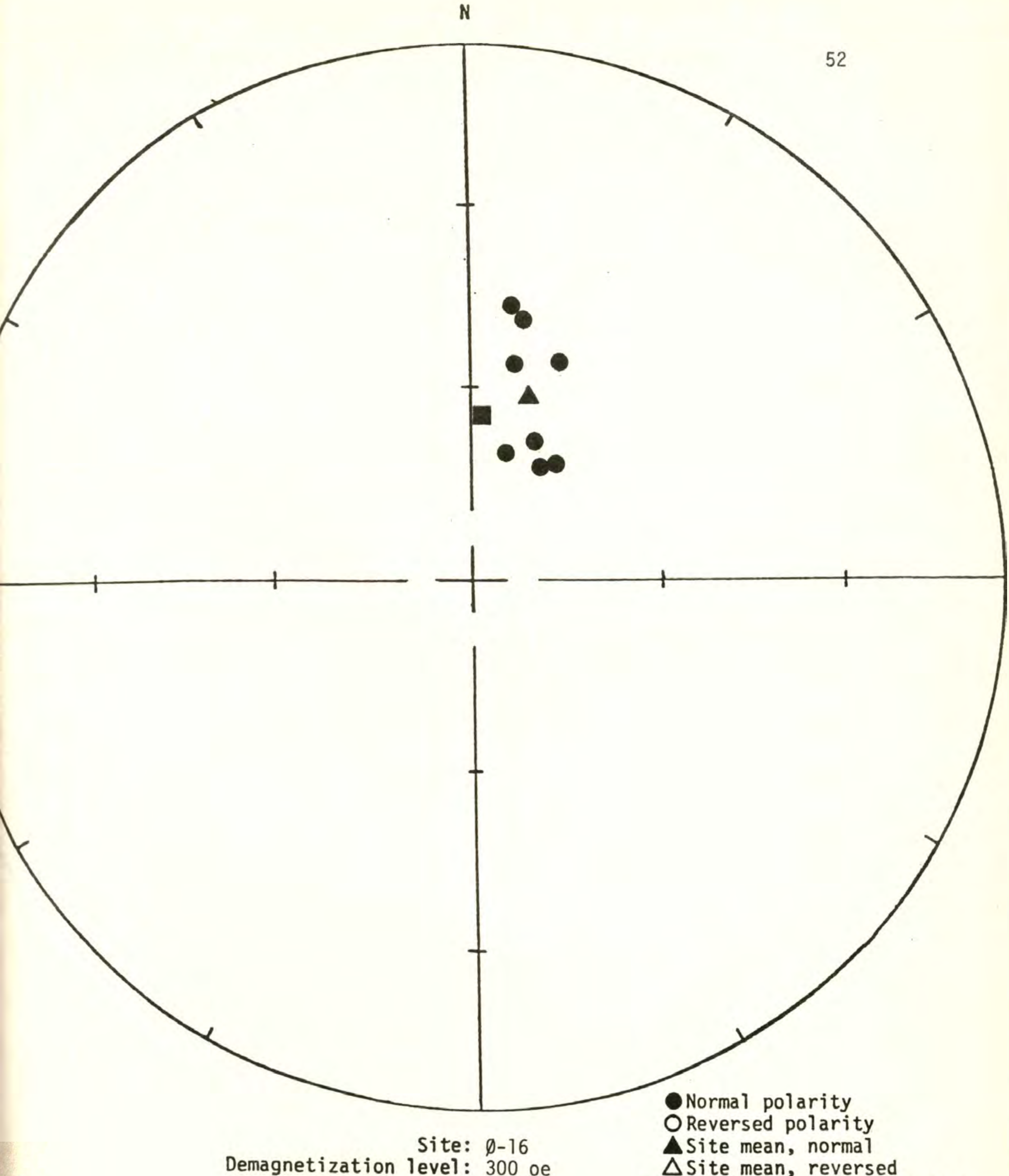


Site: Ø-14
Demagnetization level: 300 oe



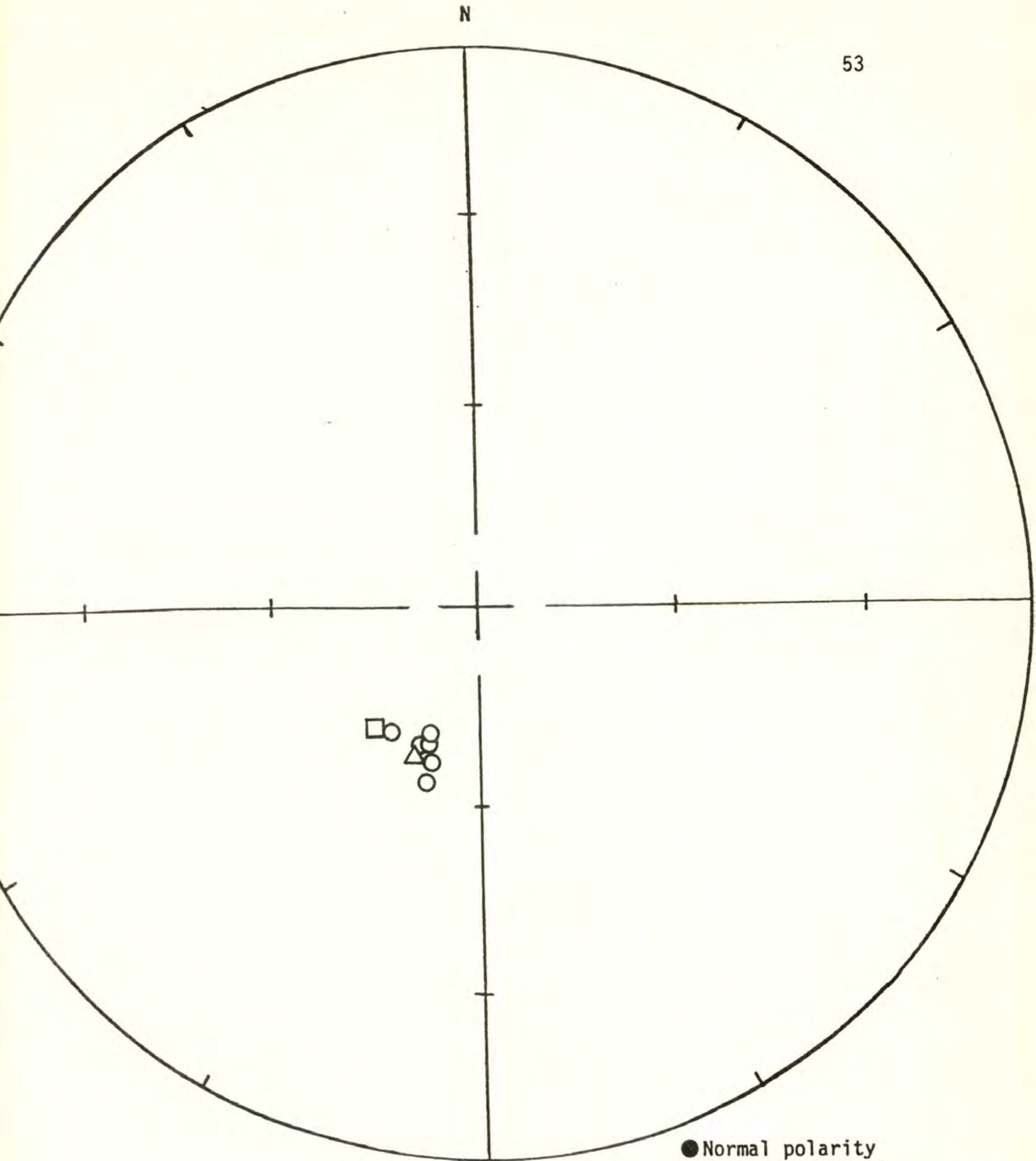
Site: Ø-15
Demagnetization level: 500 oe

● Normal polarity
○ Reversed polarity
▲ Site mean, normal
△ Site mean, reversed
■ □ Site mean, tilt corrected



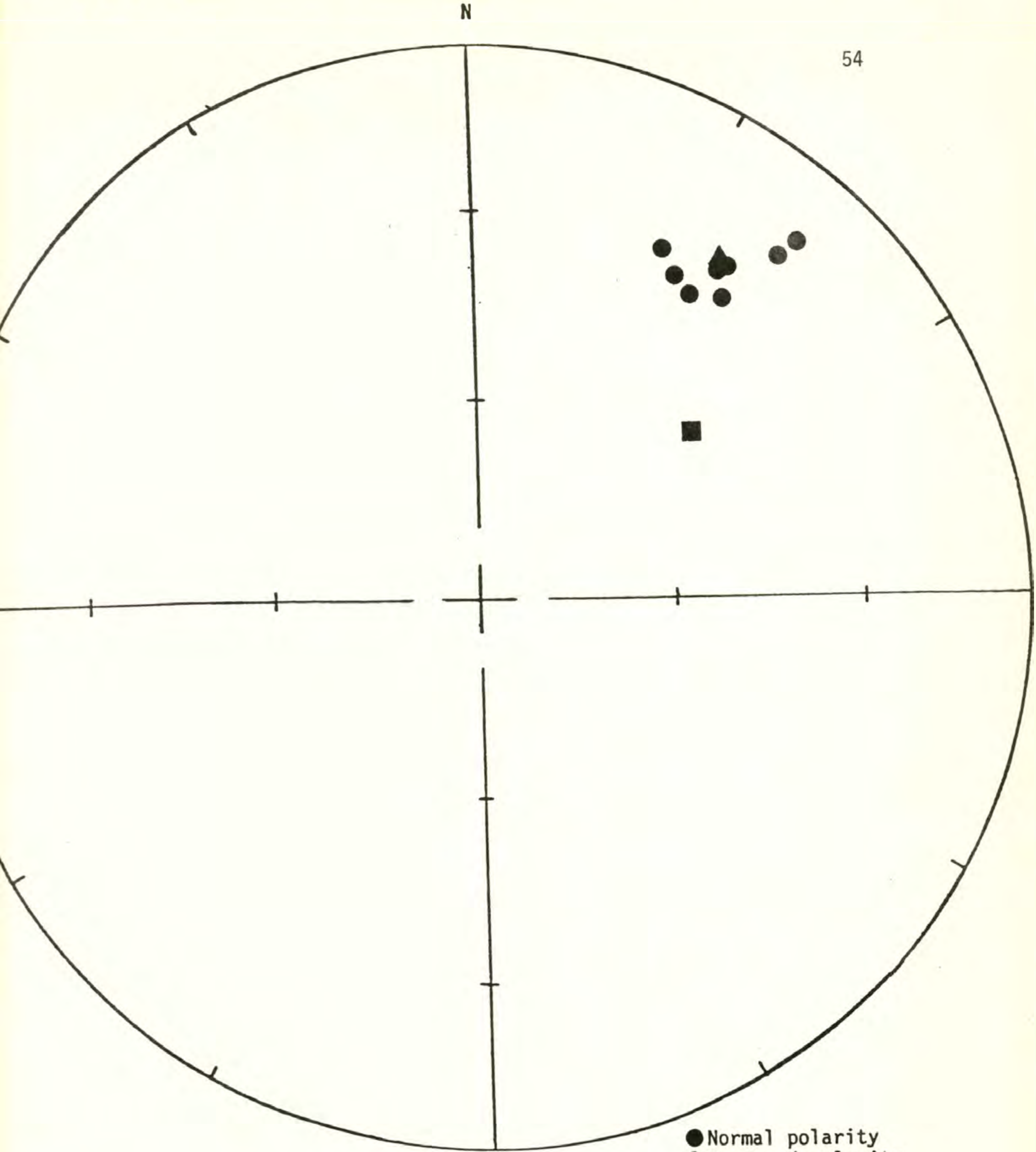
Site: Ø-16
Demagnetization level: 300 oe

●Normal polarity
○Reversed polarity
▲Site mean, normal
△Site mean, reversed
■□Site mean, tilt corrected



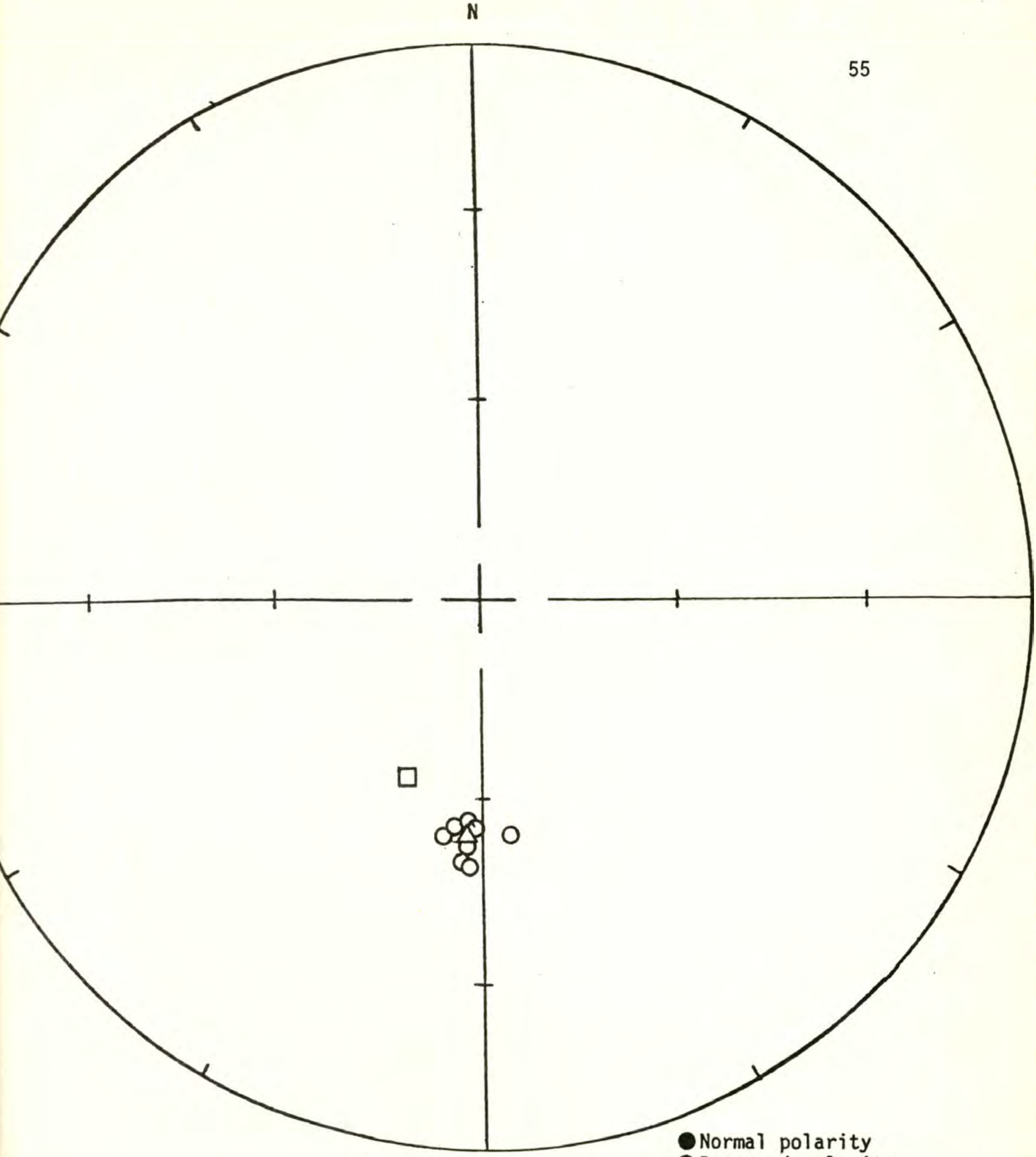
Site: Ø-18
Demagnetization level: 400 oe

