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Detailed record of high amplitude secular variation in Northwestern Patagonia, Argentina /

David Bufo
Lehigh University

Detailed Record of High Amplitude Secular Variation in Northwestern Patagonia, Argentina.

by

David Bufo

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Professor in Charge

Chairman of Department

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ABSTRACT

In January, 1985, K. P. Kodama sampled pichileufu-age dry lake beds at La Pilila. These samples revealed anomalous paleomagnetic behavior. The sediments were again sampled in 1986, along with sediments from three other sites, to study this anomalous behavior in more detail and to correlate glacial stratigraphy over the field area. Plastic cubes were used to collect 120 independently oriented sediment samples. Sample cores from the Cathedral basalt were collected in an effort to date the anomalous behavior. Samples from two of four sediments sites displayed the anomalous behavior reported by Kodama in 1985. This behavior is characterized by dramatic looping of the geomagnetic field outside the normal range of secular variation, far-sided behavior, and decreased paleointensities. Sediment samples from a third site show near normal behavior without the dramatic movement seen in the other two sites, but outside the normal range of secular variation. The final site displays bahavior associated with the present day field. Dating was not possible using the Cathedral Basalt.

Correlation of glacial sediments in the field area was accomplished using the paleomagnetic record and stratigraphy.

INTRODUCTION

In 1985 K. Kodama, et al. (1985a) collected samples of glaciolacustrine sediments in northwest Patagonia, Argentina for paleomagnetic study as part of an ongoing project to correlate the glacial stratigraphy in the region. Kodama, et al (1985a) reported anomalous geomagnetic behavior recorded in the sediments collected. Due to the reconnaissance nature of the sampling, the characteristics of the anomaly were not precisely determined and only limited correlation of glacial stratigraphy was accomplished.

A more detailed sampling scheme of the sediments was used for this study in order to more accurately date and correlate the glacial stratigraphy and to precisely determine the nature of the paleomagnetic anomaly reported by Kodama, et al (1985a). One basalt unit in the northern portion of the field area was sampled in an attempt to constrain the age of the anomalous signal recorded by the sediments. Known as the Cathedral Basalt, this flow unit was reported to overlie the oldest glaciolacustrine sediments in the northernmost portion of the field area (Evenson et al, 1986). This paper is a report of the results derived from the detailed study of galciolacustrine sediments in northwest Patagonia, Argentina.

GLACIAL GEOLOGY

The research area is located between latitude 39°10'S and 41°20'S in northwest Patagonia, Argentina (figure 1). The first major study of glacial drift in the area was completed by Caldenius (1932). Flint and Fidalgo (1964) completed a more detailed study in 1964 which confirmed the eastern limits of glaciation reported by Caldenius (1932).

Flint and Fidalgo (1964) described three separate glaciations in the region, the Pichileufu, the El Condor, and the Nahuel Huapi, from oldest to youngest, based on regional mapping and the degree of weathering of granite clasts in the glacial drift. The oldest glaciation identified, the Pichileufu, is characterized by an average 93% weathering of granitic clasts. Pichileufu drift is generally found at the highest elevation above river banks, when it can be located. In many cases the Pichileufu drift is virtually indistinguishable from the younger El Condor drift. This is attributed to the great age and high degree of weathering of both the Pichileufu and El Condor drifts. Where it is distinguishable, the Pichileufu drift generally exists as outwash or scattered erratics. Flint and Fidalgo (1964) report one instance of till and deformed lacustrine sediments which overlie outwash in the Rio Limay valley, indicating that the Pichileufu is a real glacial event and its remnants can be distinguished from those of younger glaciations in the field area.

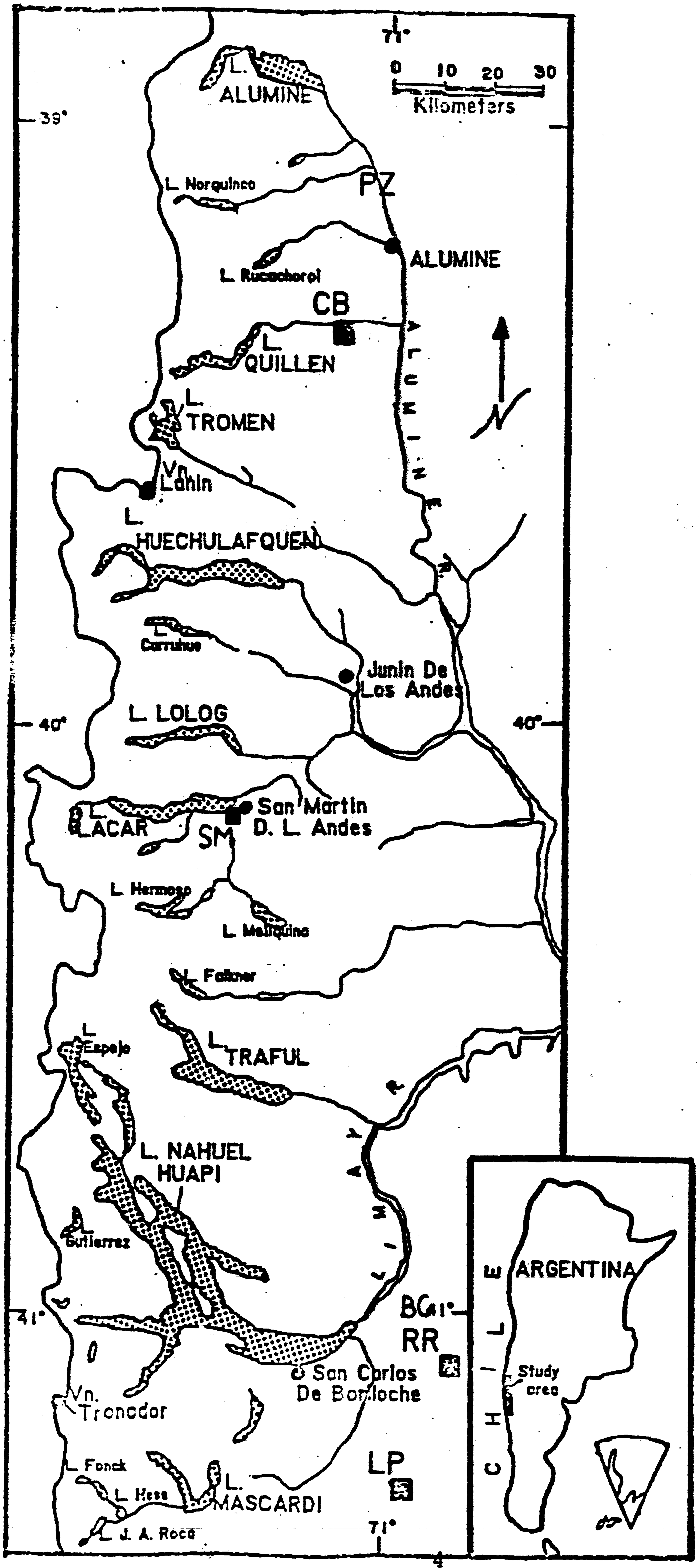


Figure 1 - Location map showing sampling sites
CB - Cathedral Basalt
SM - San Martin
LP - La Pilila
RR - Railroad/Bridge
(Adapted from Kodama, 1984)

INCLINATION	DECLINATION	ALPHA-95
-79.43	337.60	6.42
-75.14	324.68	9.13
-69.20	289.79	17.55
-76.79	260.45	5.74
-47.30	265.80	7.25
-31.35	267.75	19.54
-62.89	264.36	8.72
-69.82	267.84	6.87*
-67.00	230.37	7.19
-76.07	349.19	9.47
-73.90	230.60	10.74
-71.50	284.76	13.24
-79.35	354.03	5.42
-66.37	353.53	5.23
-67.37	24.49	5.70
-69.41	108.47	1.90
-74.80	58.45	10.75*
-68.57	21.14	4.65
-55.50	79.50	5.70
-57.82	62.92	1.44
-56.75	80.87	2.07*
-61.29	81.24	4.48
-53.31	80.18	4.88
-61.15	61.71	9.07
-63.38	80.19	3.98*
-59.03	81.75	4.38
-66.39	87.14	3.71
-79.48	43.67	15.32
-70.48	98.82	1.97

Table 1 - La Pilila characteristic directions with corresponding alpha-95 confidence limits. In all cases N=3, except * where N=2.

INCLINATION	DECLINATION	ALPHA-95
-26.60	11.80	5.52
-29.20	10.70	3.72*
-33.20	16.20	3.55
-26.10	10.30	1.70
-25.70	11.30	2.31
-34.30	8.70	0.61*
-26.30	11.90	1.92
-31.70	15.40	1.45

Table 2 - San Martin characteristic directions with cooresponding alpha-95 confidence limits. In all horizons N=3, except * where N=2.

INCLINATION	DECLINATION	ALPHA-95
-45.80	70.60	3.02
-44.50	72.30	2.04
-29.90	77.10	2.59
-29.90	68.50	4.87
-50.30	90.80	11.57
-50.50	95.60	4.22*
-63.90	99.80	5.33
-40.70	106.40	13.75
-46.30	101.00	12.37

Table 3 - Bridge Section characteristic directions with cooresponding alpha-95 confidence limits. In all cases N=3, except * where N=2.

Flint and Fidalgo (1964) recognize one glacial event between the Nahuel Huapi and Pichileufu glaciations. It was labeled the El Condor glaciation and is distinguishable from the Naheul Huapi and Pichileufu glaciations by several characteristics. The El Condor glacial drift is characterized by 78.5% weathering of granitic clasts. It is found at intermediate elevations above river banks when compared to Pichilufu and Nahuel Huapi glacial drift. El Condor terminal moraines are slightly smoother than those of Nahuel Huapi age, and also show less constructional relief. In some localities, El Condor moraines also have lag concentrates of cobbles and boulders, due to the selective removal of fine grained material.

The Nahuel Huapi is considered to be the youngest glaciation in the region since its drift is typically found at the lowest elevation above the river banks (Flint and Fidalgo, 1964). Flint and Fidalgo (1964) characterize the drift as having only 55% weathered granite clasts. Nahuel Huapi also displays the most deformed outwash of the three glaciations. An additional characteristic that separates the Nahuel Huapi from earlier glaciations is that of erosional morphology. Due to the young age of the Nahuel Huapi, there has been less erosion and, thus, its features are easily distinguishable from the other glaciations.

Recent field work in the study area suggests that Pichileufu age sediments are not of glacial origin (Schlieder, #1988). Schlieder (1988) believes that his inability to find points of ice damming for Pichileufu age lakes, along with the lack of dropstones in the sediments from these lakes, may indicate that the lakes are terrestrial. Schlieder reports that the points of damming may be found with further field work and that the lack of dropstones may be due to a shallow lake restricting the movement of floating ice (Schlieder, 1988). Although the origin is in question, the lake sediments are still considered to be of Pichileufu age (Schlieder, 1988).

PREVIOUS PALEOMAGNETIC WORK

Creer, et al (1983 a&b) have conducted paleomagnetic studies on sediments cored from three small lakes 60 km west of the field area. These studies provide information on secular variation during the past 14,000 years for this area (Creer, et al, 1983a & b). While the studies by Creer, et al (1983a & b) involve sediments younger than the glacial sediments we have studied, it is significant that the sediments show that VGP's remain within 10^{o} of the geographic pole and no shallowing of inclination with respect to the axial dipole field. Reconnaissance paleomagnetic work on the Pichileufu-age sediments from northwest Patagonia suggest anomalously low inclination/low amplitude geomagnetic field behavior in addition to high inclination/high amplitude geomagnetic field behavior (Kodama et al., 1985a & b). An anisotropy of magnetic susceptibility measurements suggest that these sediments have a primary depositional fabric (Kodama et al, 1985a) and a resedimentation experiment performed by Kodama et al (1985a) suggests that these sediments are capable of recording steep inclination geomagnetic fields.

The high inclination/high amplitude - low inclination/low amplitude behavior reported by Kodama et al (1985 a & b) suggests the possibility that the Pichileufu sediments record an excursion or polarity transition of the Earth's magnetic field. It was the intent of this study to further determine the nature of the anomalous behavior. In addition, it was hoped that our results would add to the database of excursions and transitions from the southern hemisphere.

SAMPLING PROCEDURES AND SITE DESCRIPTIONS

A total of 4 separate exposures of glaciolacustrine sediments were sampled in the field area. Three exposures; La Pilila, the Railroad Cut, and the Bridge Section (figure 1), consist of glaciolacustrine sediments which may be associated with what is thought by some (Flint and Fidalgo, 1964) to be the oldest glaciation (Pichileufu) in the valley. Also sampled were sediments at San Martin de los Andes, approximately 100 km north of San Carlos de Bariloche, and the Cathedral Basalt located in the Quillen Valley (figure 1).

Our sample collection procedure can be described as follows: 1) Dry, weathered sediment was scraped away from the cliff face. 2) 3 2x2x2cm cubic pedestals were carved on the cliff face, from the same stratigraphic horizon. These were left attached to the cliff face. 3) 2x2x2cm plastic boxes were placed over the carved sediment pedestals and were oriented with respect to North and horizonatal with a Brunton compass. 4) Caps were then glued on the plastic boxes to prevent drying of the sediments.

Oriented cores of the Cathedral Basalt were taken with a Pomeroy gasoline powered, diamond coring drill and oriented with a sun compass. Samples were approximately 2.5cm in diameter and 4cm in length. The weathered end was cut off in the laboratory using a diamond blade saw. Broken cores were cemented together using water glass (sodium silicate).

SAMPLING SITES

La Pilila

The La Pilila sampling site is located approximately 25 km southeast of San Carlos de Bariloche (figure 1). Pichileufu age glaciolacustrine sediments form a cliff with a face sloping approximatly 45^{o}. The cliff is approximately 8 to 10 meters high.

The surface of the sediments is highly weathered, but is easily scraped away revealing unweathered sediment 15 to 20 cm from the surface. Distinct marker beds were followed along the section to a point where it was possible to continue sampling stratigraphically older sediments. The sediments at the site are rhythmically bedded. There is no sign of deformation of the bedding. The rhythmites consist of silt-sized coarse layers and clay-sized fine layers (Rabassa, 1975). The spacing of the layers changes within the section, with a closer spacing near the top and bottom of the section, however, an average thickness for one rhythmite pair is approximately 1 cm. If the rythmites are interpreted as annual, the section represents between 800 and 1000 years of deposition. A total of 120 samples were taken at La Pilila, three samples were collected per horizon. Sampled horizons were approximately 20cm apart and spanned approximately 8 meters of the 10 meter section.

Railroad Section

The Railroad Section is located approximately 30 km east of San Carlos de Bariloche along a railroad line from San Carlos de Bariloche to Buenos Aires (figure 1). Pichileufu age glaciolacustrine sediments are exposed on a cliff face with dips approximately 60^{o} from horizontal. The sediments are surprisingly fresh, having a very thin veneer of weathered material over the surface. The section is 200 meters long and 15 to 20 meters high. The sediments dip slightly (approx. 2-3^{o}) to the west, revealing older sediment to the east of the section. The bedding was undeformed and continuous. When it was necessary, distinct benches in the section were used as markers which were followed along the section to a point where it was possible to continue sampling stratigraphically down section. The sediments in this area are rhythmically bedded silt and clay layers. The average rhythmite thickness is 1.25cm. The rythmites are thicker at the bottom of the section and thinner toward the top. According to Kodama, et al (1985a), if the rythmites are interpreted as varves, the 10m section they sampled represents 400 to 500 years. In this study, a total of 90 samples were taken at the railroad site. Three closely spaced samples were taken from each sampling horizon. The stratigraphic spacing between sampling horizons was approximately every 50 cm. 30 horizons were sampled, covering approximately 15 meters of a 15 to 20 meter section. If the rhythmites are interpreted as annual, our section covers 1200 years.

Bridge Section

The Bridge Section is located approximately 2 km east of the Railroad Section, over a train trestle, along the same rail line (figure 1). The Bridge Section sediments are stratigraphically below the Railroad Section. There is a 7 to 12 meter elevation difference between the Railroad section and the Bridge Section. Accounting for the 2.5^{o} dip of the Railroad sediments, this gap represents approximatley 8000-7500 years. The section is almost identical in description to the Railroad Section, however it is only 8 meters high, 15 to 20 meters across, and is a north facing cut. The rhythmites are similar in nature and size to those at the Railroad Section. Here the section may represent 1000 years, if rhythmites are interpreted as annual varves. 45 samples were taken from the Bridge Section. Horizons were sampled every 0.5 meter, covering 7.5 meters of an 8 meter section.

San Martin

San Martin sediments are located approximately 120 km north of the La Pilila, Railroad and Brige sediments, along the north side of the main road to San Martin, approximately 5 km west of San Martin (figure 1). San Martin sediments are the youngest in the valley and are thus considered to correlate with the Nahuel

Huapi glaciation to the south. While the San Martin sediments are not from the same valley as the Pichileufu age sediments sampled, it was hoped that they would indicate geomagnetic field behavior during the Nahuel Huapi glaciation and, possibly, a relationship to the paleomagnetic signal obtained from the older sediments to the south. The section is 8 meters high and 10 to 20 meters wide. The slope of the face is approximately 60° from horizontal. The sediments are virtually unweathered. The thin weathered surface can easily be scraped off, revealing fresh sediments. Clay and silt rhythmites are approximately 0.5 to 1 cm thick and may indicate that the section represents 750 to 1500 years, if the rhythmites are considered to be annual.

Reconnaissance sampling was done at San Martin. 3 samples were taken from each horizon, with horizons being spaced 1 meter apart. A total of 24 samples was taken, representing 8 horizons over an 8 meter section.

Cathedral Basalt

The Cathedral Basalt is located 50 km east of Alumine, in the northernmost portion of the field area (figure 1). At the time it was sampled, Evenson and Rabassa (personal communication) believed that the flow lay on top of, and incorporated sediments from, the oldest glaciation in the valley. This would suggest correlation with the Pichileufu sediments we have sampled near San Carlos de

Bariloche. More recent work by Evenson, Rabassa, and Schlieder (personal communication) indicates that this relationship may not exist. Based on the earlier interpretation, it was hoped that this unit recorded the same anomalous geomagnetic behavior found in the oldest glacial sediments to the south. This correlation, combined with an $^{40}Ar/^{40}Ar$ date planned for the basalt, was to be used to date the anomalous field behavior. 7 samples were collected at the Cathedral Basalt site near Alumine.

MEASUREMENT

Step-wise, alternating field demagnetization of the samples was performed using a Schonstedt GSD-5 tumbling AF demagnetizer capable of a peak field of 100 mT. Thermal demagnetization of basalt samples was performed in a Schonstedt TSD-1 thermal demagnetizer which provided a residual magnetic field of less than 5 nT in the cooling chamber. Thermal demagnetization was attempted on 8 sediment horizon samples from the La Pilila Section. Samples were permeated with water glass and progressively heated up to a temperature of 250° C in four steps. No thermal demagnetization was attempted on sediment samples from other sampling sites.

The remanent magnetization of each sample was measured between each demagnetization step by a Molspin digital fluxgate slow spinner magnetometer enclosed in 2m Helmholtz coils. Six orientations of each sample were used during each measurment cycle (Collinson, 1983) and phase and amplitude data of the signal was automatically determined by a fast Fourier transform routine.

Characteristic magnetizations were determined using principle component analysis (Kirshvink, 1980). The longest linear segment which included the origin was considered to be the characteristic magnetic vector of the sample.

The mean inclination and declination for the 3 characteristic magnetizations from each horizon were obtained by Fisher statistical analysis (Fisher, 1953). If the alpha-95 value for any horizon was higher than 35^{o} the internal consistency of the three sample directions for that horizon were checked. If one sample direction was found to be far from the other two, it was considered to be an outlier and discarded. The mean direction was calculated using the remaining two sample directions. If two standard deviations of the error could not be decreased to less than 25^{o} by discarding an outlier, the horizon was not included in the final data set. The virtual geomagnetic pole (VGP) for each horizon was calculated from the horizon means.

ROCK MAGNETISM

To determine the paleointensity behavior of the field corresponding to the anomalous directional behavior recorded by glacial sediments, it is necessary to normalize the NRM intensities. The method used in this study was normalization of NRM's with anhysteretic remanent magnetization (ARM) (Levi and Banerjee, 1976). Anhysteretic remanent magnetization aquisition experiments were performed in a 60cps alternating field demagnetizer at a peak field of 100 mT in the presence of the earth's magnetic field (.05mT). All samples were oriented the same, in coils and with the field ramped down to zero over a 10 minute period. The alternating field demagnetization plots of the ARM and NRM of the samples were compared to insure that the ARM acquired by the samples was carried by grains with the same coercivity grains as those contributing to the NRM. Samples which became disaggregated by tumbling during AF demagnetization could not be used in subsequent ARM acquisition work. This resulted in 39 horizons from La Pilila, 10 from the Bridge Section, and 26 from the Railroad Section available for paleointensity work. One sample was used from each horizon.

RESULTS

The thermal demagnetization attempted on eight horizons from La Pilila was unsuccessful. When heated to 250°C, samples which were permeated with water-glass expanded to fill the furnace cavity and had to be removed with a brass rod. This process eliminated the oldest eight horizons from La Pilila data. The remaining data are AF demagnetization data.

Coercivities were generally in the range of 10 to 100 mT with a mean destructive field of 50 mT. Most samples showed similar behavior during demagnetization regardless of their section.

La Pilila Section

During alternating field demagnetization, La Pilila sediments show stable behavior. Orthogonal projections show univectoral decay into the origin, indicating no overprint and making characteristic directions easily resolvable (figure 2). NRM's are strong (10-100mA/m) in all samples. Most samples lose 90% of their magnetization by 80mT (figure 3). Mean directions for each sampling horizon have an average precision parameter of 465.74 with a corresponding alpha-95 confidence limit of 8.24°. Three horizons gave spurious results, with alpha-95 values not correctable to less than 25° by discarding a sample which