●Normal polarity
○Reversed polarity
▲Site mean, normal
△Site mean, reversed
■□Site mean, tilt corrected



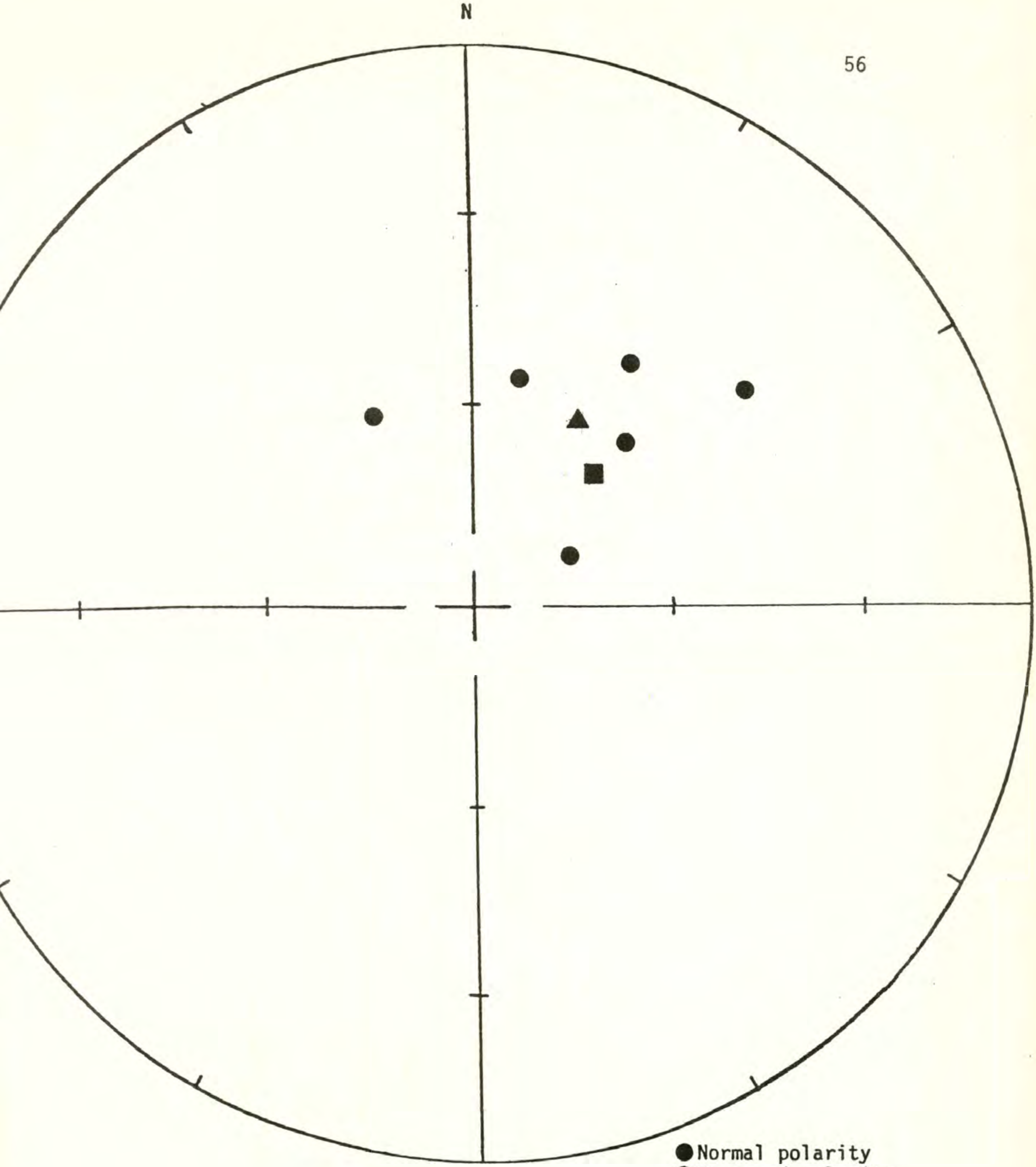
Site: Ø-19
Demagnetization level: 300 oe

●Normal polarity
○Reversed polarity
▲Site mean, normal
△Site mean, reversed
■□Site mean, tilt corrected



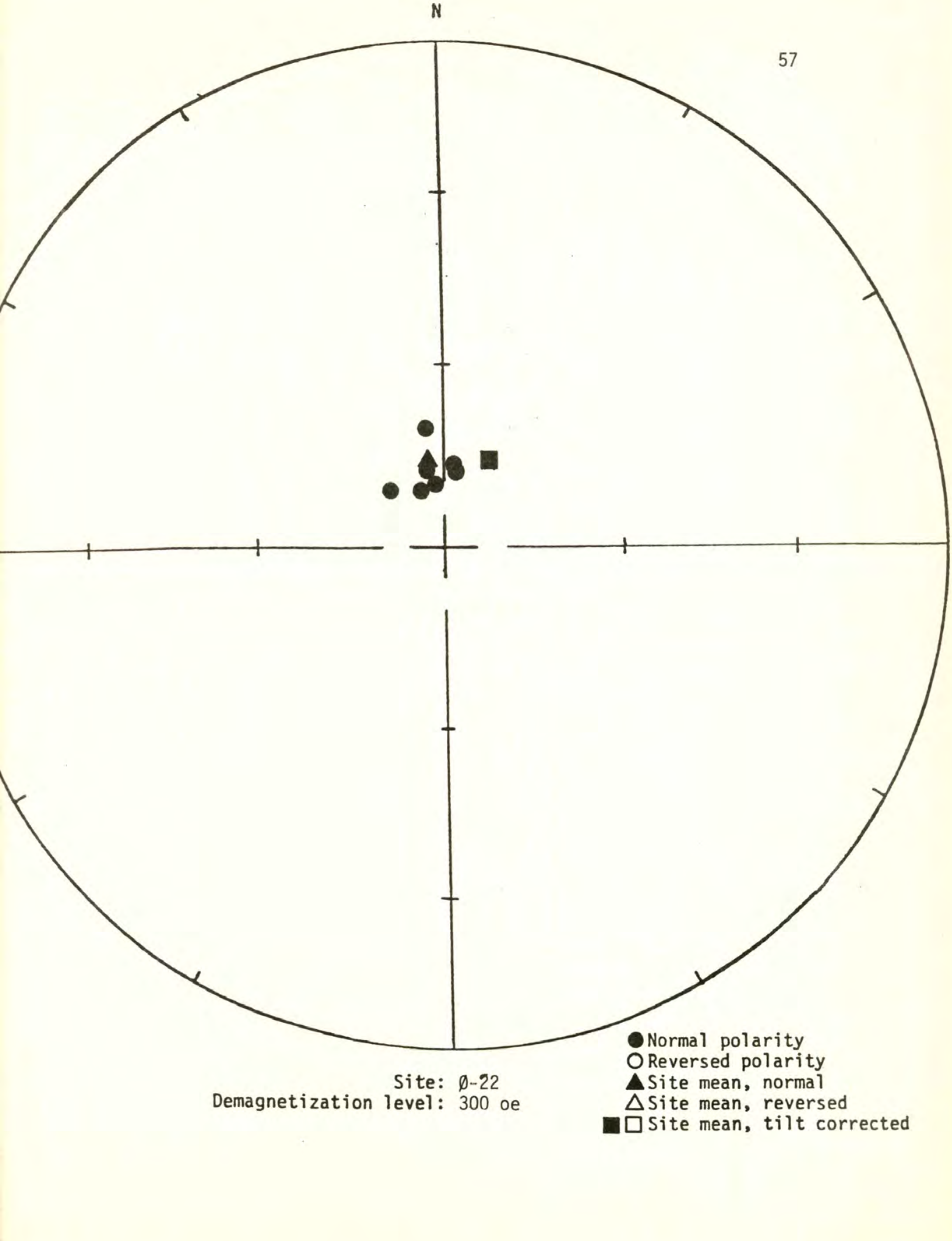
Site: Ø-20
Demagnetization level: 400 oe

● Normal polarity
○ Reversed polarity
▲ Site mean, normal
△ Site mean, reversed
■□ Site mean, tilt corrected

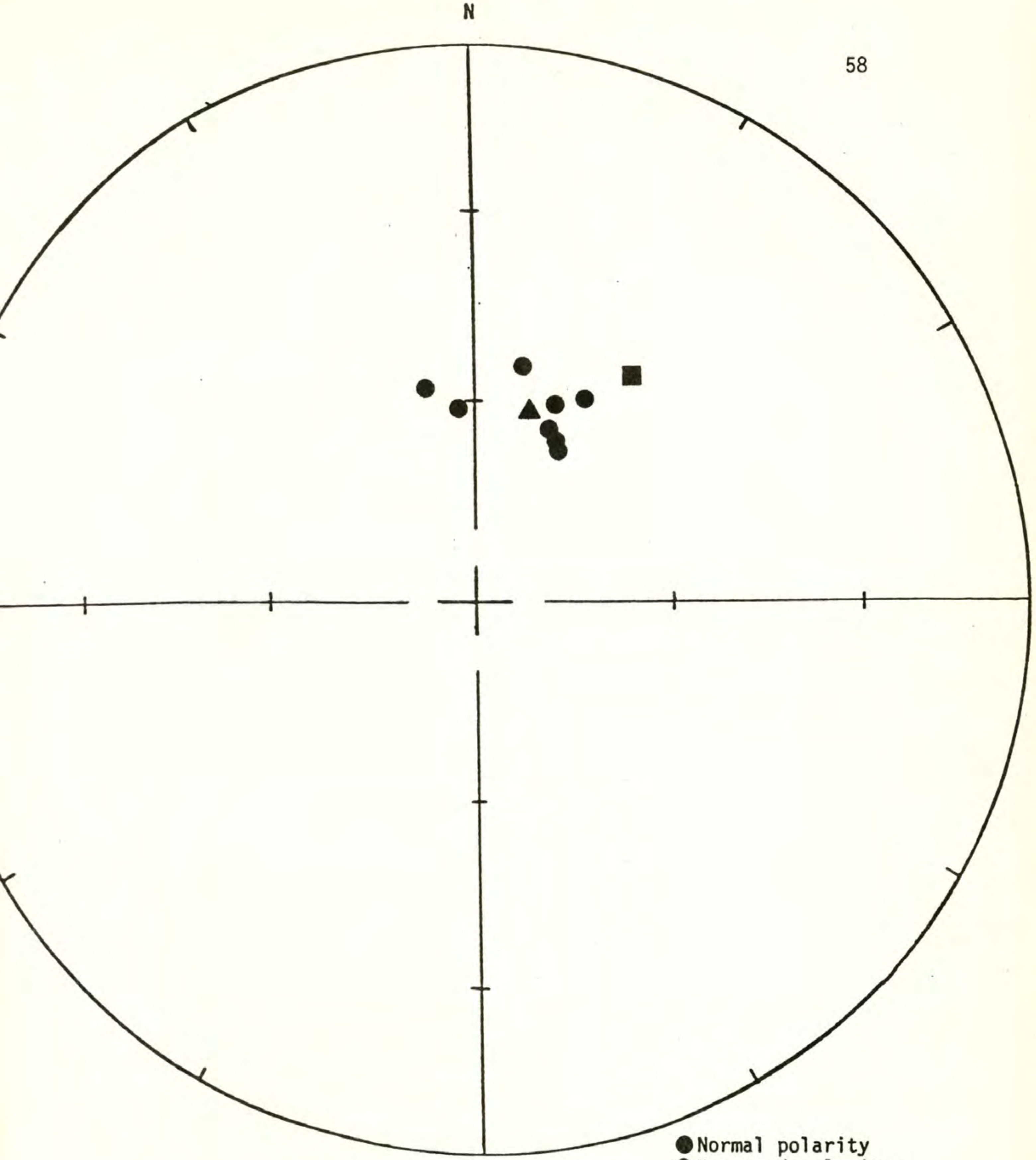


Site: Ø-21
Demagnetization level: 200 oe

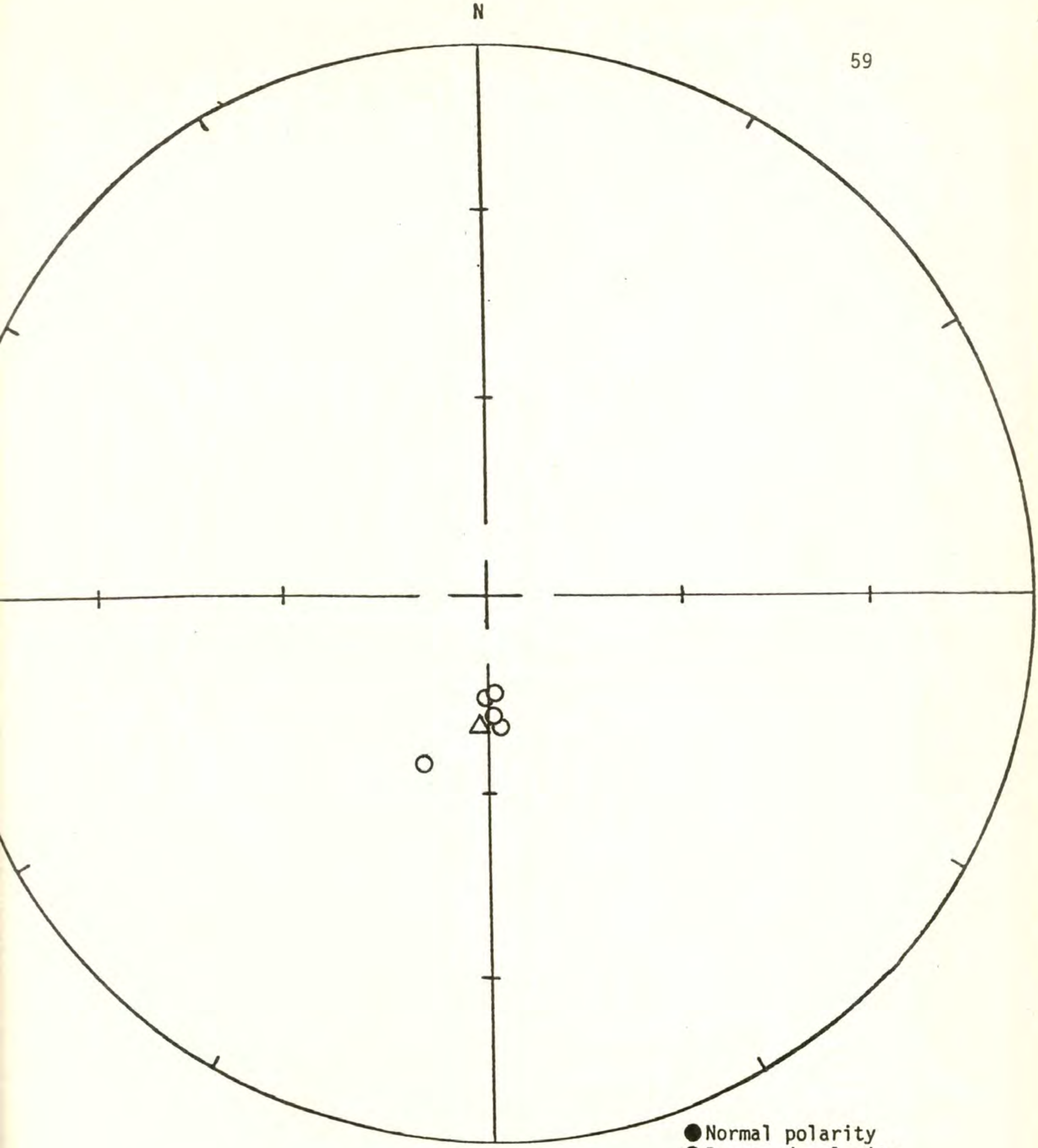
● Normal polarity
○ Reversed polarity
▲ Site mean, normal
△ Site mean, reversed
■ □ Site mean, tilt corrected



Site: Ø-22
Demagnetization level: 300 oe

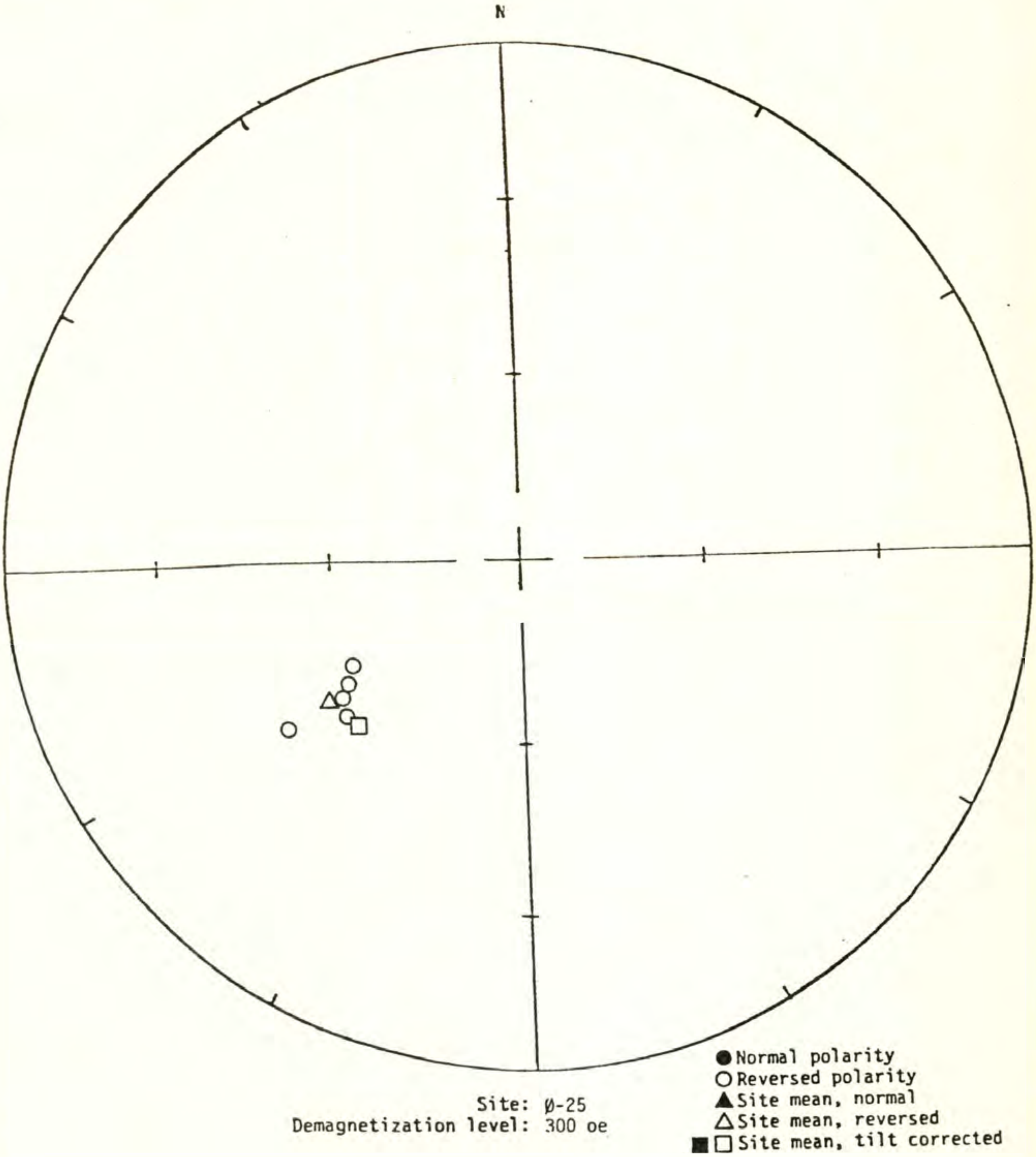


Site: Ø-23
Demagnetization level: 400 oe

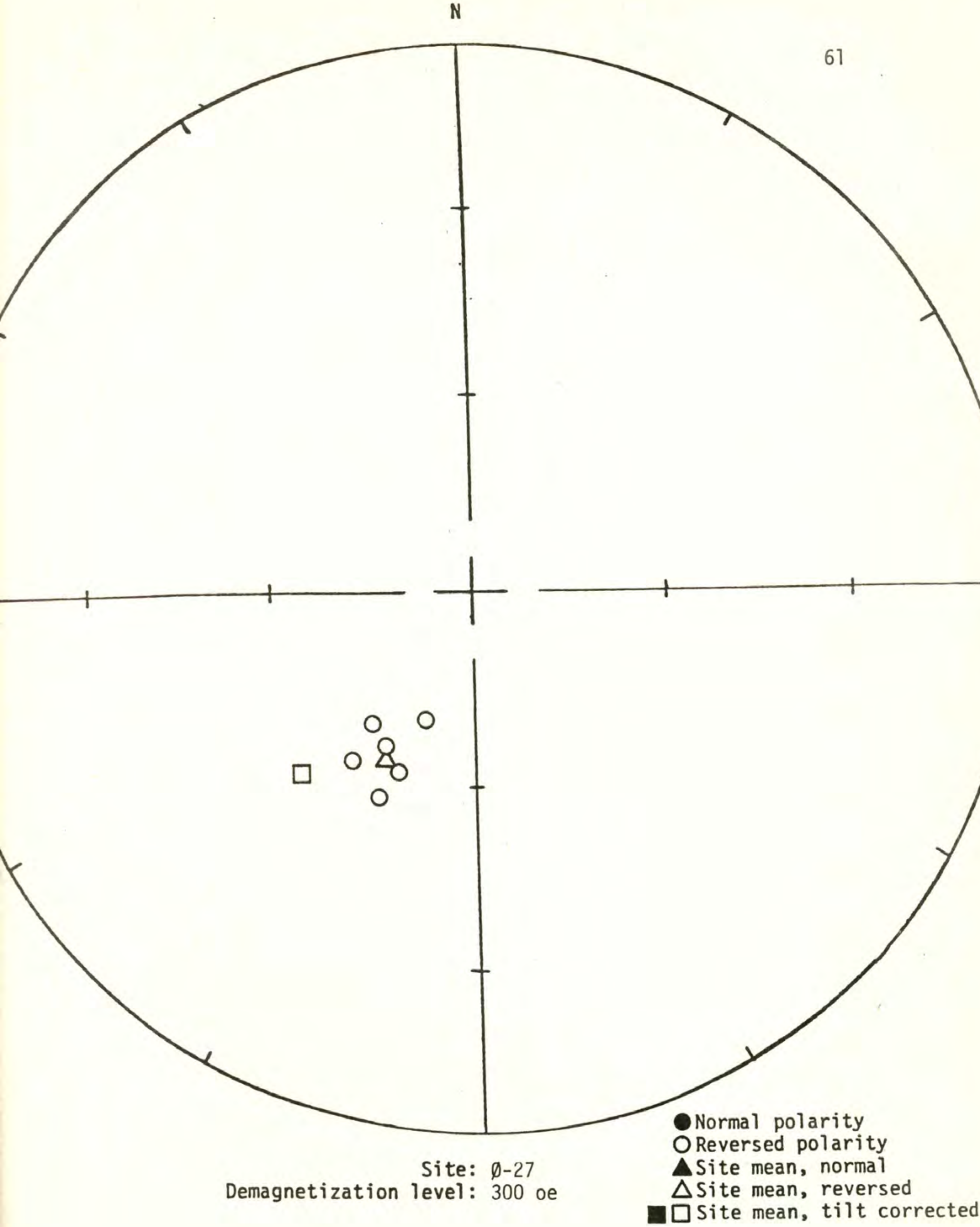


Site: Ø-24
Demagnetization level: 200 oe

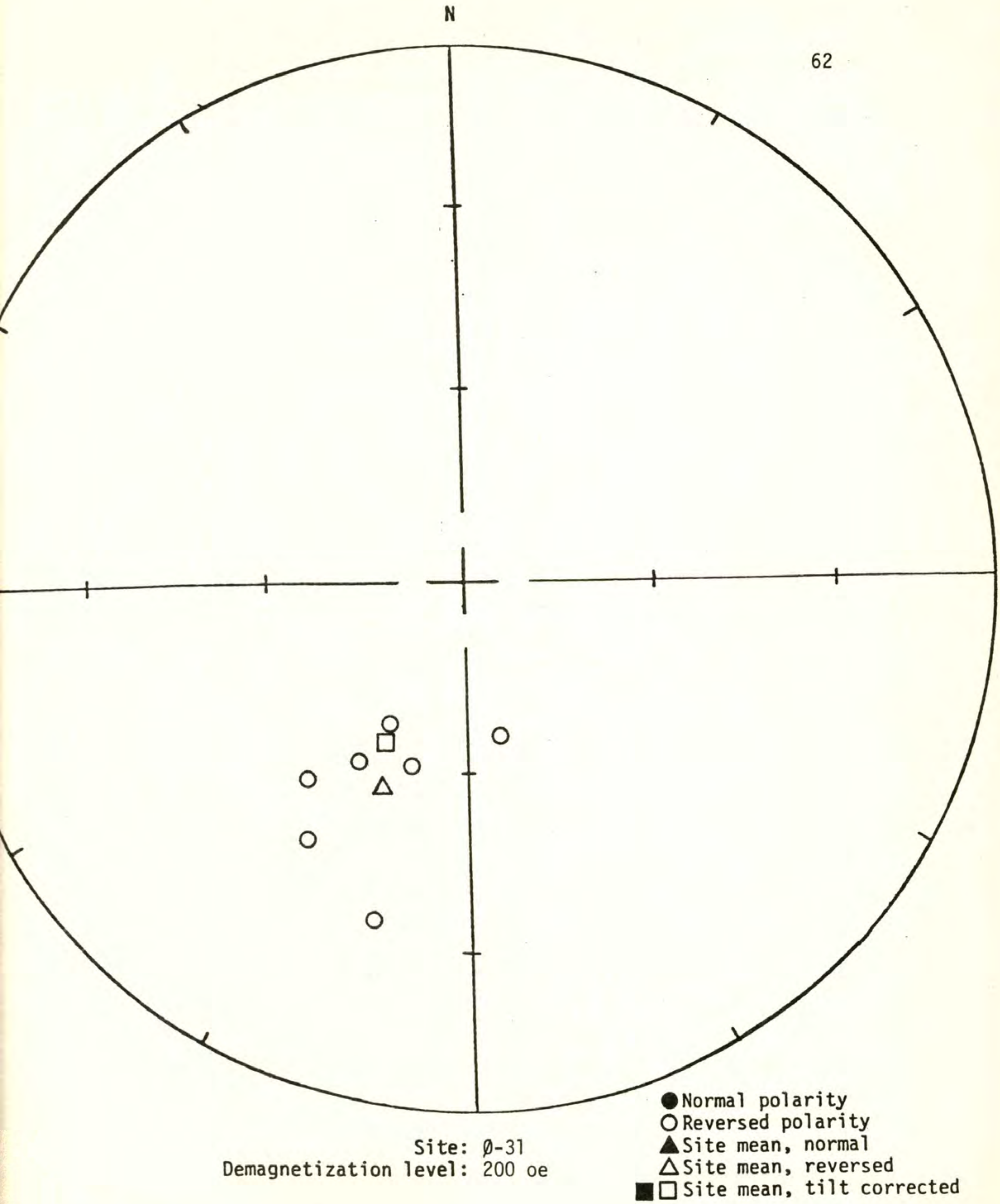
● Normal polarity
○ Reversed polarity
▲ Site mean, normal
△ Site mean, reversed
■□ Site mean, tilt corrected