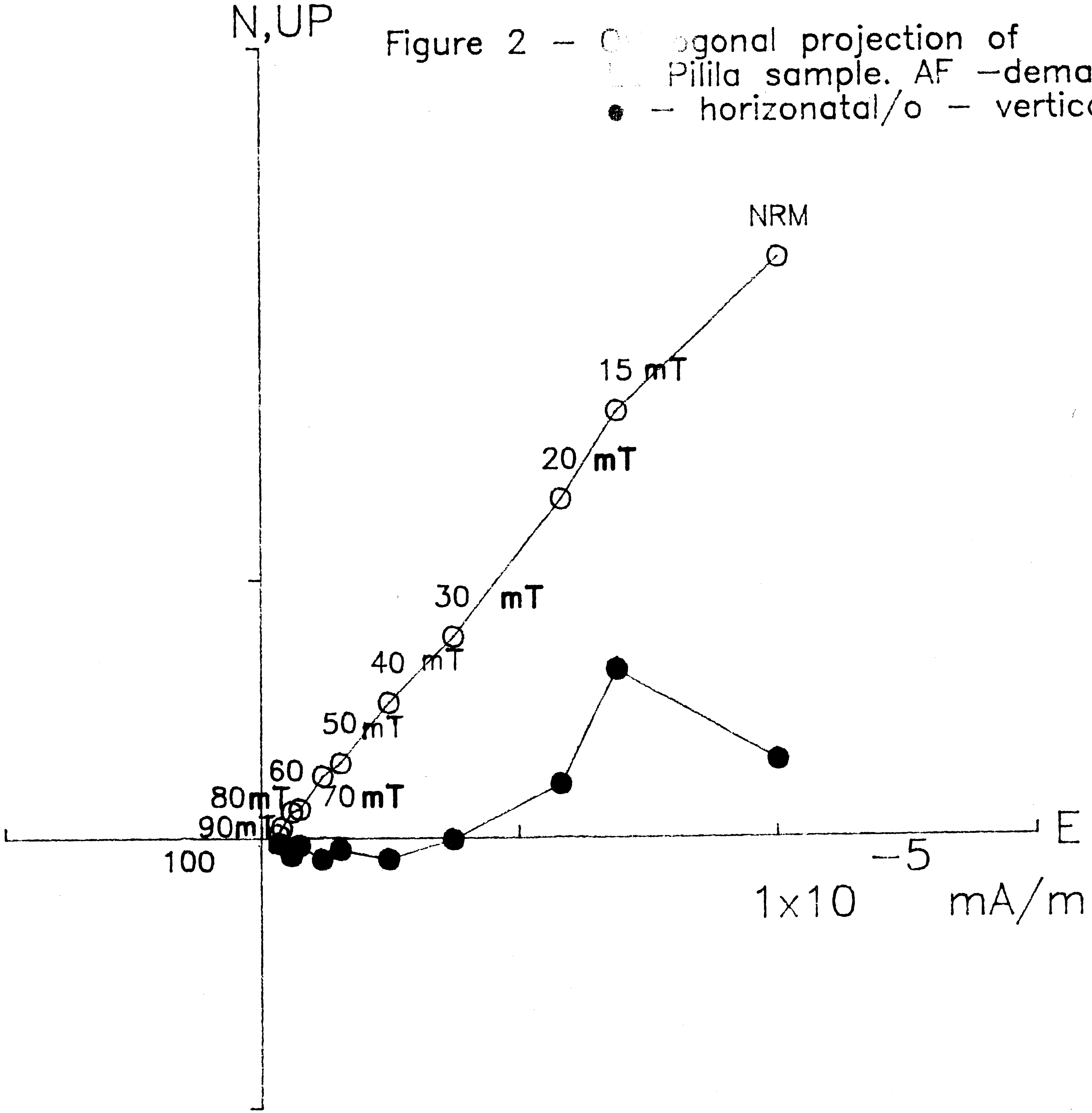


Figure 2 – O[illegible]gonal projection of [illegible] Pilila sample. AF –demag. • – horizonatal/o – vertical.

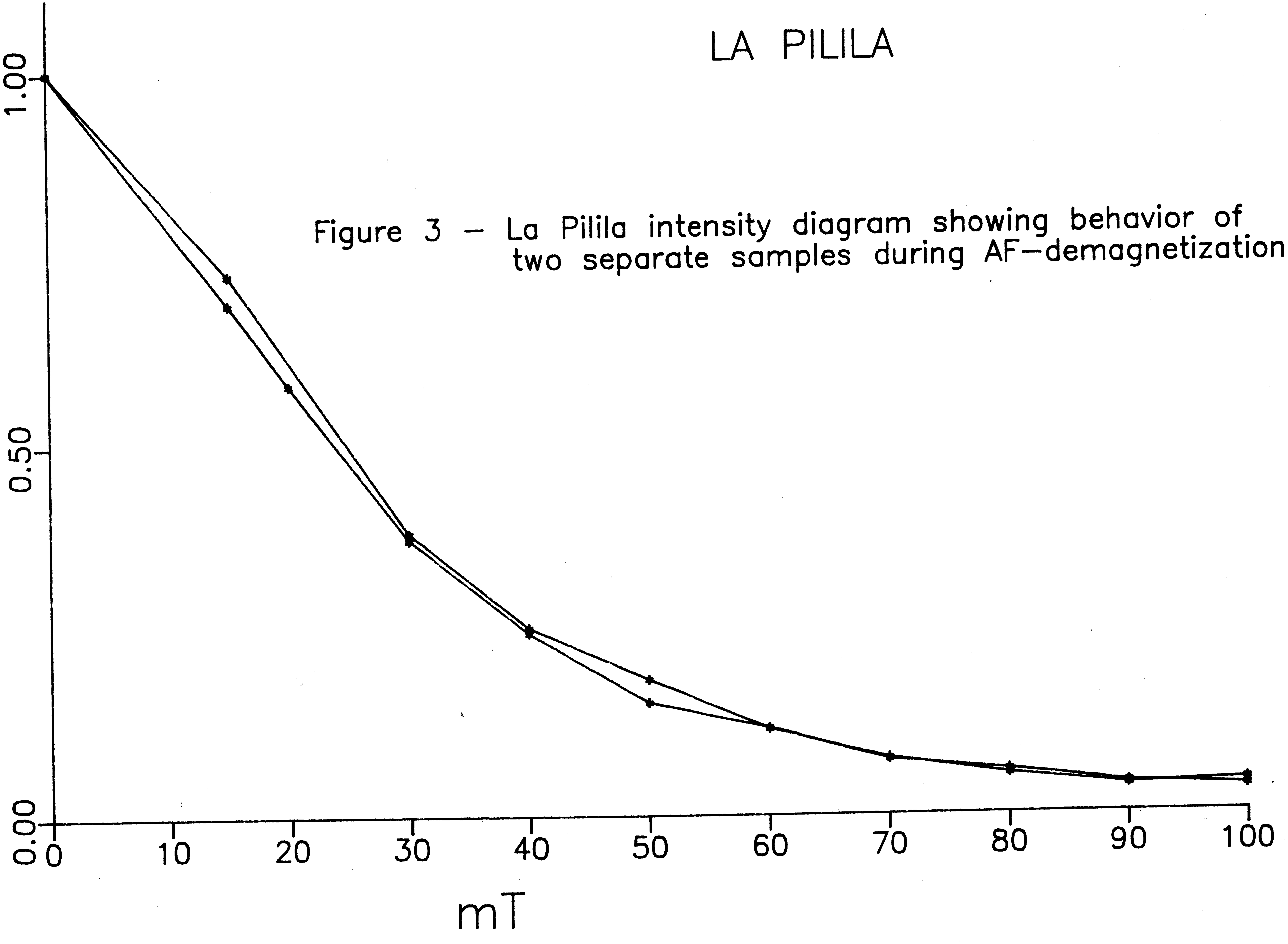


Figure 3 – La Pilila intensity diagram showing behavior of two separate samples during AF–demagnetization.

displayed a direction that did not agree with the other two directions obtained for each horizon.

The horizon means for the La Pilila Section show dramatic movement (figure 4). Inclinations are up to 29^{o} steeper than the expected axial dipole inclination of -60^{o}. Declination swings from 90^{o} to 270^{o} are seen. The data show two loops. The first loop has a counter-clockwise sense of motion and shows very little change in the rate of motion of the pole during the loop. The second loop has the opposite sense of motion and displays rapid motion of the field at its onset. The motion of the field slows at the end of the second loop. This behavior can best be illustrated by VGP plots of the data.

VGP's calculated from the horizon means also show this erratic looping and dramatic movement. Two large swings of 70^{o}-80^{o} from the north geomagnetic pole are seen (figure 5). The earlier loop is approximately 20^{o}-30^{o} in amplitude and the VGP moves in a clockwise sense. The loop includes 6 horizons which appear to be evenly spaced, indicating uniform movement through the loop. A smaller loop of amplitude 10^{o} is superimposed on the larger loop. This smaller loop seems to be a period of slower motion of the field, including at least 6 horizons which are spaced quite closely. Alpha-95 values of points within these loops are typically small (2^{o}-10^{o}) making resolution of the larger loop quite good and that of the smaller loop somewhat more

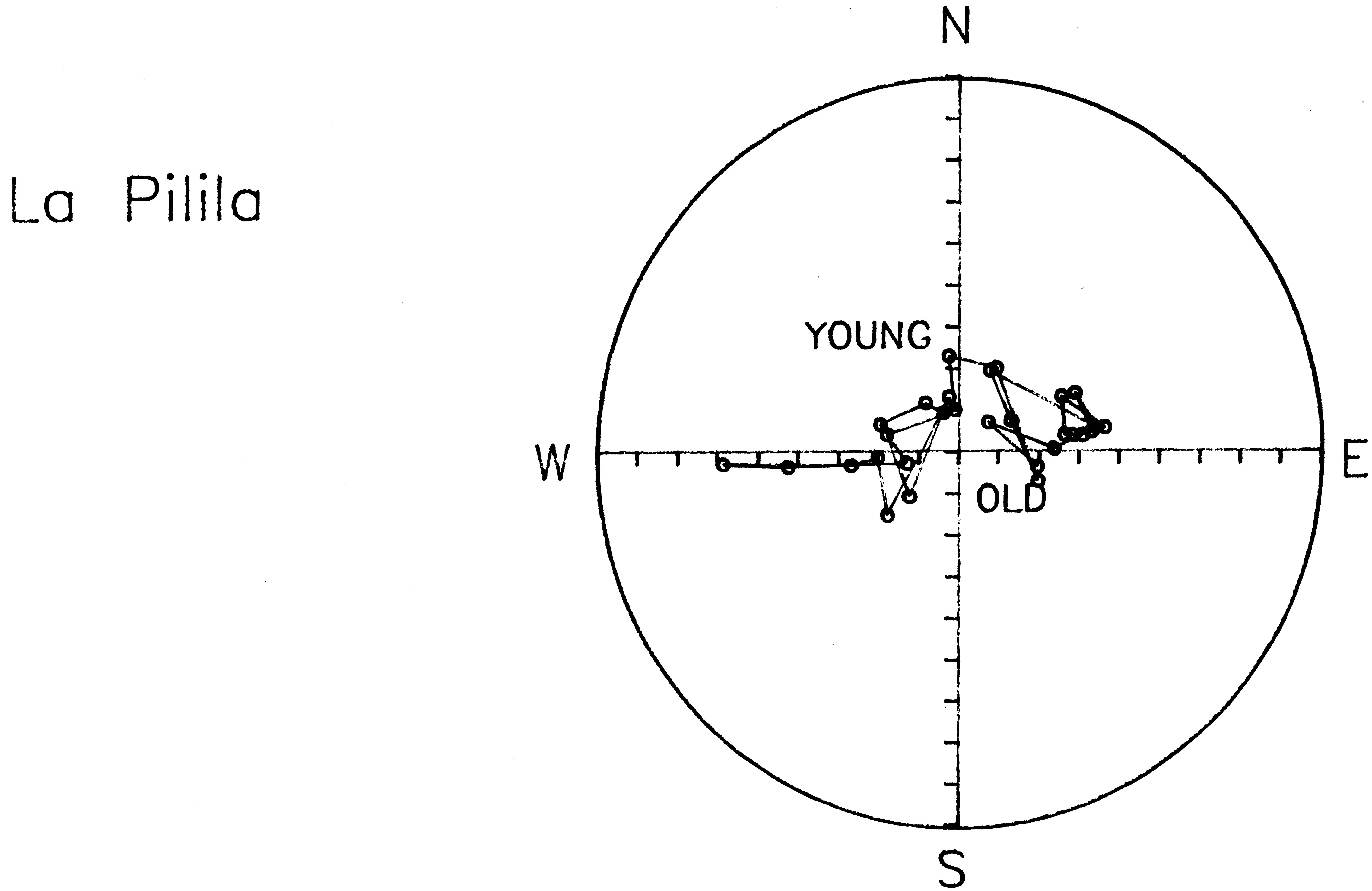


Figure 4 — La Pilila paleomagnetic directions.