Site: Ø-25
Demagnetization level: 300 oe



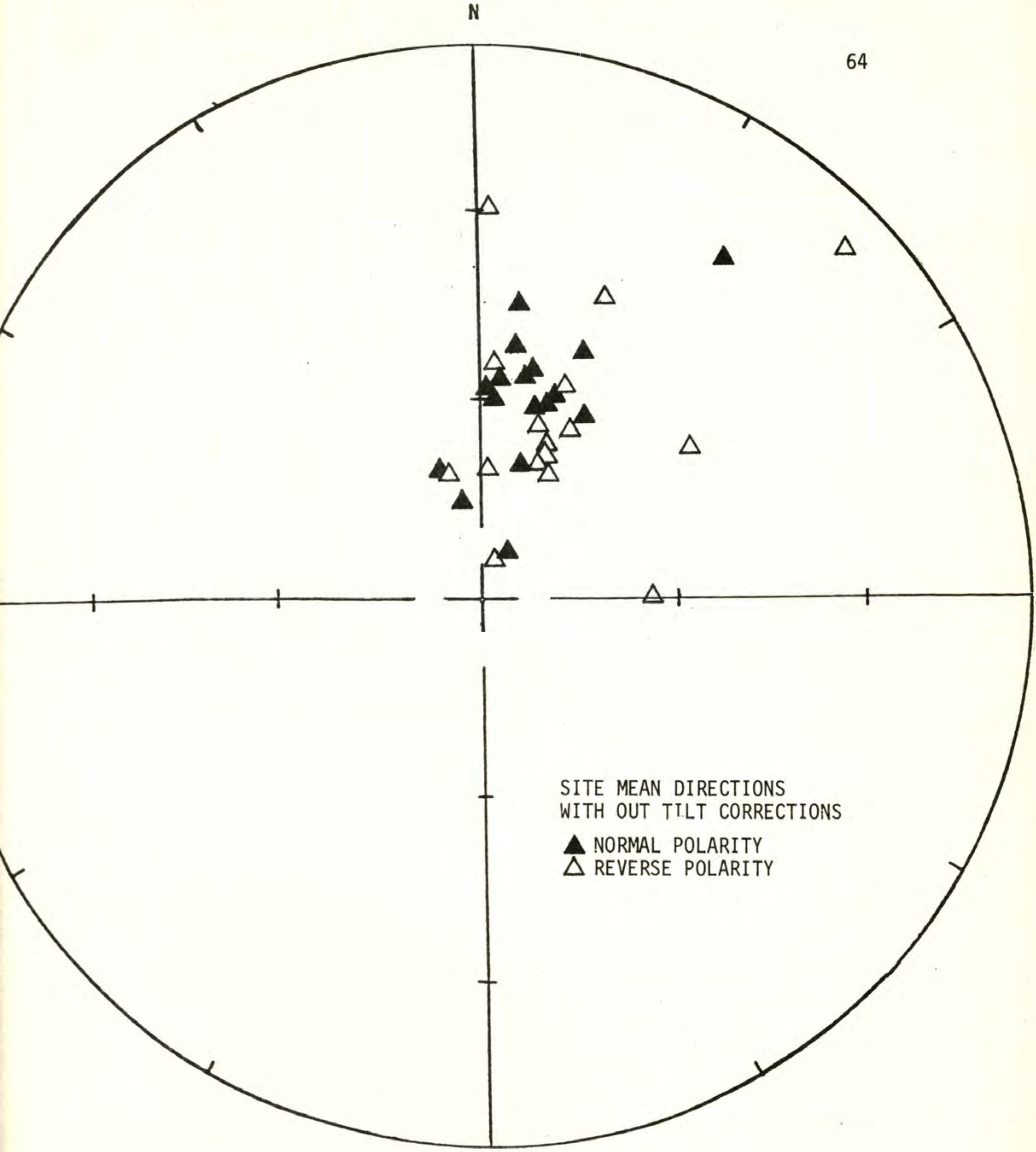
Site: Ø-27
Demagnetization level: 300 oe

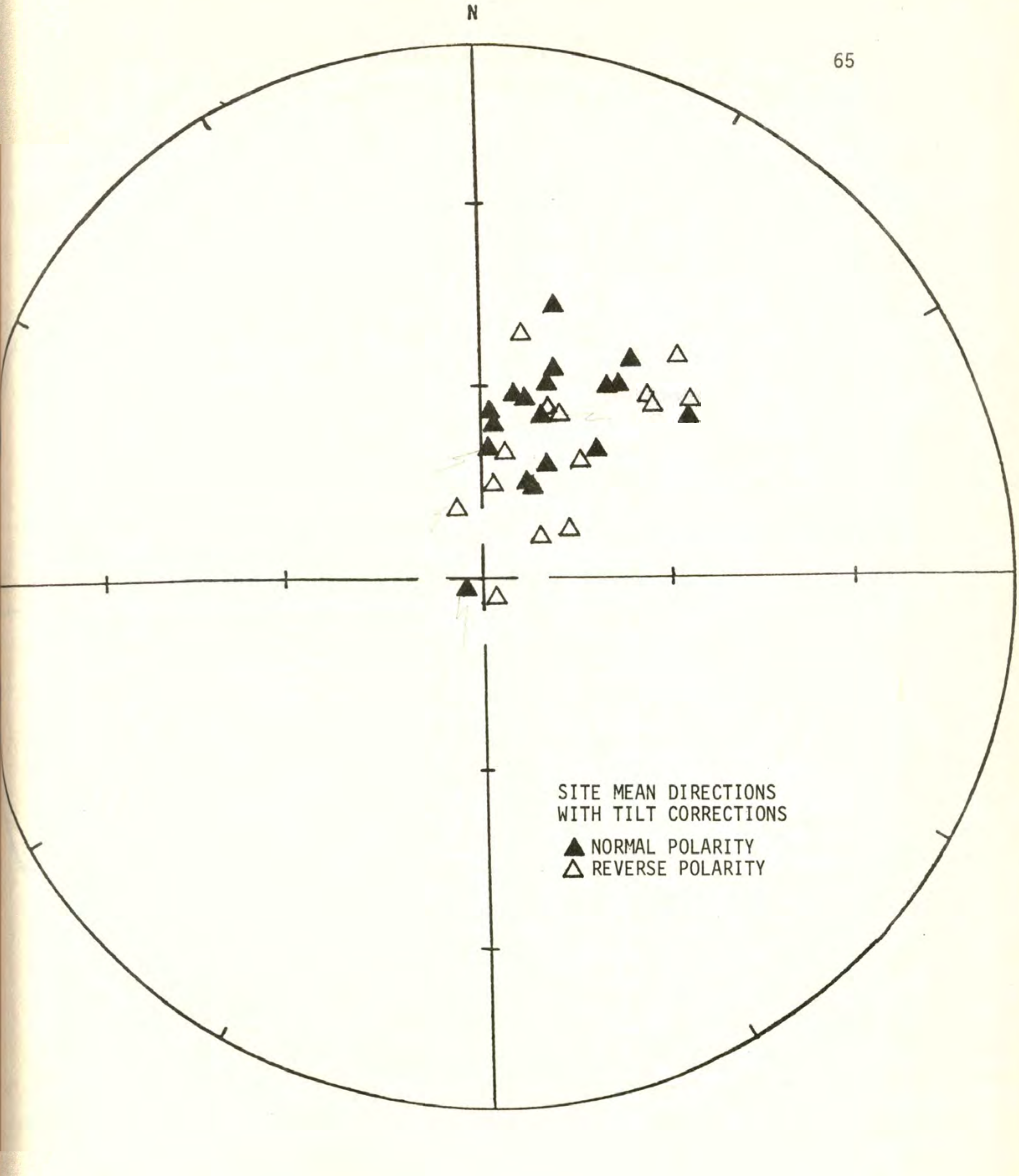


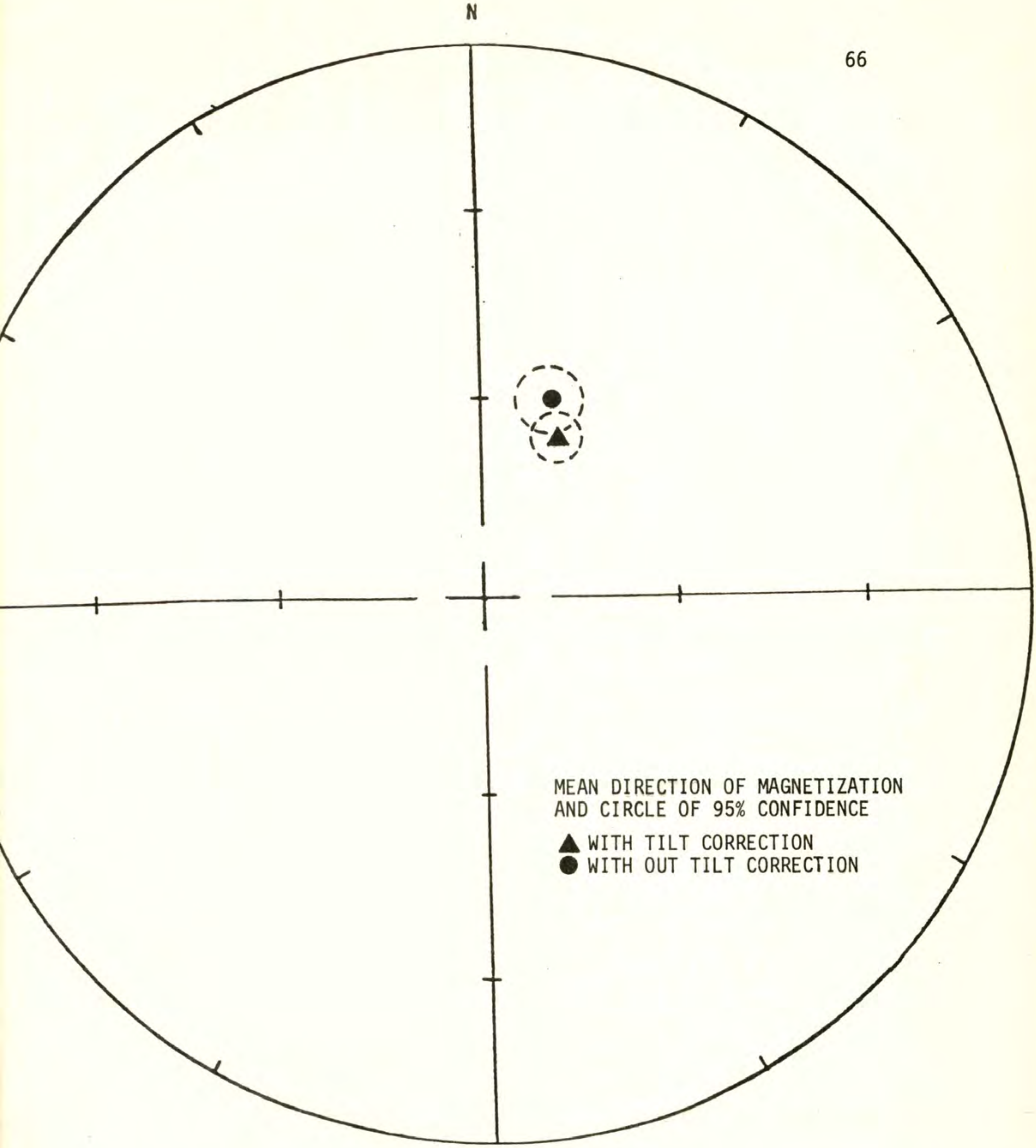
Site: Ø-31
Demagnetization level: 200 oe