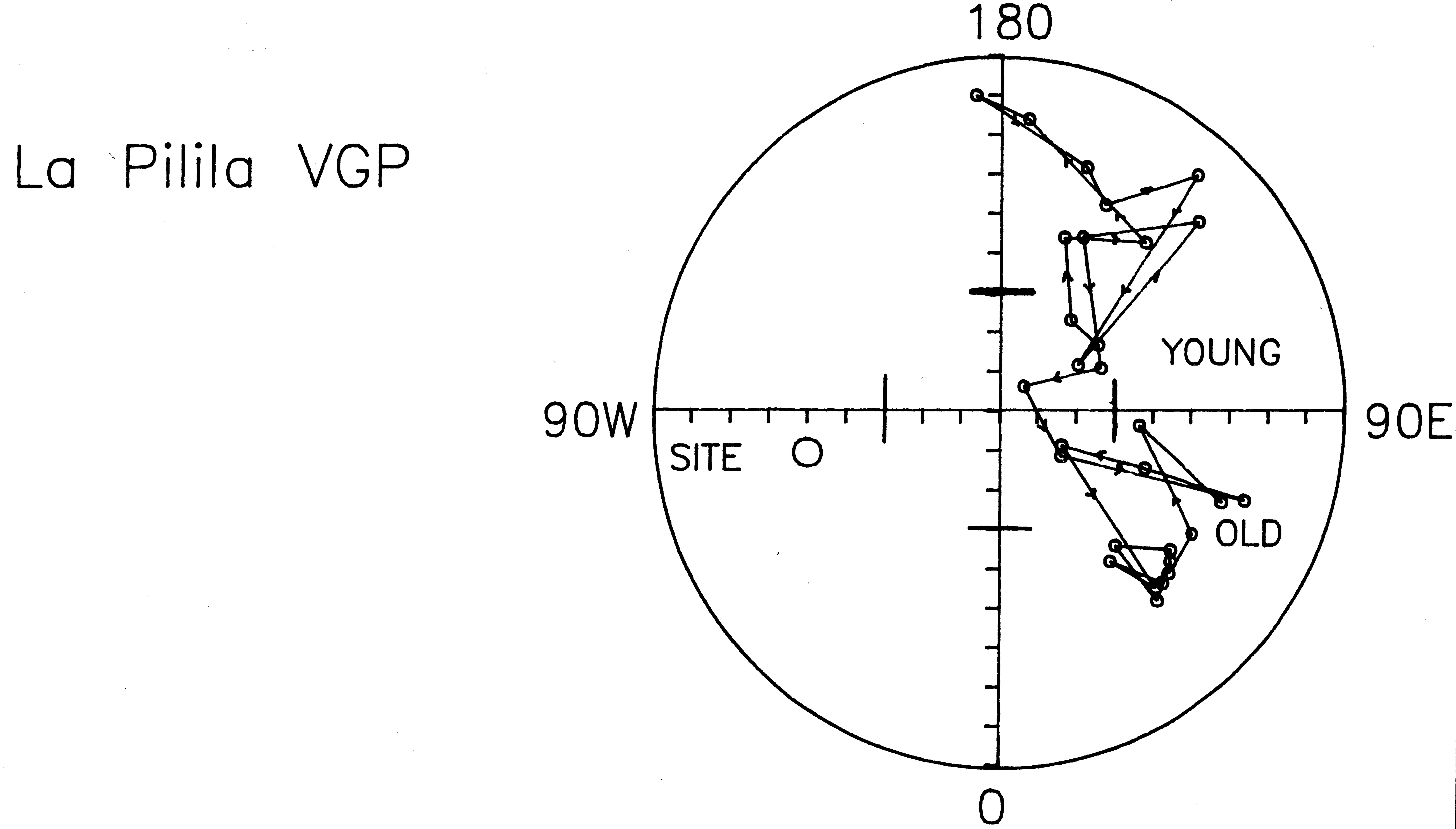


Figure 5 – La Pilila VGP locations.
Northern hemisphere projection.

difficult, but possible. The VGP then returns to the north pole.

A second, later loop within the La Pilila sediments is less circular than the earlier loop and has a counter-clockwise sense of motion. This loop is larger (approximately 30^{o}), but is less well defined than the earlier loop. Field movement during the later loop appears to be fast at the onset and during most of the loop and slows down at the very end. Alpha-95 values in the later loop are small (1.5^{o}-9^{o}), making the loop easily resolvable. The VGP then returns to the north geographic pole. VGP locations are found in the hemisphere opposite the hemisphere which contains the site longitude, indicating that they are far-sided.

Results obtained by Kodama, et al (1985b) at La Pilila show the same location and general movement of the VGP (figure 6). Kodama, et al's results (1985b) suggest a loop with a clockwise sense of motion in the VGP's from the oldest sediments. The VGP subsequently does not return to the pole as seen in this study, but does continue in a large counter clockwise loop recorded in the youngest sediments. Kodama et al (1985b) also sampled a 2 meter section of glaciolacustrine, rhythmically bedded sediments approximately 1 km away from the La Pilila Section across a small stream valley. Based on a basal conglomerate seen at both the 2 meter section and 10 meter sections, this 2 meter section is stratigraphically equivalent to the bottom 2 meters of the 10 meter section. The results from the smaller section agree, in

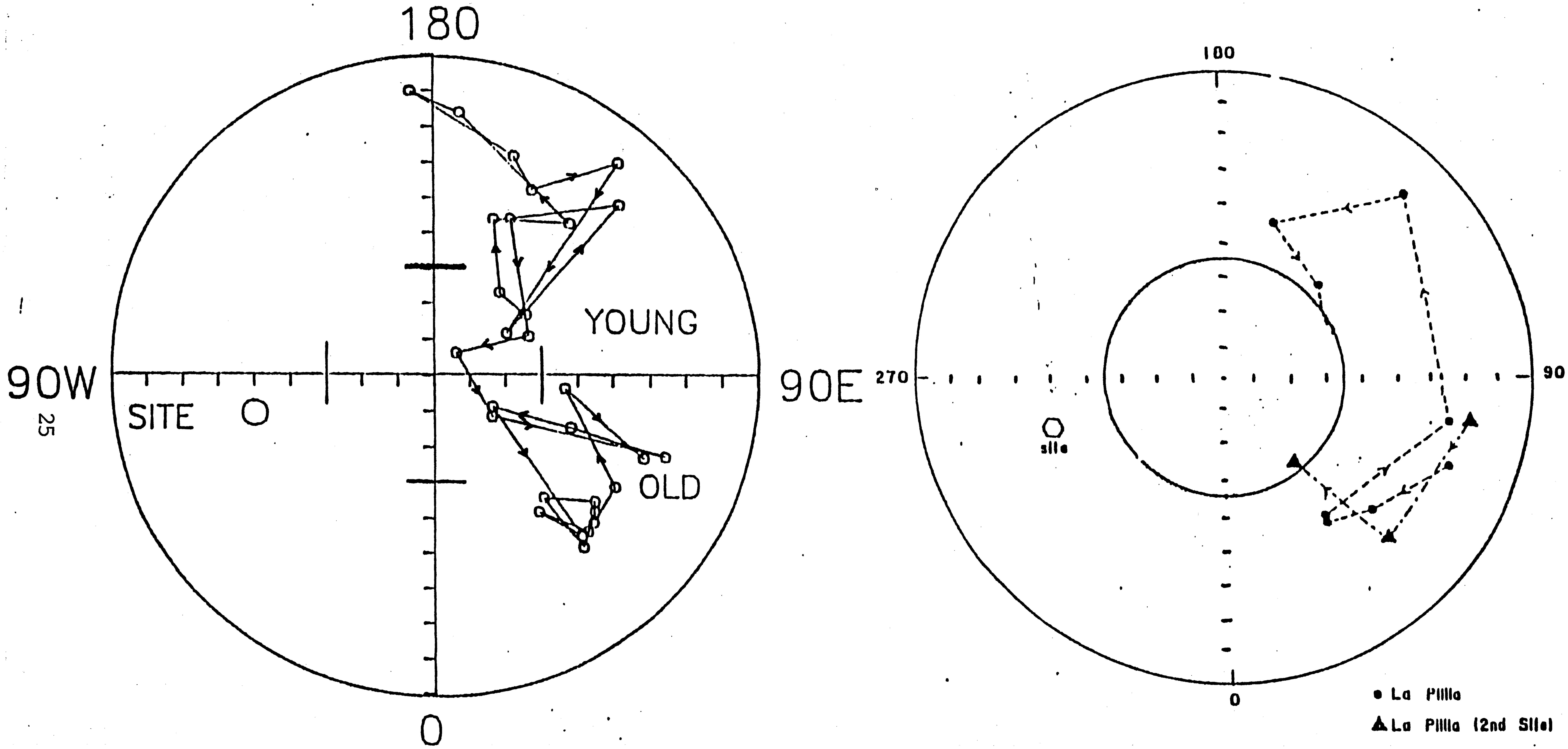


Figure 6 -VGP's from this study (left) and
from [illegible]dama (1985) (right).

general, with the results seen by Kodama et al (1985b) in the oldest part of the 10 meter section. They show anomalous VGP directions with clockwise looping of the VGP's.

Railroad Section

The sediments from the Railroad Section behaved well during alternating field demagnetization. Orthogonal projections showed univectoral decay into the origin for all samples (figure 7). NRM's were typically strong (10-100 mA/m) and had a broadly distributed coercivity spectrum with a mean destructive field of 36mT (figure 8).

Horizon means for the Railroad Section have an average precision parameter of 337.69 and an average alpha-95 confidence limit of 7.17^{o}. Variation in the amplitude of the alpha-95 vlaues is similar to that in La Pilila sediments. In cases of large alpha-95 values ($>25^{o}$), if one direction was an outlier, it was discarded. This generally improved the alpha-95 value significantly, however, one horizon's alpha-95 could not be improved to below the maximum allowable alpha-95 of 25^{o} and could not be used.

Horizon means are generally 30^{o} shallower than the expected axial dipole inclination of -60^{o} and have an average direction of -20^{o}, 330^{o} (figure 9). They do not show the looping behavior or

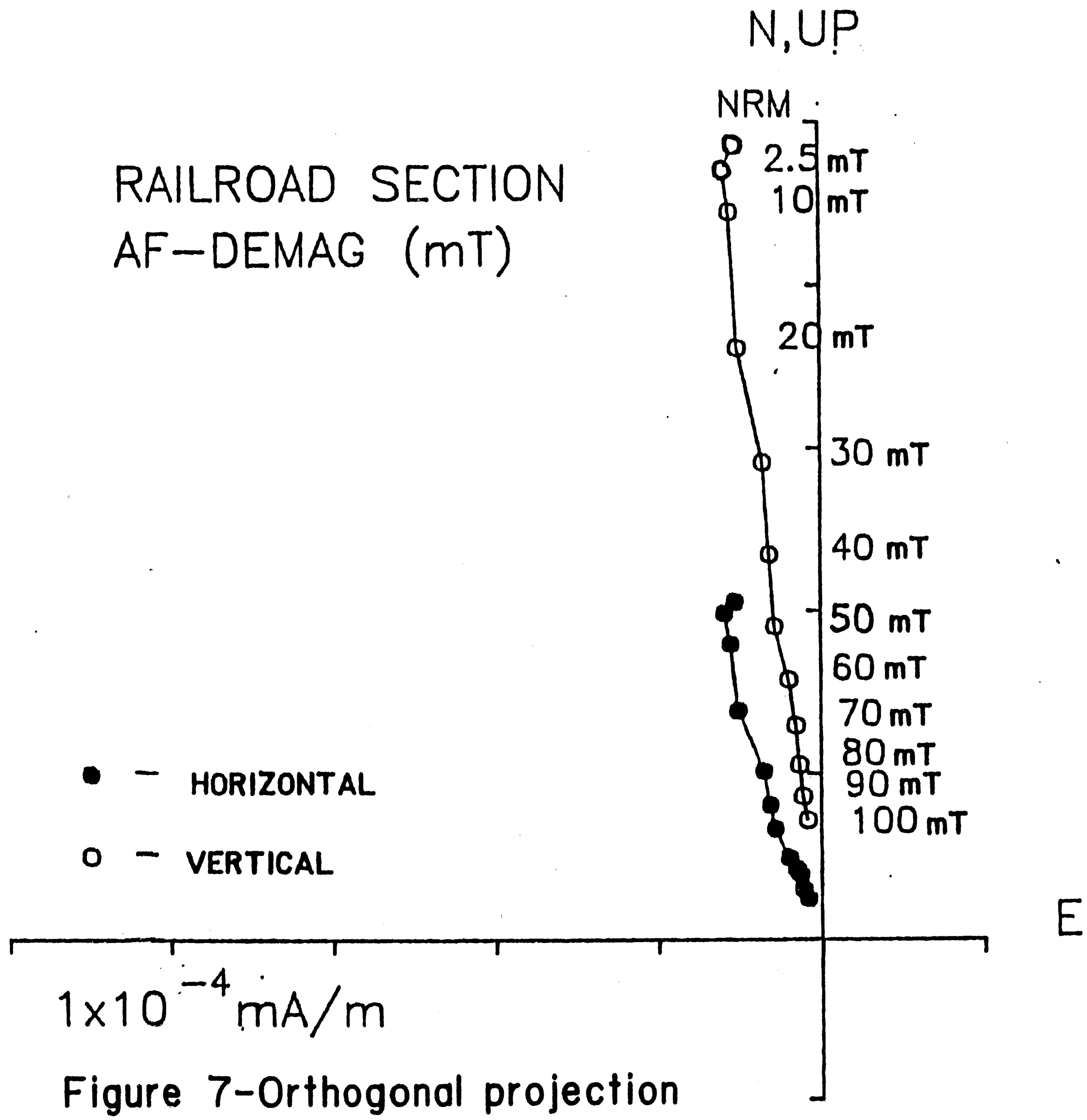


Figure 7-Orthogonal projection of Railroad sample. AF-demagnetization.

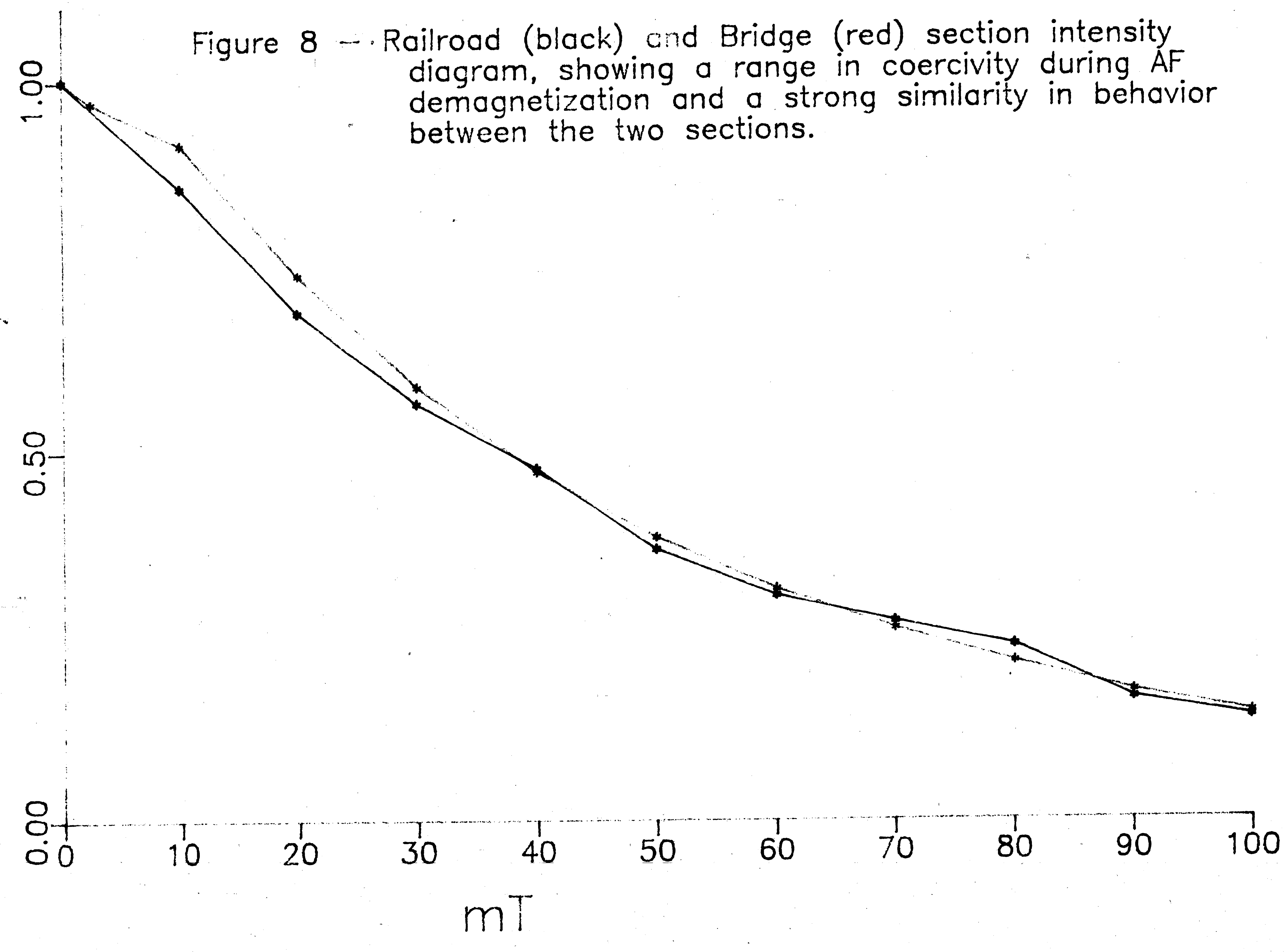


Figure 8 — Railroad (black) and Bridge (red) section intensity diagram, showing a range in coercivity during AF demagnetization and a strong similarity in behavior between the two sections.

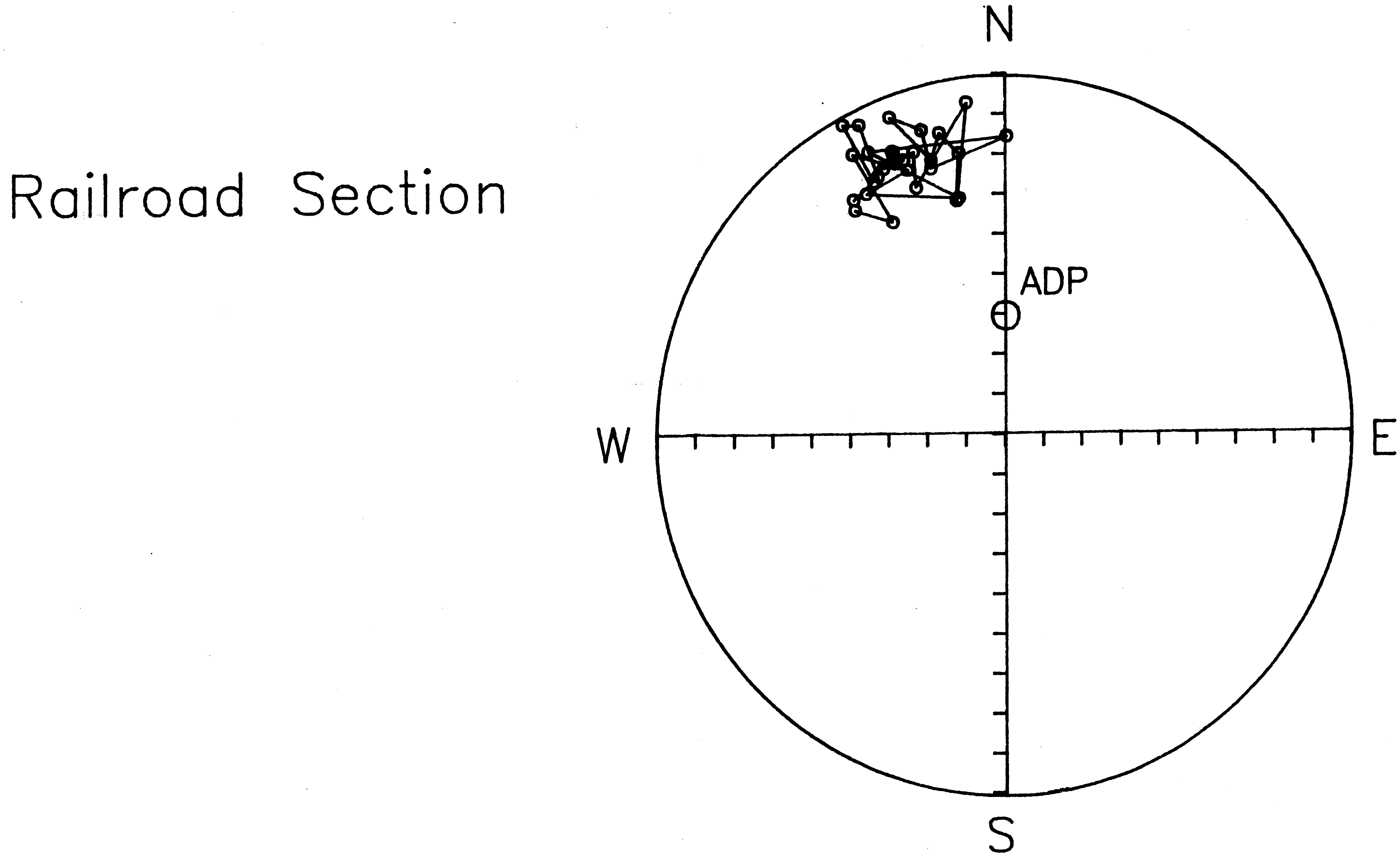


Figure 9 – Railroad section paleomagnetic directions. Upper hemisphere projection.

the variation in the speed at which the field changes which characterized the La Pilila sediment directions.

VGP's calculated from the horizon means show a cluster centered around 54.4^{o} latitude and 254.8^{o} longitude (figure 10). The VGP's indicate no dramatic movement or looping as seen in La Pilila sediments. The Railroad VGP's do show an east-west motion, but it is much less pronounced than that of the La Pilila VGP's. The precision parameter for the Railroad VGP's is 58.76 with alpha-95 confidence limit of 3.58^{o}.

As with the La Pilila Section, results obtained by Kodama (1984) closely agree with data obtained in this study. Kodama's Railroad cut VGP's (1984) plot along with this study's results and show the same east-west movement (figure 11).

Additional unpublished results obtained by Kodama (1985b) show field behavior which is characterized by large, rapid swings of the geomagnetic vector (figure 11). Six horizons were sampled, covering a stratigraphic section which included sediments earlier, synchronous, and later than Railroad sediments sampled by Kodama et al. (1985a) and this study. Two horizons, one of which is synchronous with, and one of which is younger than the Rairoad sediments have directions which coincide with those reported by Kodama et al (1985a) and this study (figure 11). The remaining four horizons are stratigraphically below the Railroad Section,

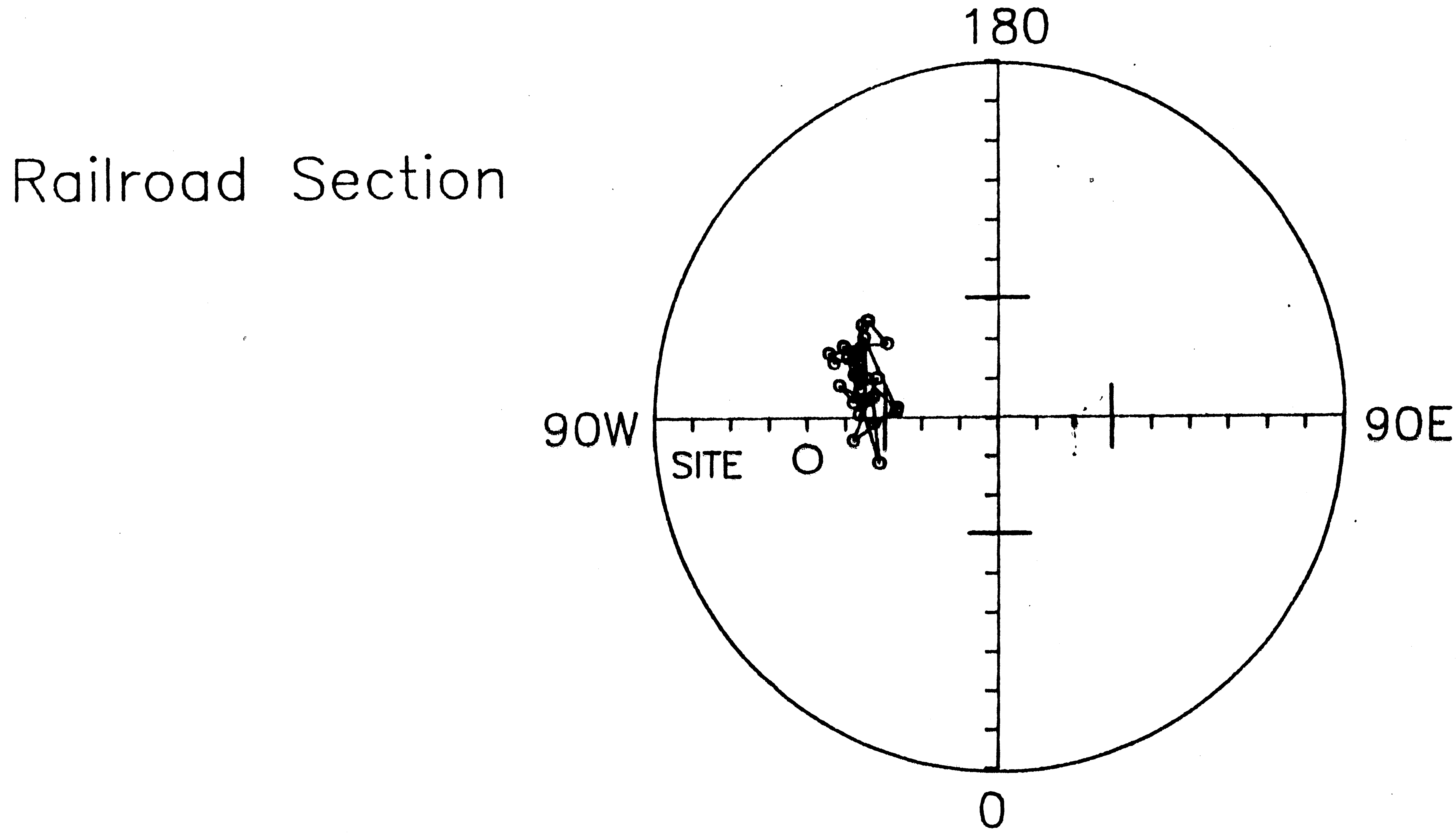


Figure 10 Northern hemisphere projection of Railroad section VGP locations.