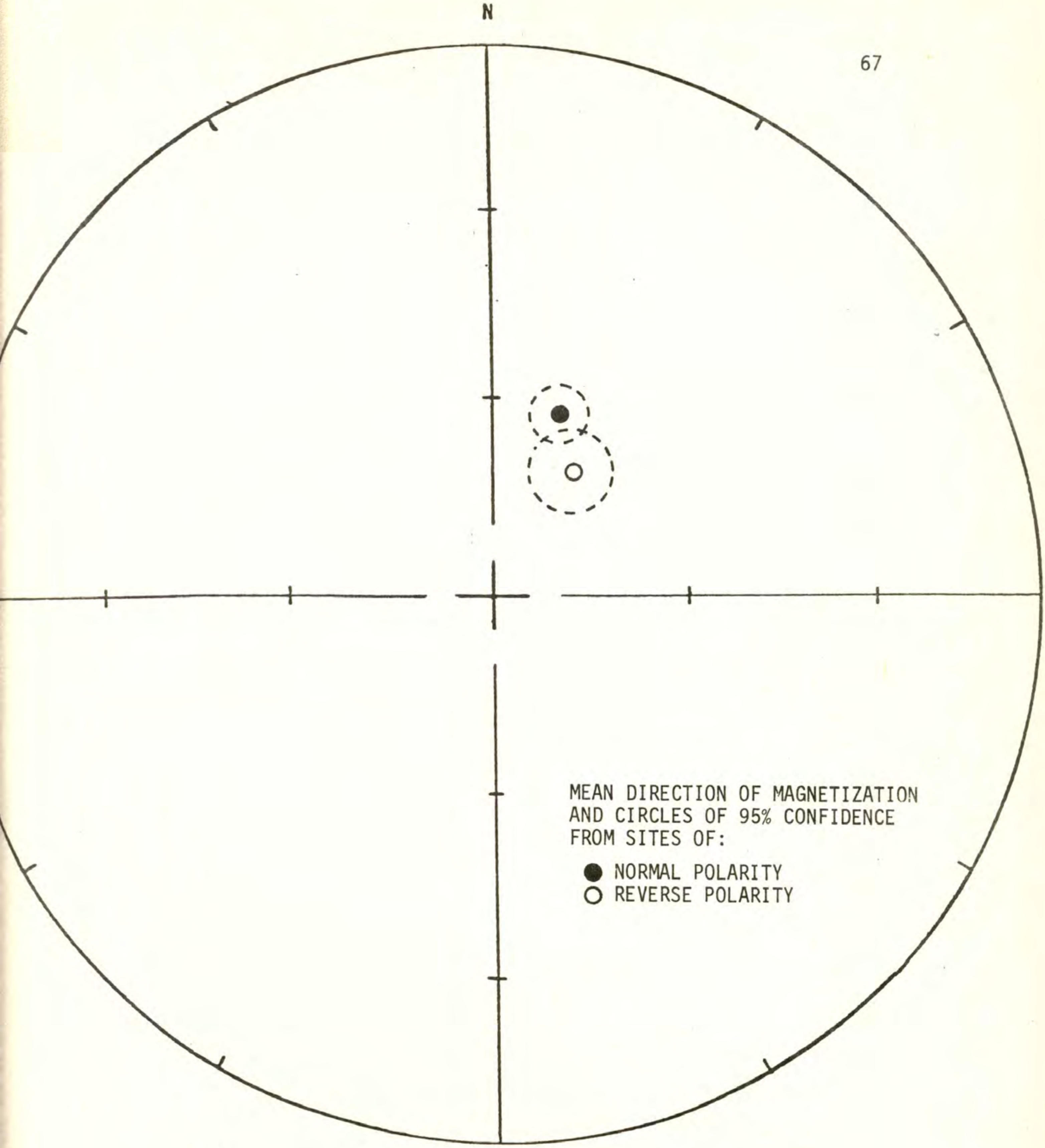
APPENDIX B

Mean directions of magnetization


N
SITE MEAN DIRECTIONS
WITH OUT TILT CORRECTIONS
NORMAL POLARITY
REVERSE POLARITY


N
SITE MEAN DIRECTIONS
WITH TILT CORRECTIONS
NORMAL POLARITY
REVERSE POLARITY


N
MEAN DIRECTION OF MAGNETIZATION
AND CIRCLE OF 95% CONFIDENCE
▲ WITH TILT CORRECTION
● WITH OUT TILT CORRECTION


N
MEAN DIRECTION OF MAGNETIZATION
AND CIRCLES OF 95% CONFIDENCE
FROM SITES OF:
NORMAL POLARITY
REVERSE POLARITY

APPENDIX C

Rejected sites

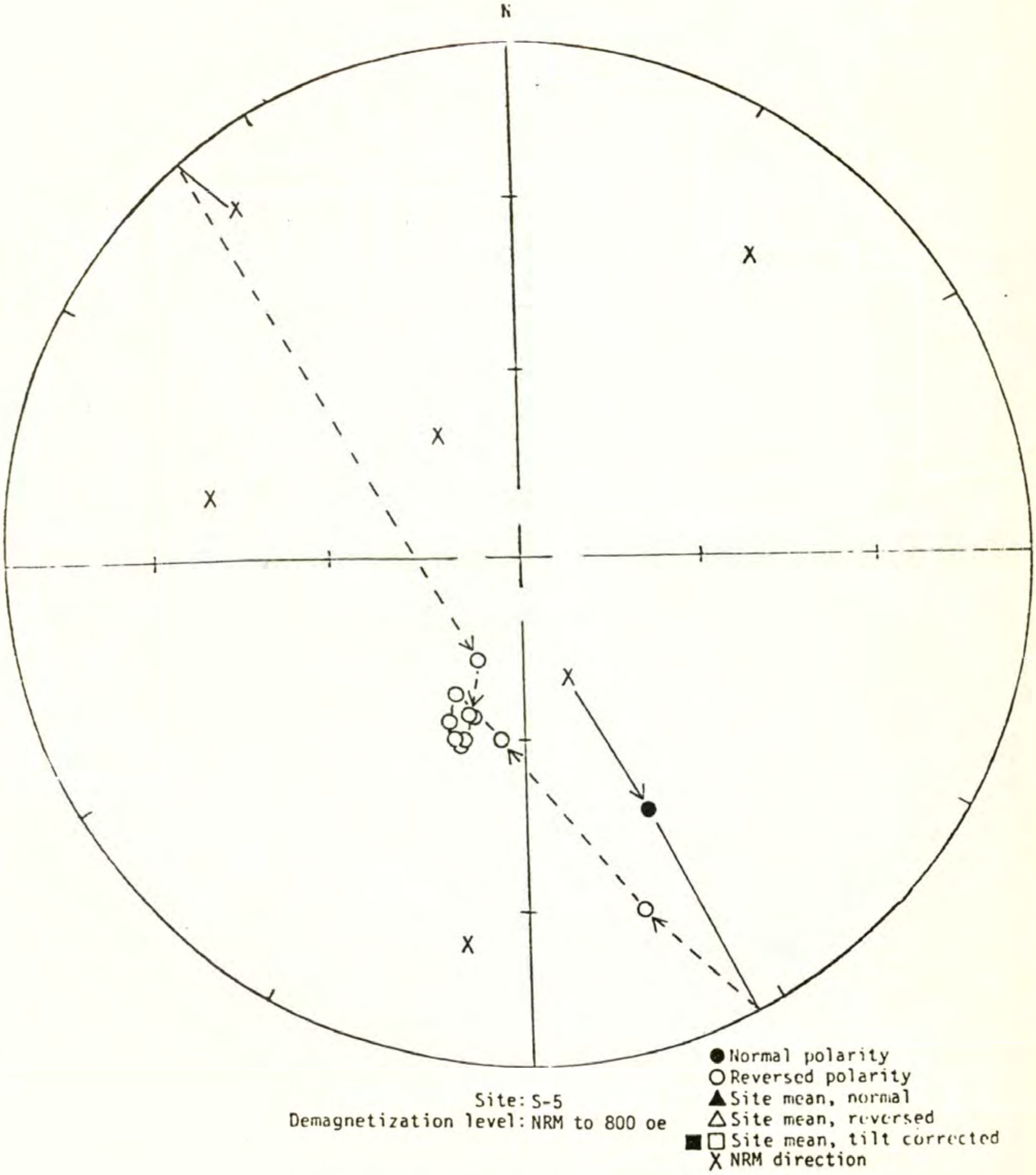
Site S-5 magnetically stable site included for comparison.

Sites E-2, E-4, S-2, Ø·12, Ø·26 rejected as being magnetically unstable.

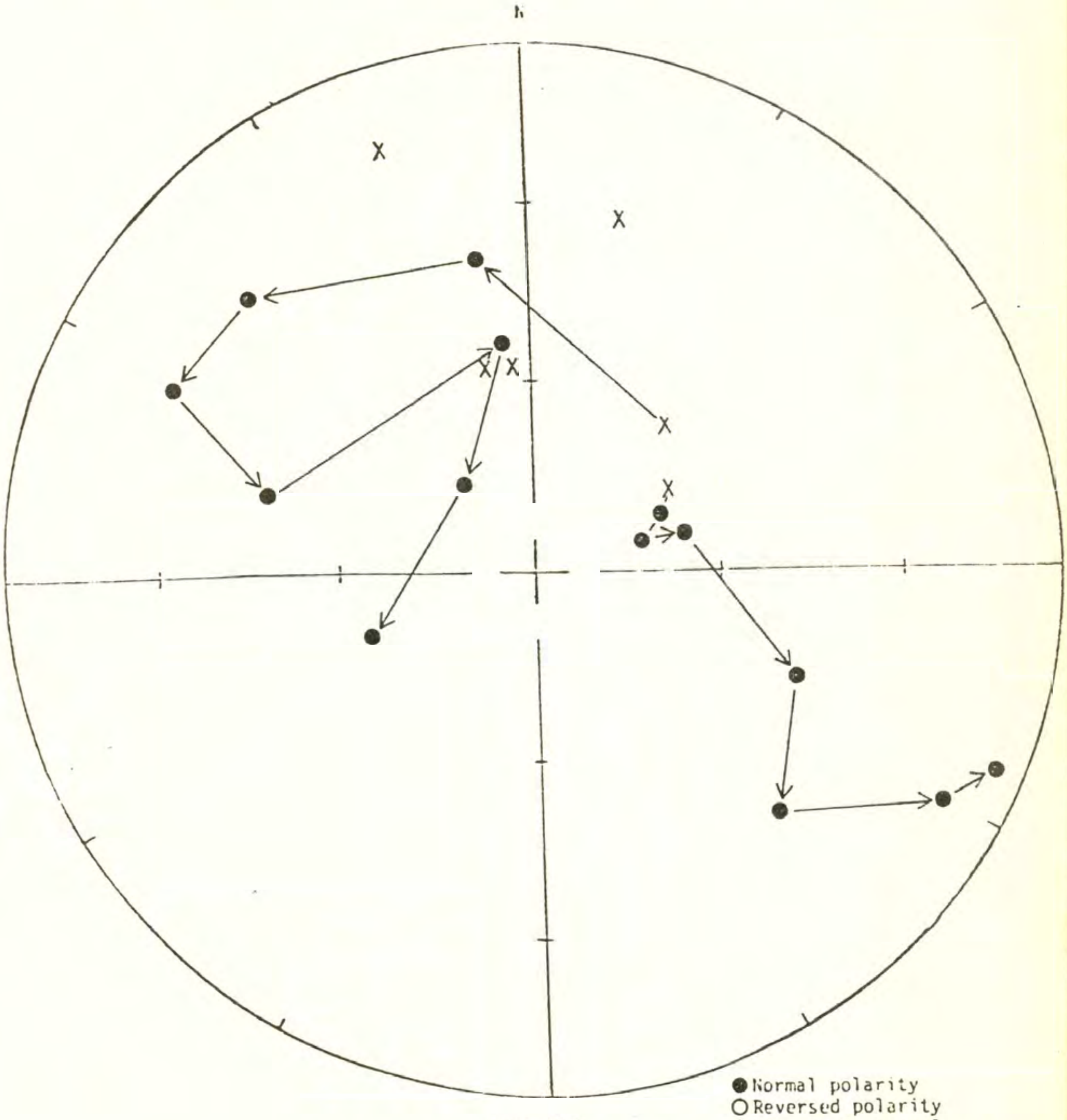
Site Ø·3 rejected for large α_{95} (25.3°).

Site Ø·6 rejected as possible displaced outcrop.

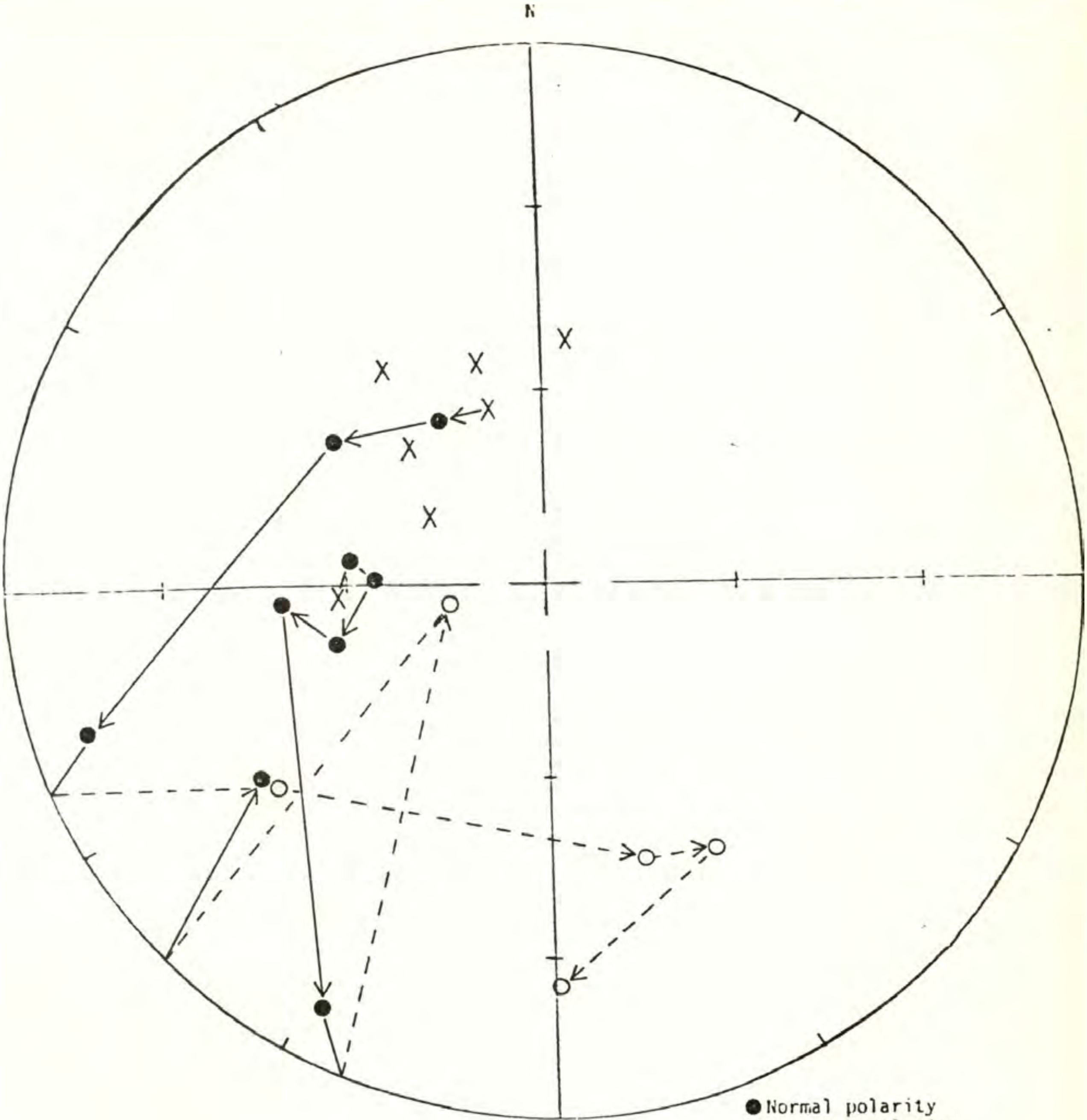
Site Ø·28, Ø·30 rejected as young dikes.