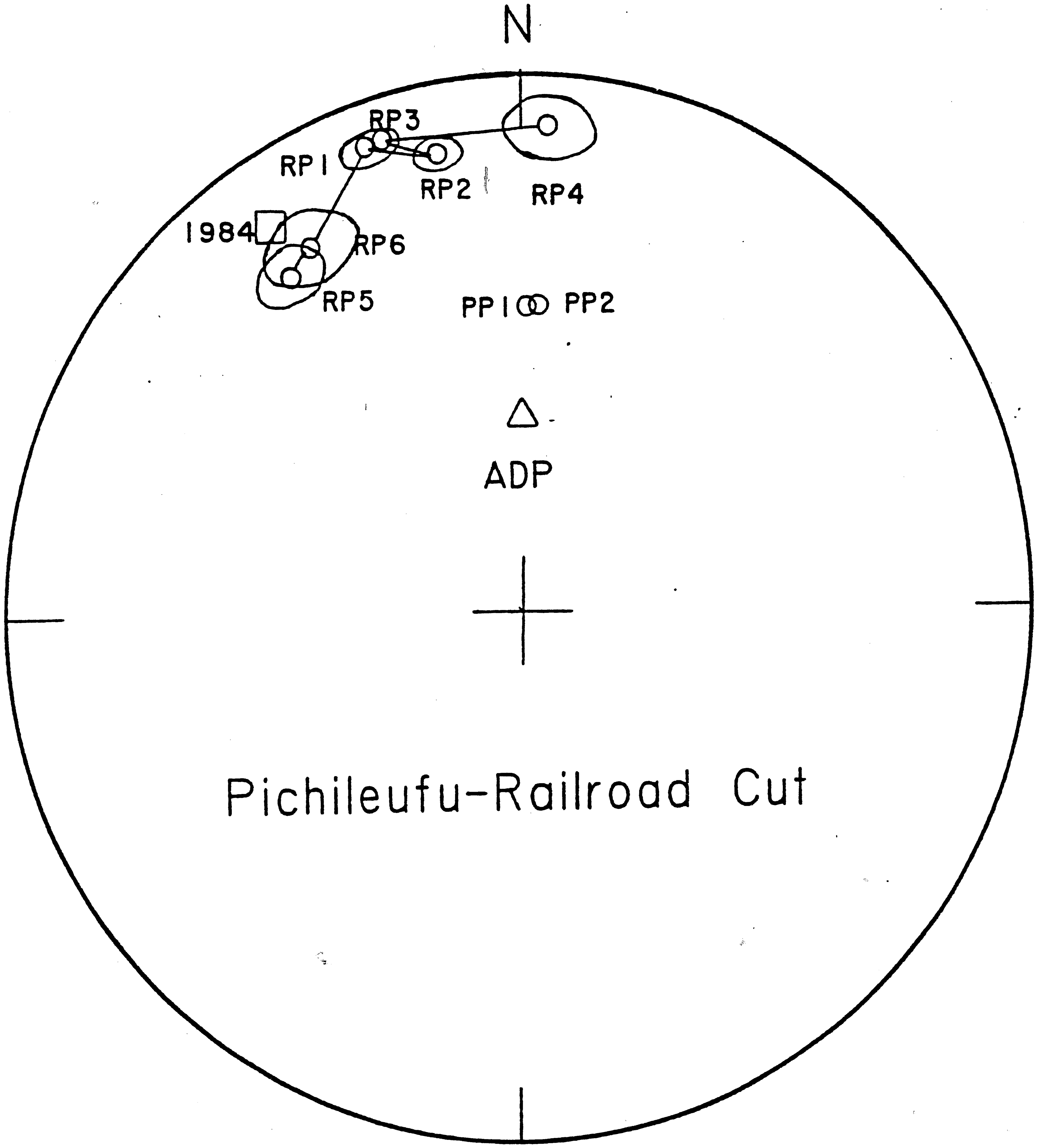


Figure 11-Railroad section paleomagnetic directions from Kodama (1984,1985) with 95% confidence limits.

but above the Bridge Section. These horizons show large movements of the geomagnetic vector with declination swings from 320° to 0° and shallow inclinations (5°-10°) (figure 11). The directions from Kodama's study (1985b) begin more toward the east than either this study or Kodama et al's 1984 study, but have shallow inclinations. The directions then swing toward those seen in the two later studies (figure 11).

Bridge Section

Bridge Section sediments show behavior identical to that of the Railroad Section sediments during alternating field demagnetization (figure 8). Orthogonal projections show univectorial decay into the origin and NRM's are strong (10-100 mA/m)(figure 12). As with other sections, the range in alpha-95 was small, however, there were outliers. If the alpha-95 confidence limit was large (>25°), outliers were discarded as discussed earlier.

Horizon means from Bridge sediments have an average precision parameter of 531.72 and an average alpha-95 confidence limit of 13.68°. VGP's calculated from horizon means show erratic behavior similar to that of La Pilila sediments (figure 14). There are no well-defined loops as seen in La Pilila sediments, however, the VGP's do show movement. VGP latitude shows a range from 59.6°N to

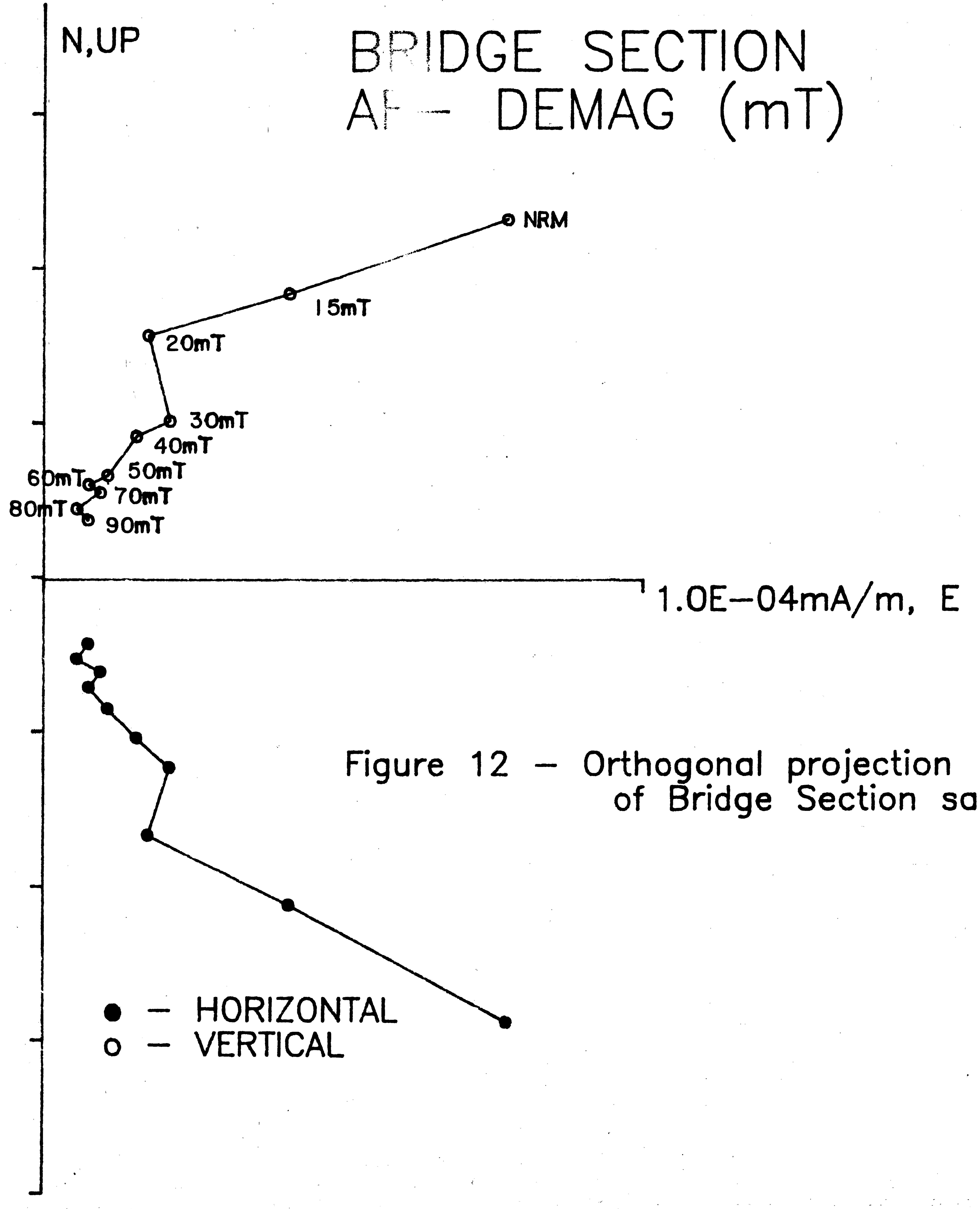


Figure 12 – Orthogonal projection of Bridge Section sample.