Site: S-5
Demagnetization level: NRM to 800 oe

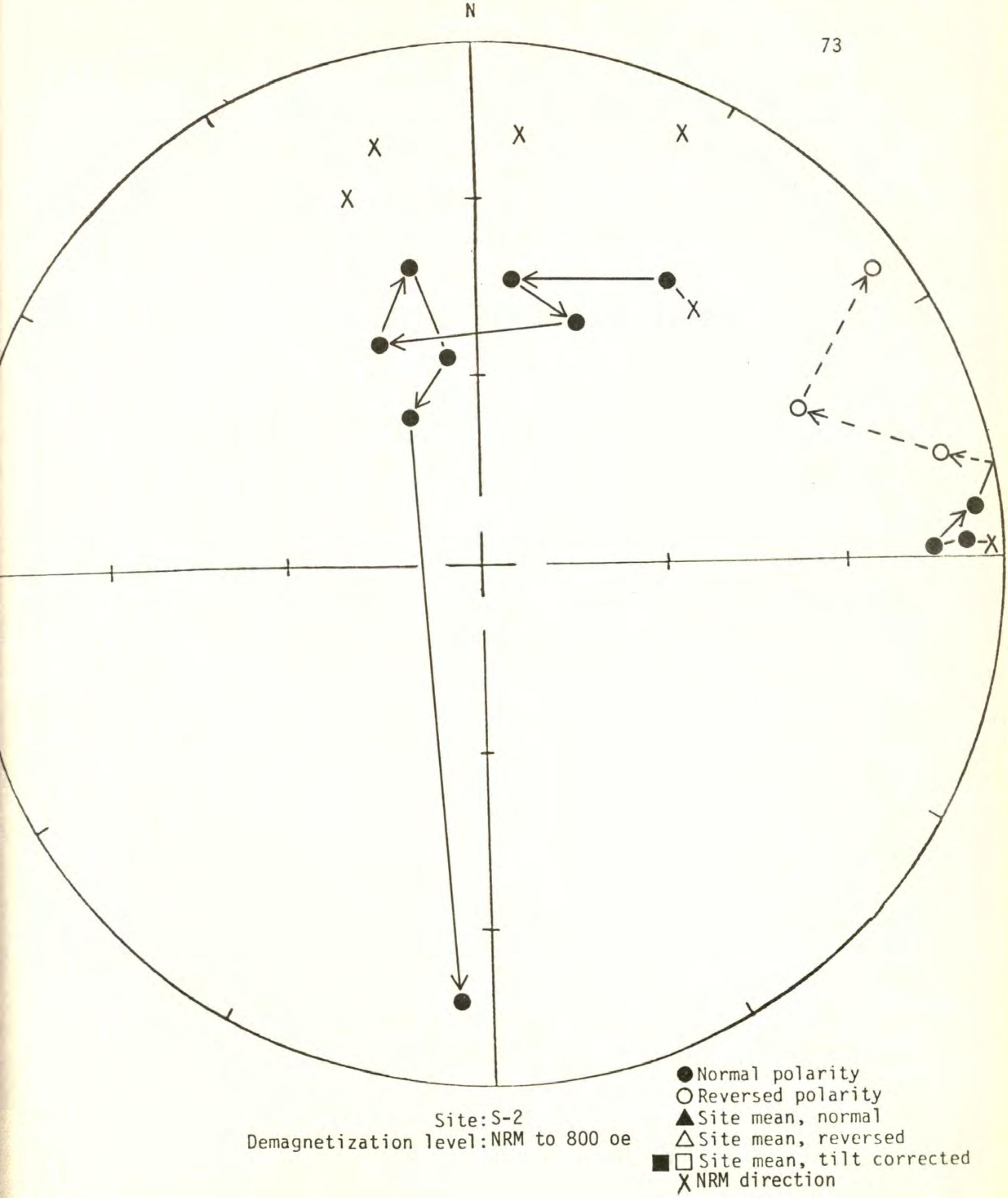


Site: E-2
Demagnetization level: NRM to 800 oe

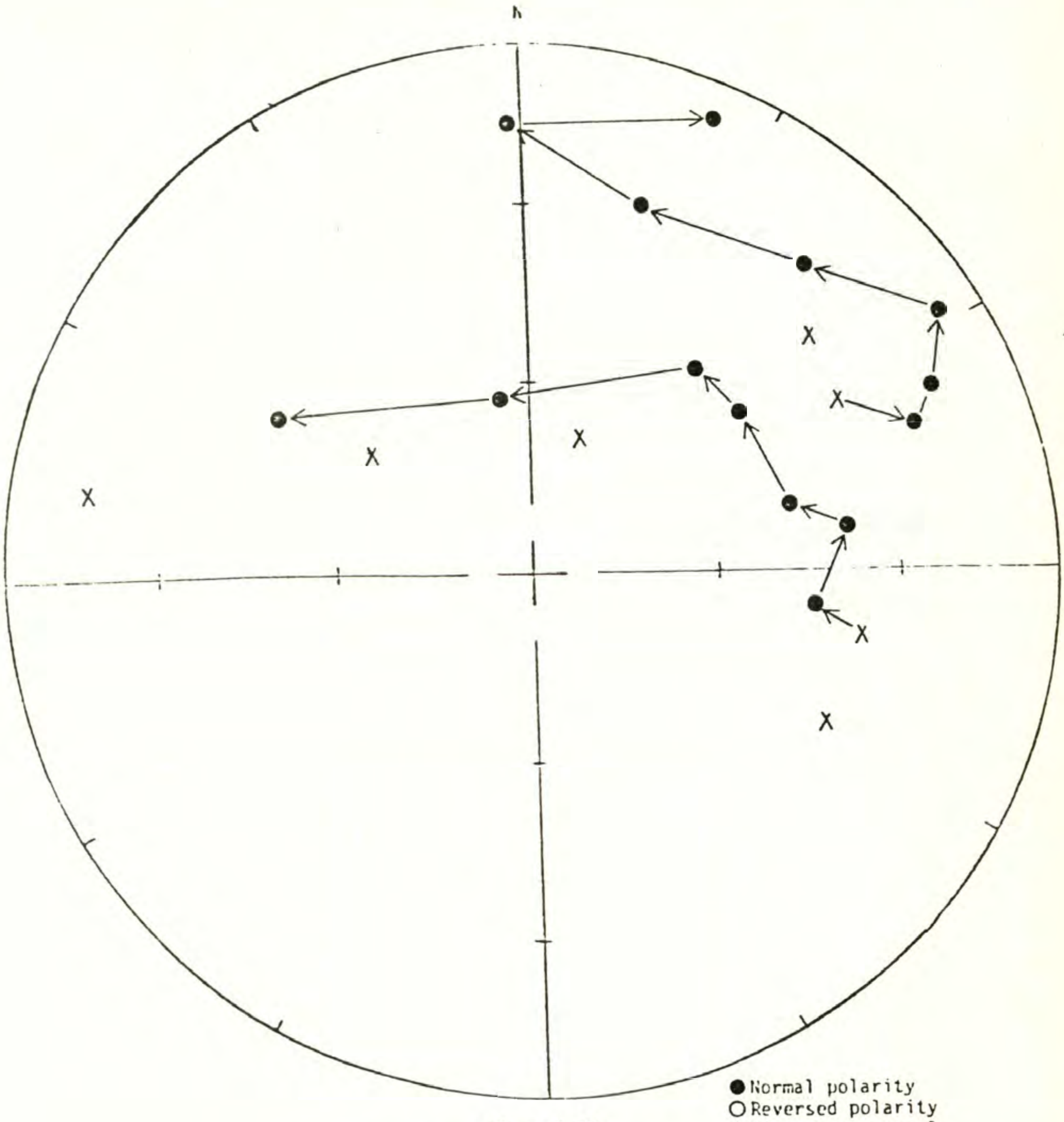


Site: E-4
Demagnetization level: NRM to 800 oe

● Normal polarity
○ Reversed polarity
▲ Site mean, normal
△ Site mean, reversed
■ □ Site mean, tilt corrected
X NRM direction