Bridge Section

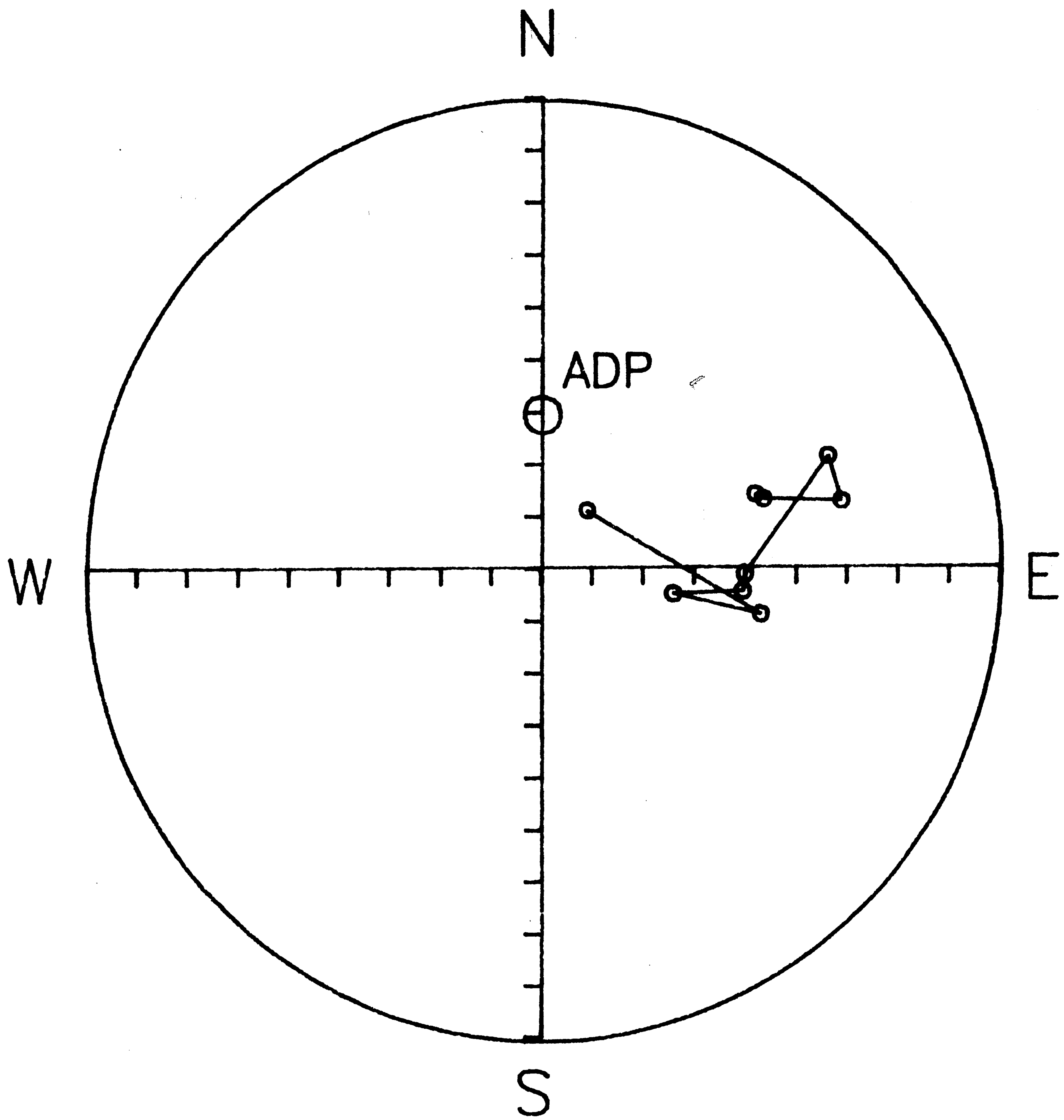


Figure 13 — Upper hemisphere projection of Bridge section paleomagnetic directions.

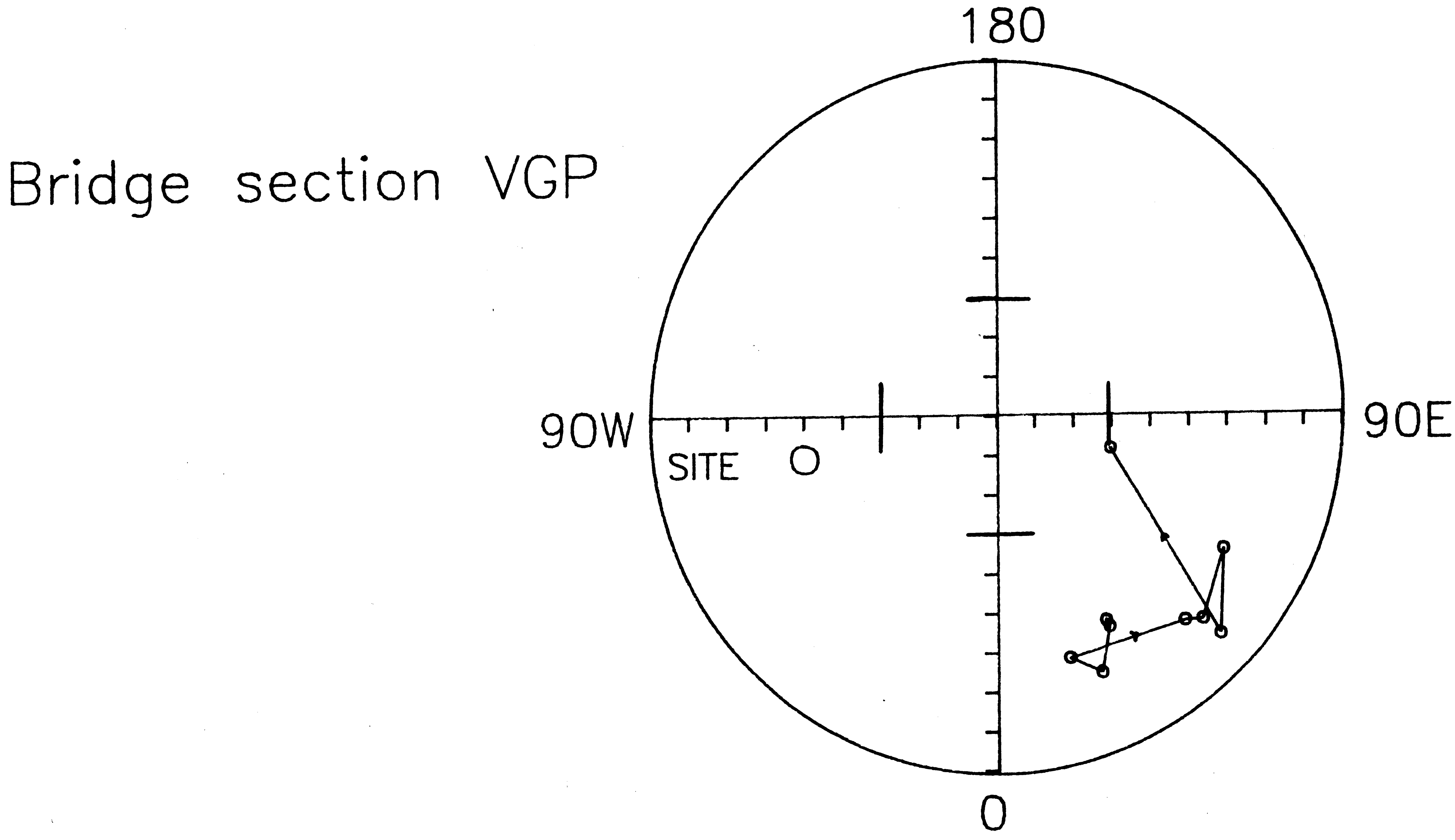


Figure 14 – Northern hemisphere projection of Bridge section VGP locations.

10.3°N. Longitude shows swings from 20°E to 80°E are seen. The Bridge Section VGP path shows strong similarities to the older portion of the La Pilila VGP path (figure 15) showing a general clockwise sense of motion. Two small loops in the Bridge Section data are not resolvable due to fairly high alpha-95 confidence limits (up to 22°), but indicate that the field slows down at these two locations. The first loop could be correlated with the first three horizons in the La Pilila VGP path and the second loop may be correlated with the loop at horizons 4-9 in the La Pilila data.

San Martin Section

During alternating field demagnetization, Samples from the San Martin sediments displayed surprisingly uniform behavior. Their magnetization was very stable, with orthogonal projections showing univectoral decay into the origin (figure 16). The average precision parameter for the horizon means is 3419.17 and the average alpha-95 confidence limit is 2.59°. There was no need to discard data from any horizon, as there were no outliers. San Martin sediments have an average direction of I=-29.8° and D=12.4° (figure 17).

Calcualted VGP's show a very tight cluster centered around 63.7° north latitude and 315.6° east longitude (figure 18). The

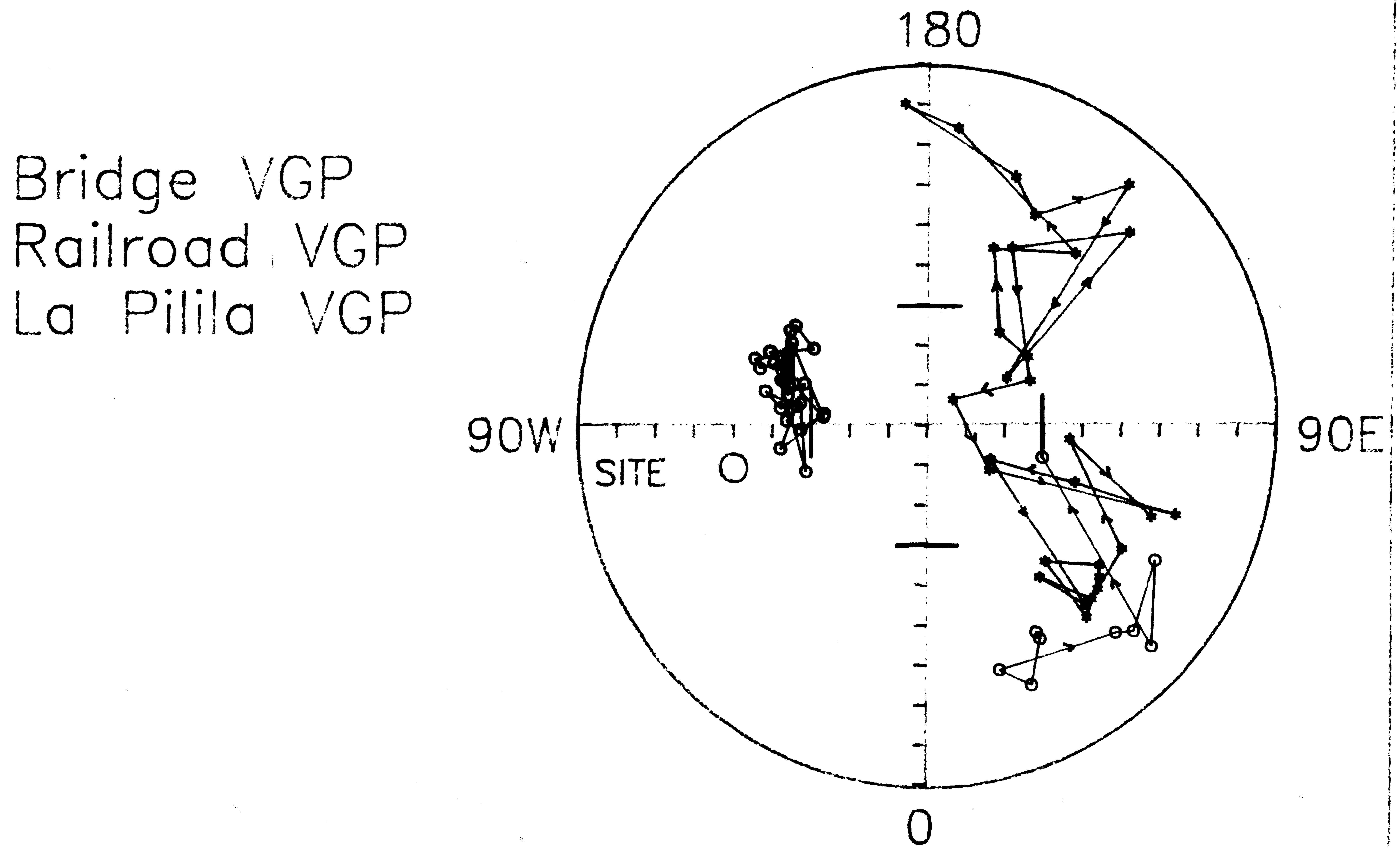


Figure 15 – La Pililo (red), Railroad (blue), and
Bridge (green) section VGP locations.
Northern hemisphere projection.