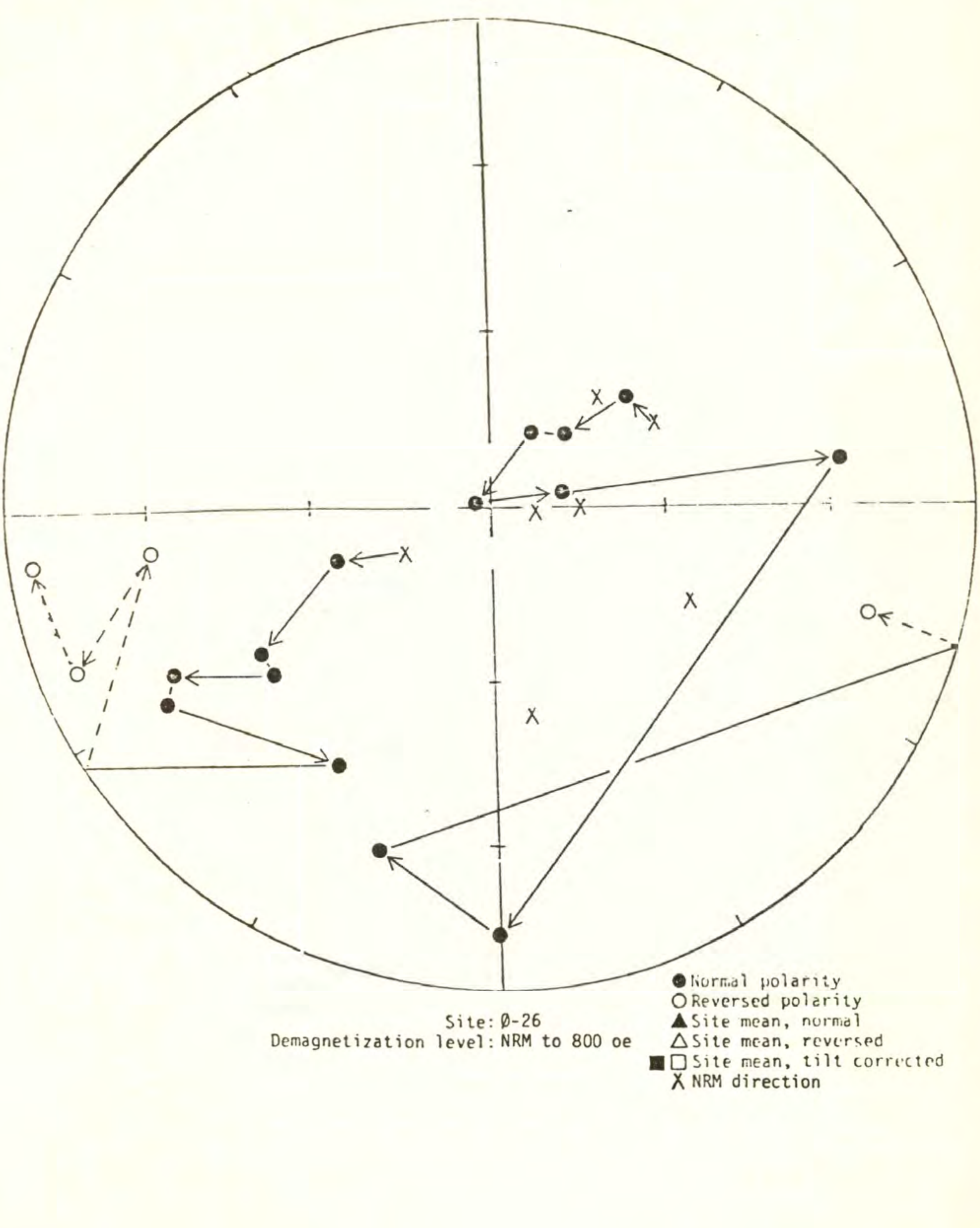


Site: S-2
Demagnetization level: NRM to 800 oe

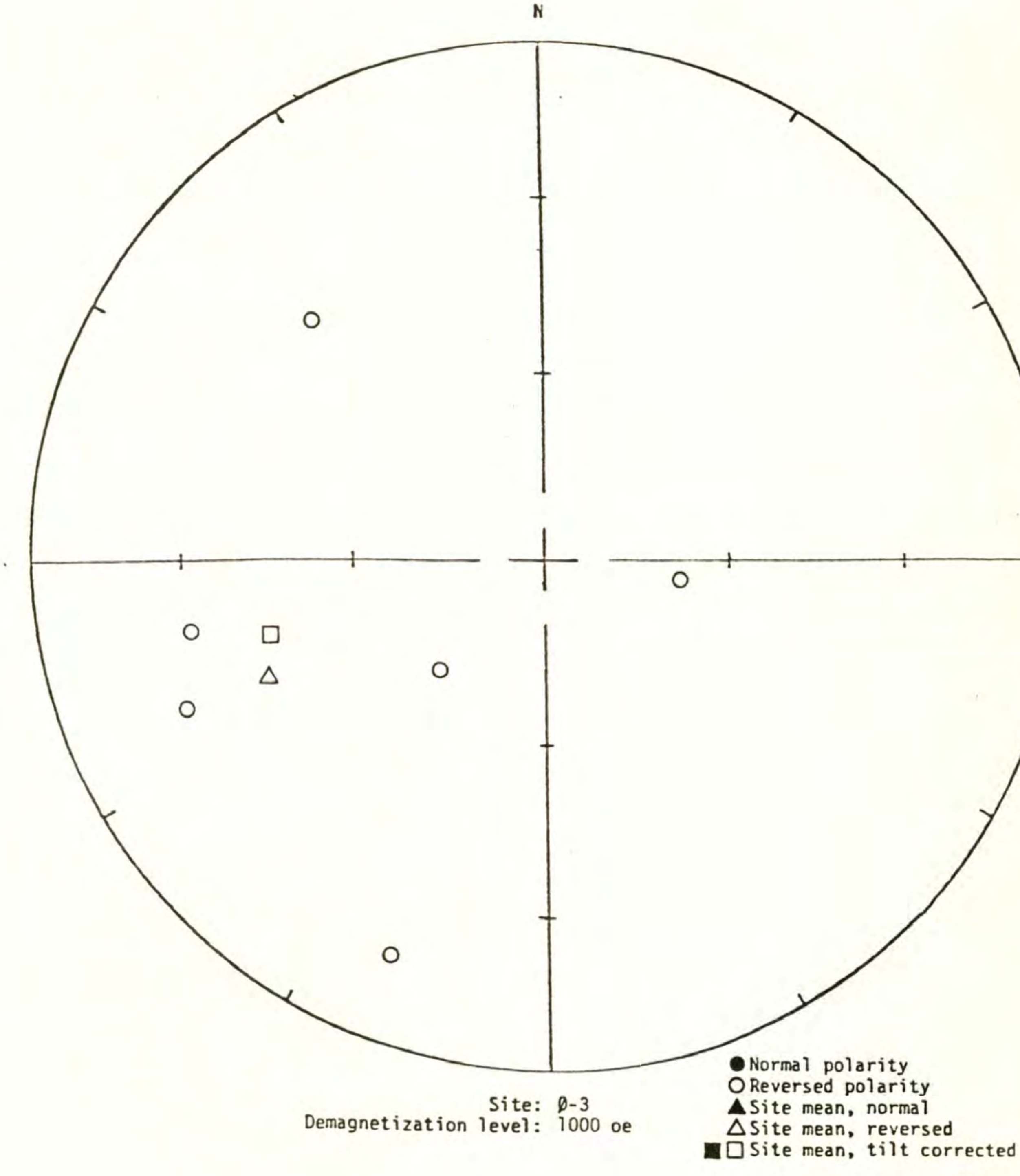


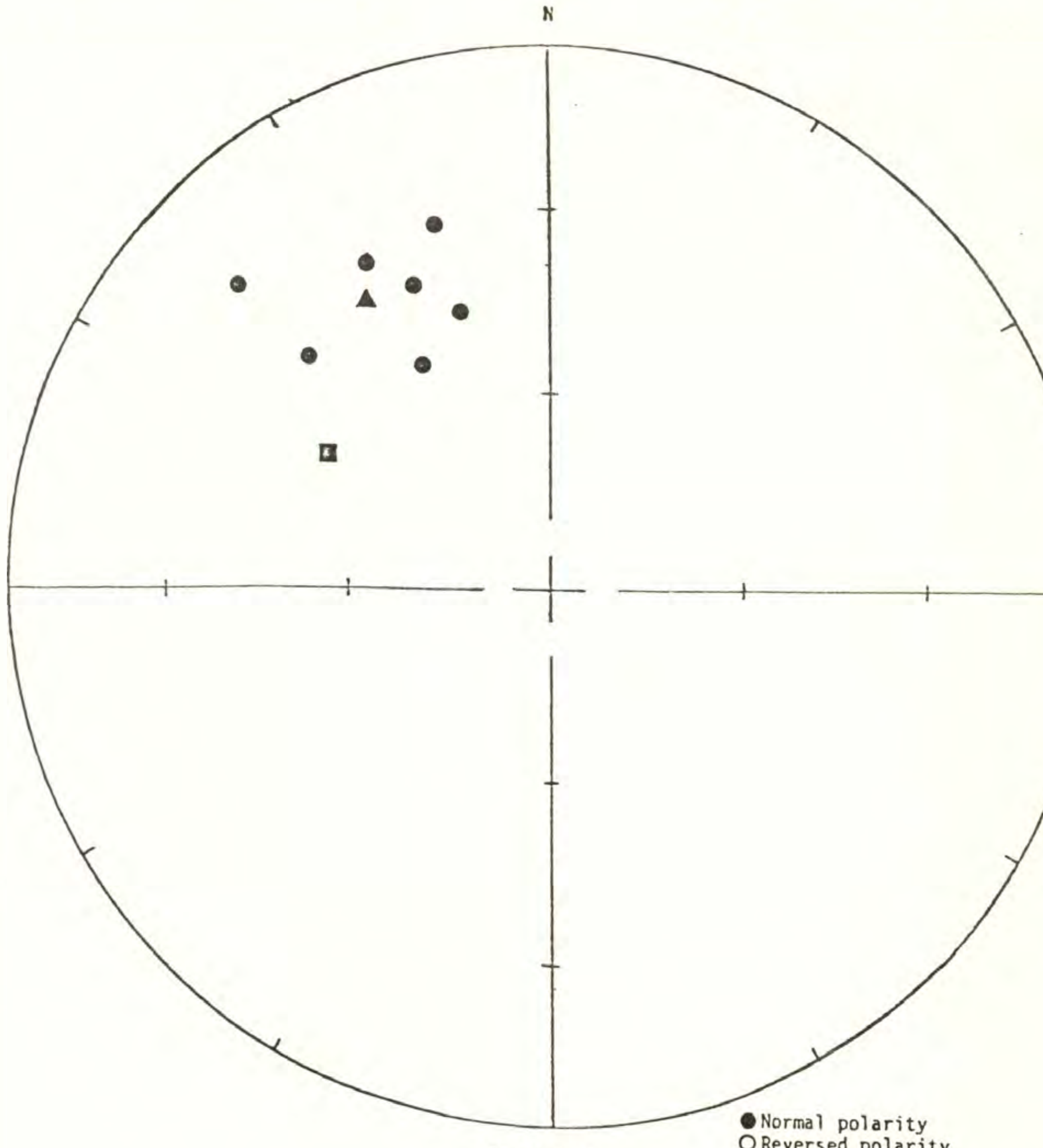
Site: Ø-12
Demagnetization level: NRM to 800 oe

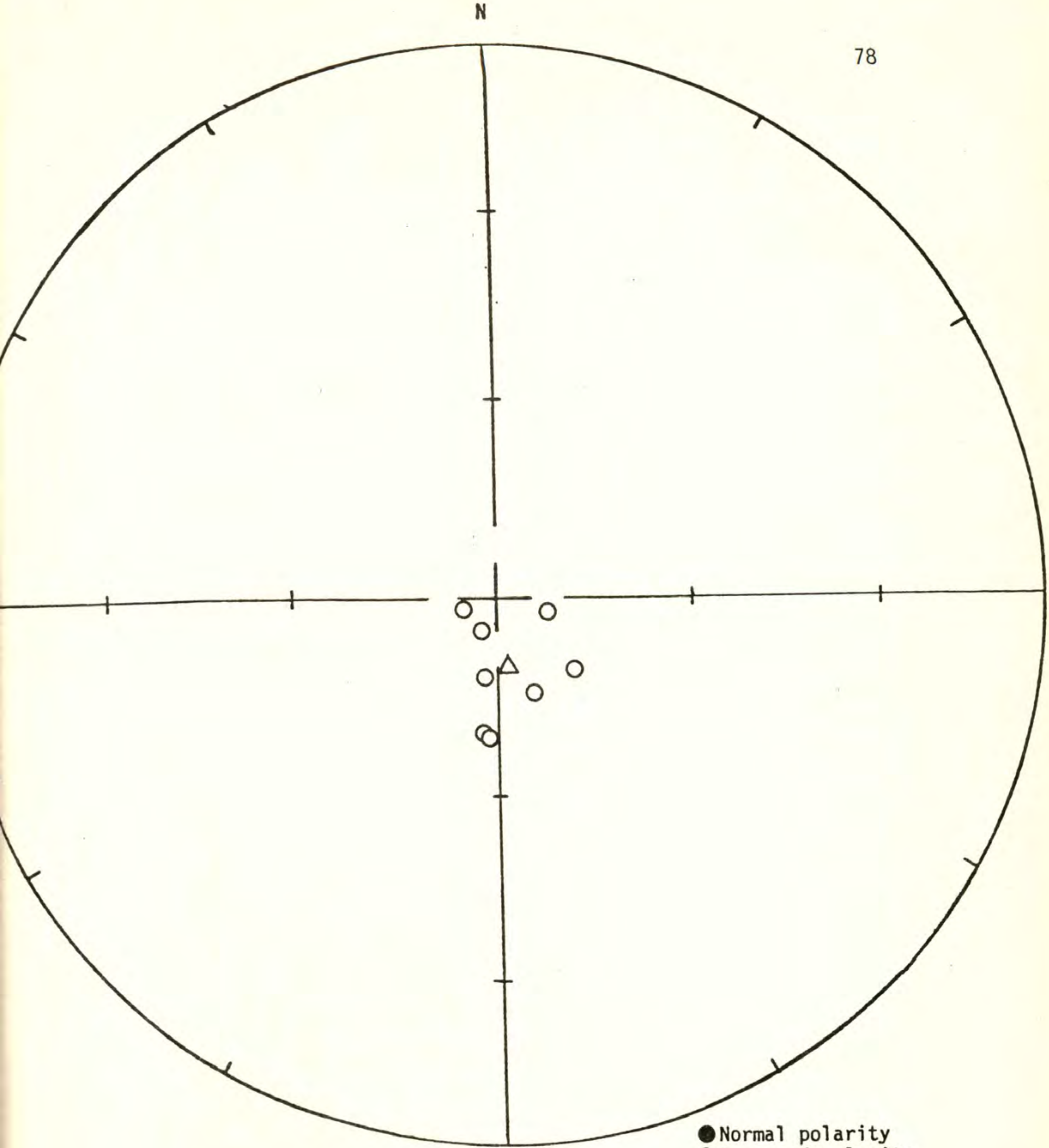
● Normal polarity
○ Reversed polarity
▲ Site mean, normal
△ Site mean, reversed
■ □ Site mean, tilt corrected
X NRM direction



Site: Ø-26
Demagnetization level: NRM to 800 oe

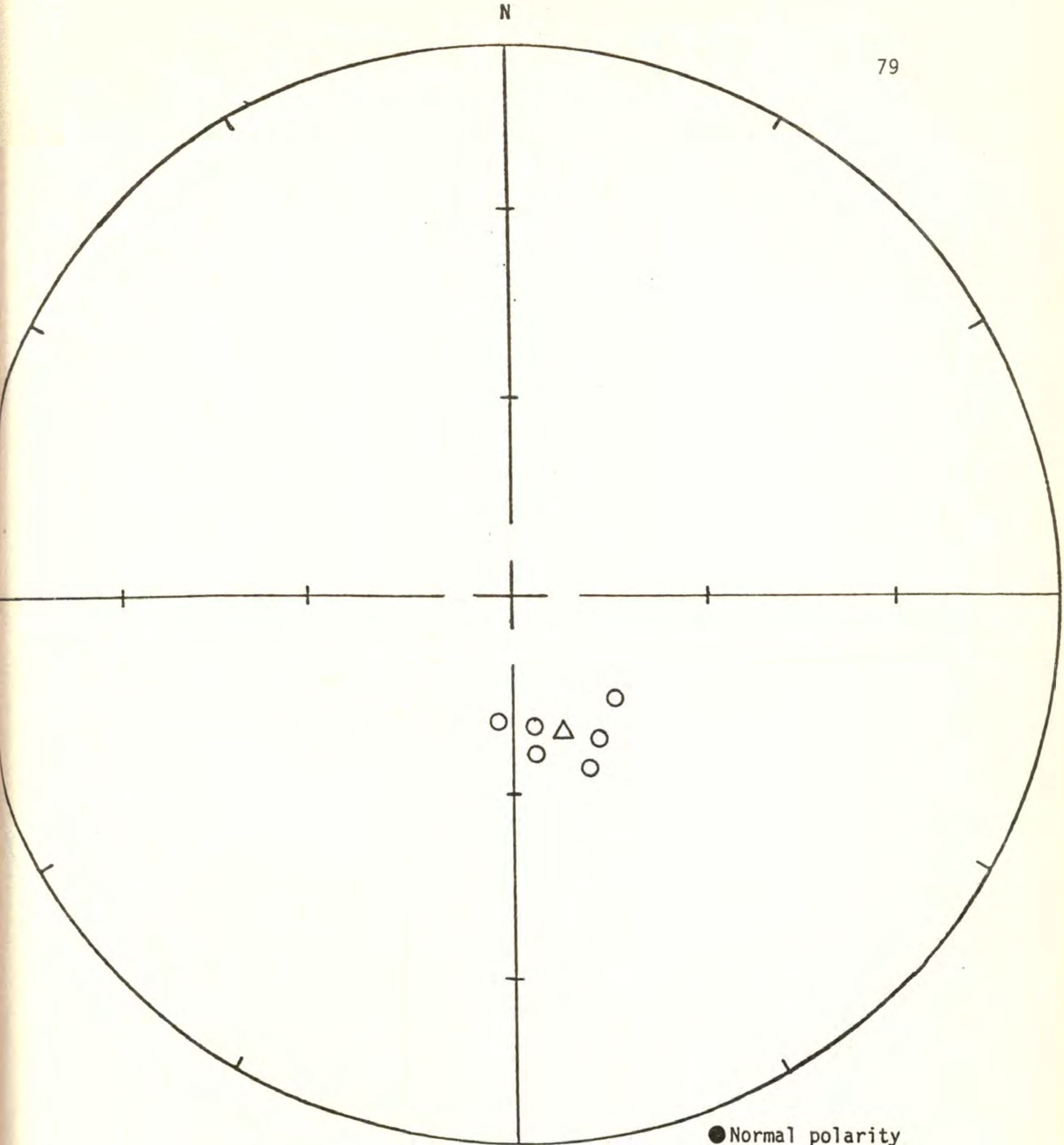

N
Site: Ø-3
Demagnetization level: 1000 oe
Normal polarity
Reversed polarity
Site mean, normal
Site mean, reversed
Site mean, tilt corrected


N
Site: Ø-6
Demagnetization level: 200 oe
Normal polarity
Reversed polarity
Site mean, normal
Site mean, reversed
Site mean, tilt corrected



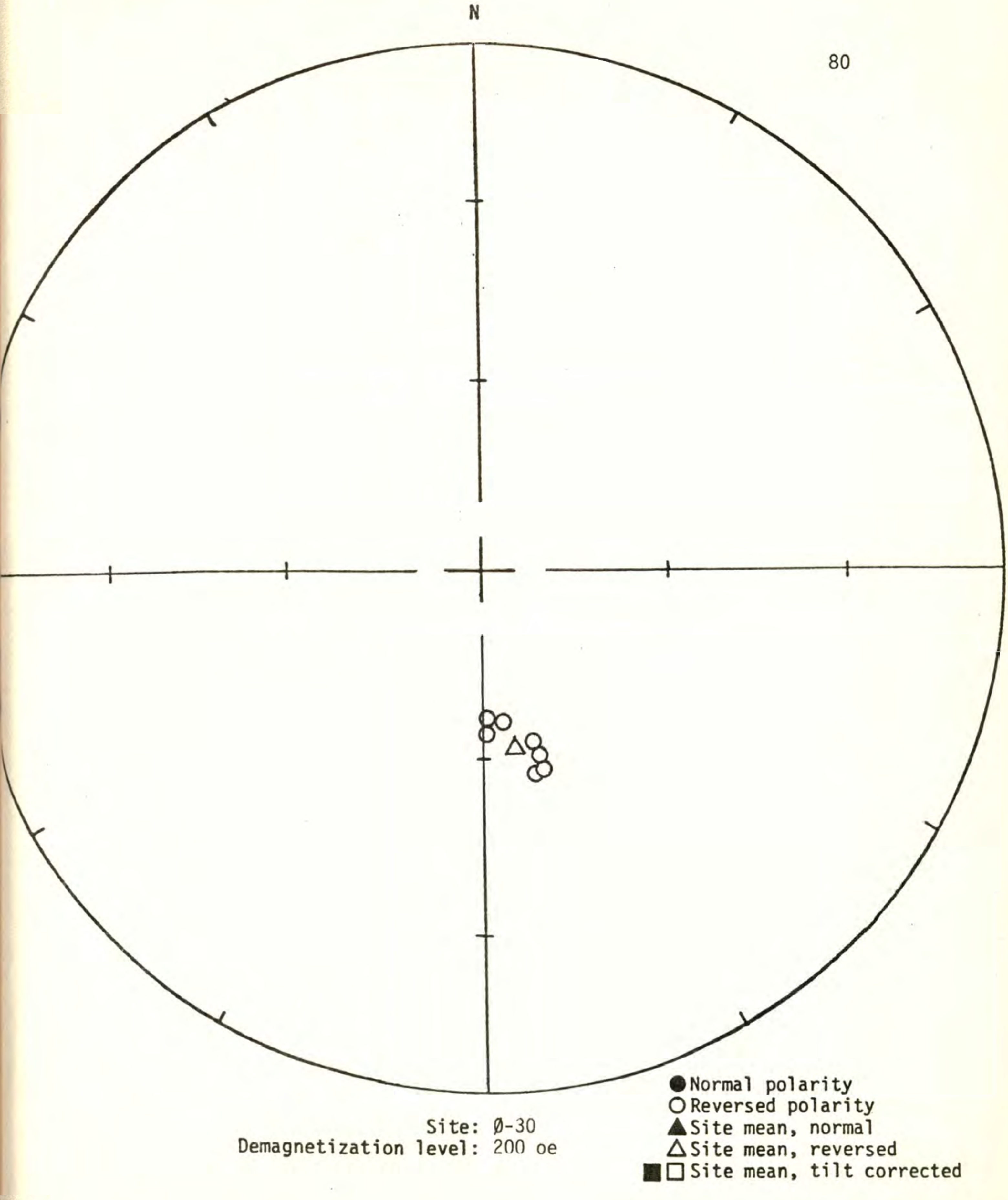
●Normal polarity
○Reversed polarity
▲Site mean, normal
△Site mean, reversed
■□Site mean, tilt corrected

Site: Ø-28
Demagnetization level: 800 oe



Site: Ø-29
Demagnetization level: 400 oe

●Normal polarity
○Reversed polarity
▲Site mean, normal
△Site mean, reversed
■□Site mean, tilt corrected



Site: Ø-30
Demagnetization level: 200 oe

APPENDIX D

Comparative petrology of magnetically stable and unstable sites

Because of the rather large number of sites rejected for apparent magnetic instability, it seemed worthwhile to search for a petrologic explanation of the difference between stable and unstable rocks. Polished thin sections were made of one specimen from each of two magnetically stable sites (S-5 and S-3) and from each of two unstable sites (S-2 and E-4).

The S-5 specimen was taken from a dacite(?) flow. Phenocrysts of feldspar and quartz lie within an aphanitic groundmass. The feldspar phenocrysts and groundmass are both altered and variably replaced by chlorite and epidote.

S-3 is a porphyritic, basaltic andesite with a trachytic groundmass. Feldspar and amphibole(?) make up the majority of phenocrysts while the groundmass contains micolites of feldspar, pyroxene(?) and alteration products (chlorites, opaques and epidote).

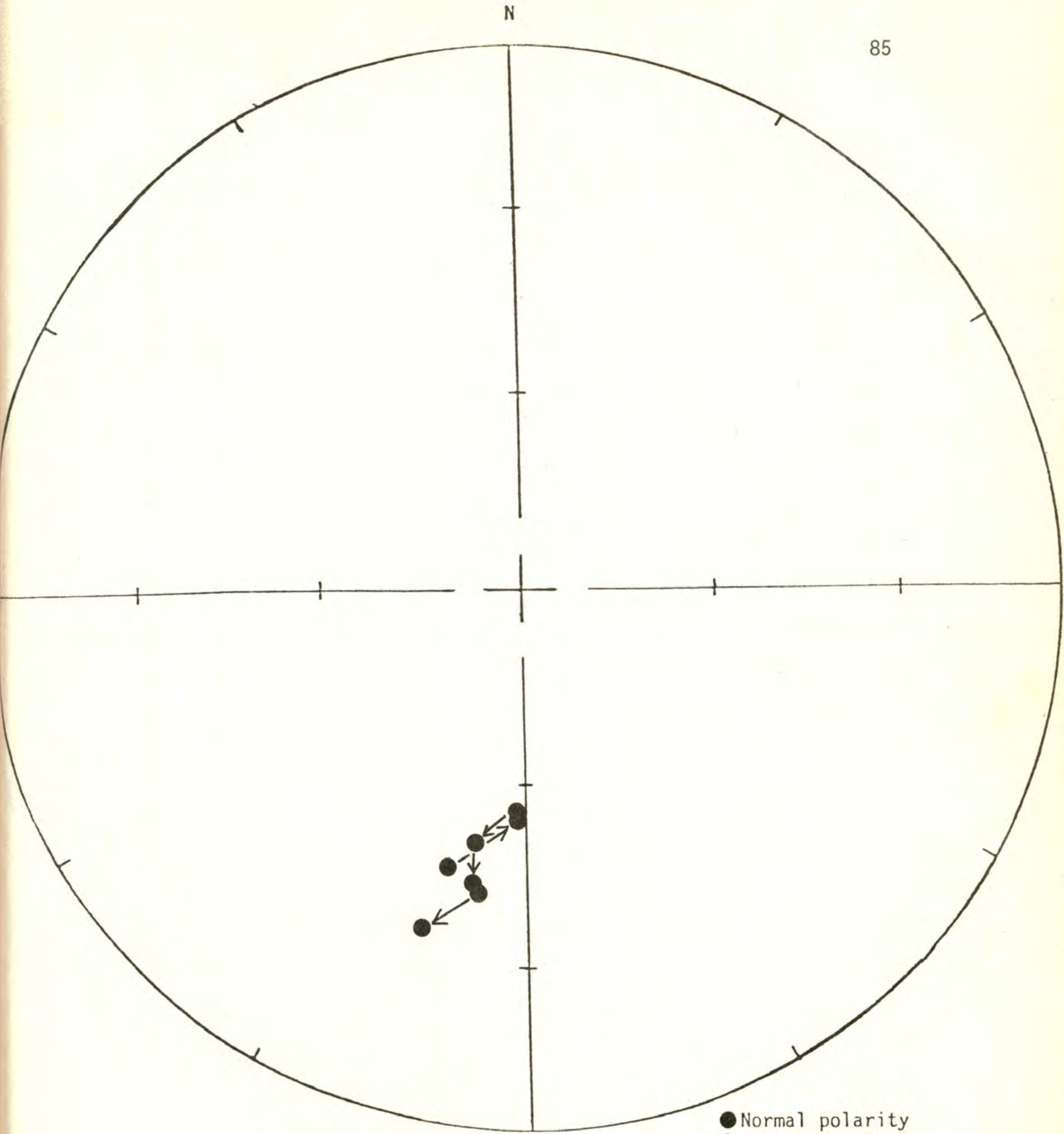
The rock has been subjected to propylitic alteration. Feldspars are variably replaced by white mica and calcite. The mafic phenocrysts are almost completely replaced by chlorite, epidote and opaques although there are some pyroxenes in the groundmass which seem to have escaped alteration.

The specimens from the unstable sites, S-2 and E-4, are both porphyritic basalts. These specimens have been more extensively altered at a higher grade then the stable specimens. In S-2 the feldspar phenocrysts have been selectively replaced by epidote and white mica. The mafic minerals are almost completely replaced by chlorite, opaques and epidote. Small amounts of pumpellyite can be seen in S-2. Alteration of E-4 is essentially complete with only relics of the original minerals remaining, having been replaced by chlorite, calcite, epidote and pumpellyite.

Under vertical illumination the polished surfaces revealed fine-grained as well as coarse-grained magnetite more or less evenly distributed throughout the stable and unstable specimens. Illmenite lamellae could not be seen in the large grains of either the stable or unstable specimens. This is somewhat puzzling but may be due, simply, to extremely fine lamellae. The magnetite grains in the unstable specimens differed from those in the stable specimens in that oxidation products (pseudobrookite?) could be seen in some grains.

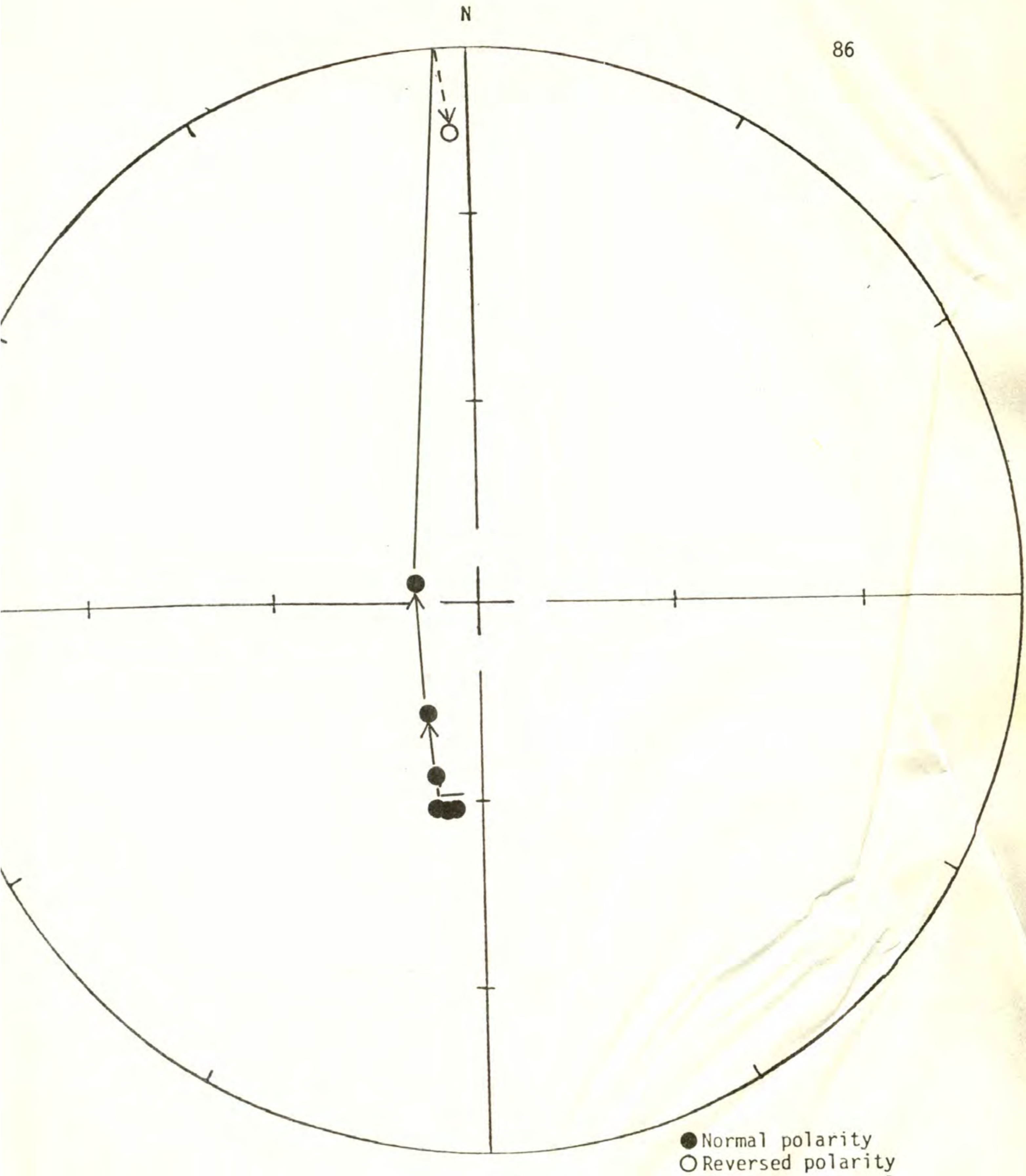
To determine if the instability was a result of actual alteration of the magnetic carriers to a nonmagnetic form or simply a loss of the original magnetization, the S-2 and S-5 specimens were given an ARM directed along their Z-axes and then stepwise demagnetized. The directions of magnetization were plotted on a lower-hemisphere, equal-area net at each step of demagnetization. The directions taken by S-5 plot in a relatively tight group on the N-S axis, as would be expected from a magnetically stable rock type in this situation. The directions obtained from S-2, however, indicate that even a saturation remanence is unstable. Normalized intensity curves show that the coercivity spectra of the unstable specimen is much lower then that of the stable specimen.

The ability of the magnetic carrier to take and hold a direction of magnetization, in the unstable specimen, has apparently been adversely affected by a low temperature alteration process resulting in metamorphism to the pumpellyite facies. How the metamorphism affected the magnetic carriers and prevented them from providing reliable information could not be determined in this brief investigation. The question is raised, however, as to the reliability of paleomagnetic data obtained from rocks which have been subjected to a low grade metamorphism.



Site: S-5
Demagnetization level: ARM to 600 oe

● Normal polarity
○ Reversed polarity
▲ Site mean, normal
△ Site mean, reversed
■ □ Site mean, tilt corrected



Site: S-2
Demagnetization level: ARM to 600 oe

● Normal polarity
○ Reversed polarity
▲ Site mean, normal
△ Site mean, reversed
■ □ Site mean, tilt corrected