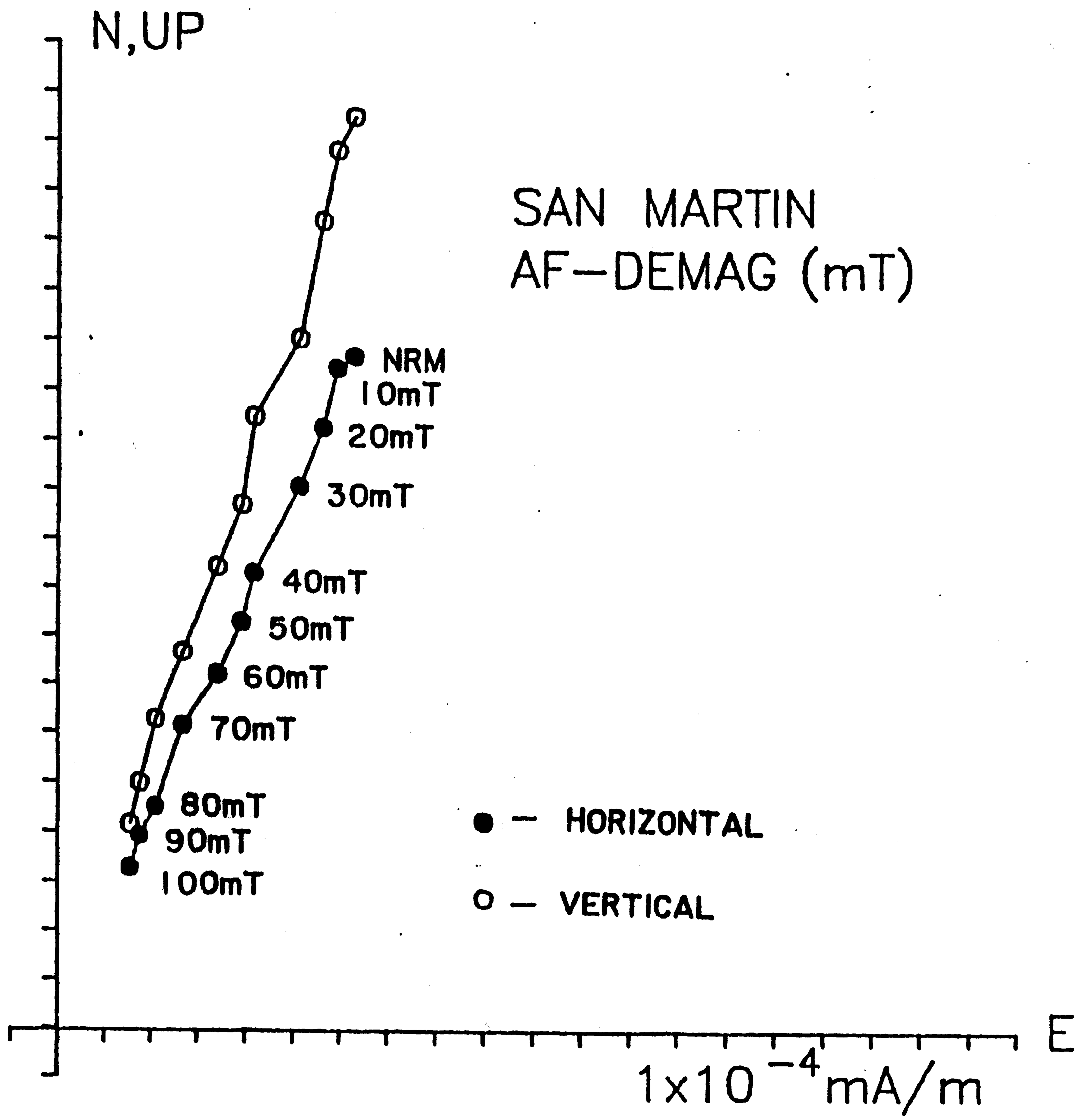


Figure 16-Orthogonal projection of San Martin sample. AF-demagnetization.

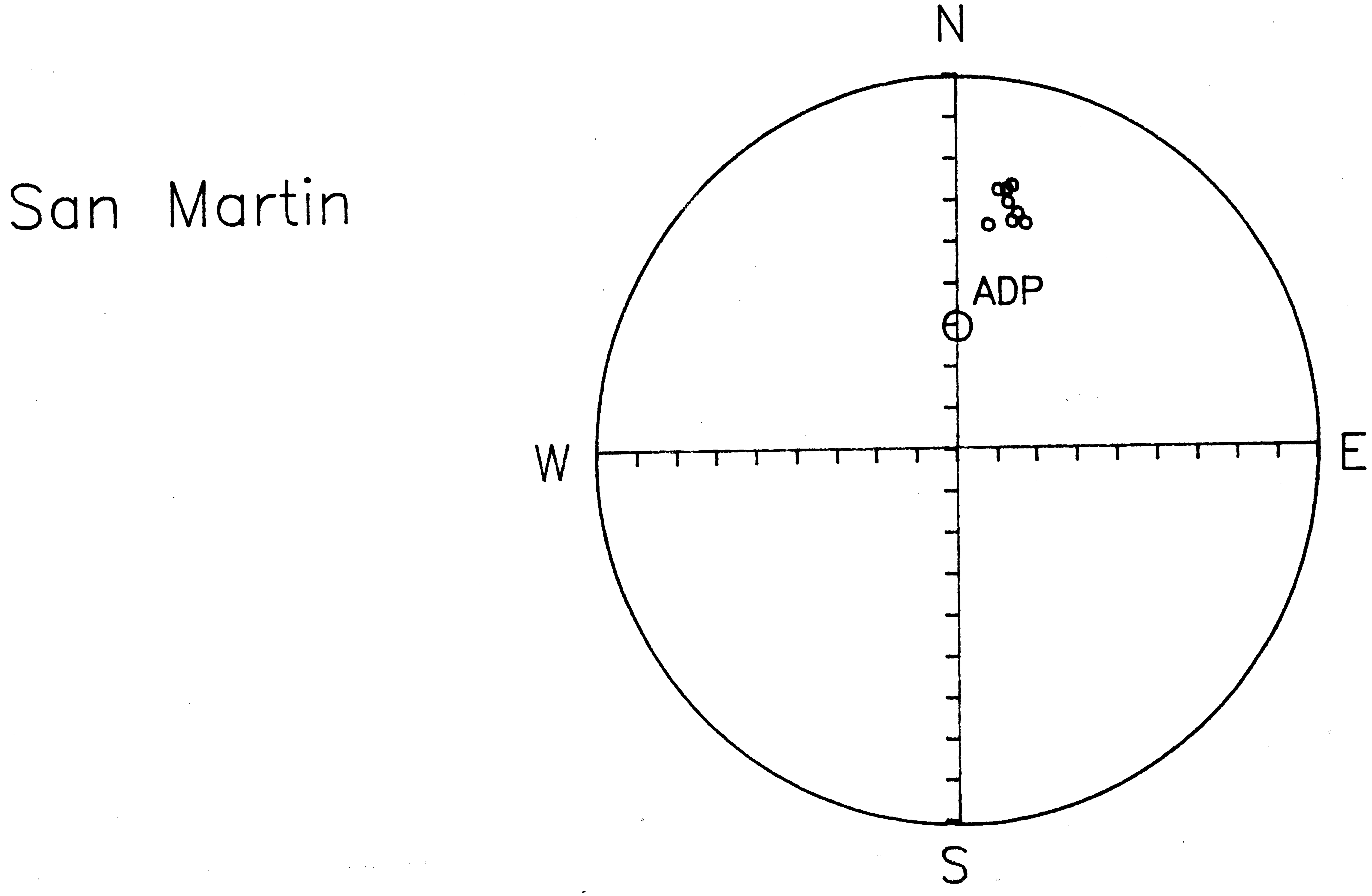


Figure 17 — Upper hemisphere projection of San Martin paleomagnetic directions.

San Martin VGP

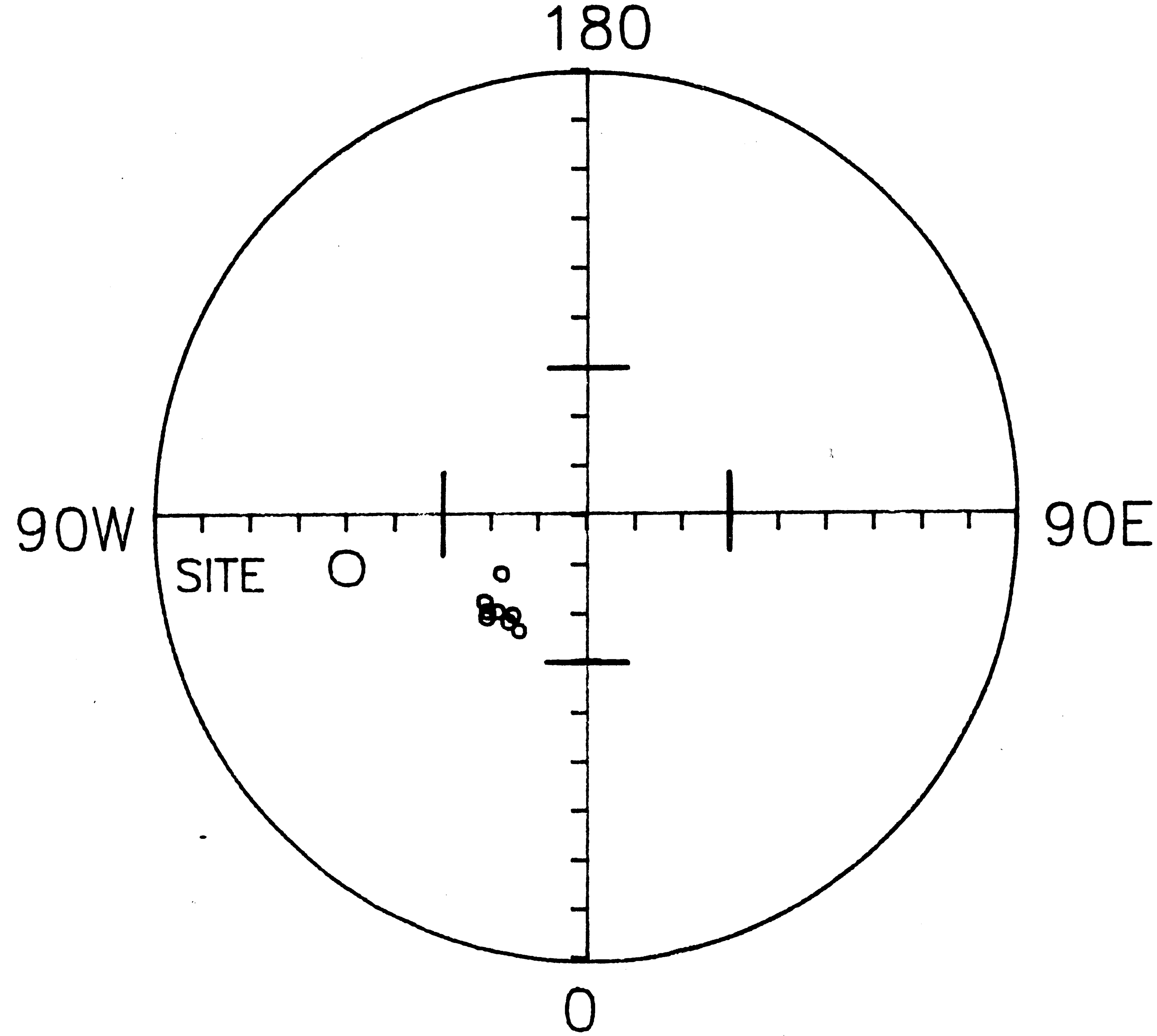


Figure 18 — Northern hemisphere projection
of San Martin VGP locations.

precision parameter for the VGP's is 353.99 with an alpha-95 confidence limit of 2.63°. There is no looping or obvious motion of the VGP's from the San Martin sediments.

Cathedral Basalt

Alternating field and thermal demagnetization produce similar results in the Cathedral basalt samples. The mean destructive field during AF demagnetization was quite low, approximately 1.5-2 mT; however, the characteristic magnetizations, when resolvable, were carried by grains with coercivities of 2.5 to 100 mT. Approximately 90% of the magnetization was removed by thermal demagnetization temperatures of 540°C. and the characteristic magnetizations were carried by grains with unblocking temperatures of 300 to 540°C. Four of seven samples were long enough to allow AF and thermal demagnetization of a specimen from each sample. In only 1 case did AF and thermal demagnetization of specimens from the same sample allow resolution of characteristic magnetizations (figure 19). In this case the characteristic magnetizations were within 5° of each other. In general, neither AF nor thermal demagnetization provide better results. Because of this, two of the remaining samples were AF demagnetized and one was thermally demagnetized. Of the seven samples, only three allowed resolution of characteristic magnetizations. VGP's calculated from these directions show low latitudes (ave.=13.1° S.) and westerly longitudes (ave.=281.7° E.) (figure 20). These nearly equatorial

Figure 19 – Orthogonal projection of Cathedral Basalt sample. AF-demagnetization.

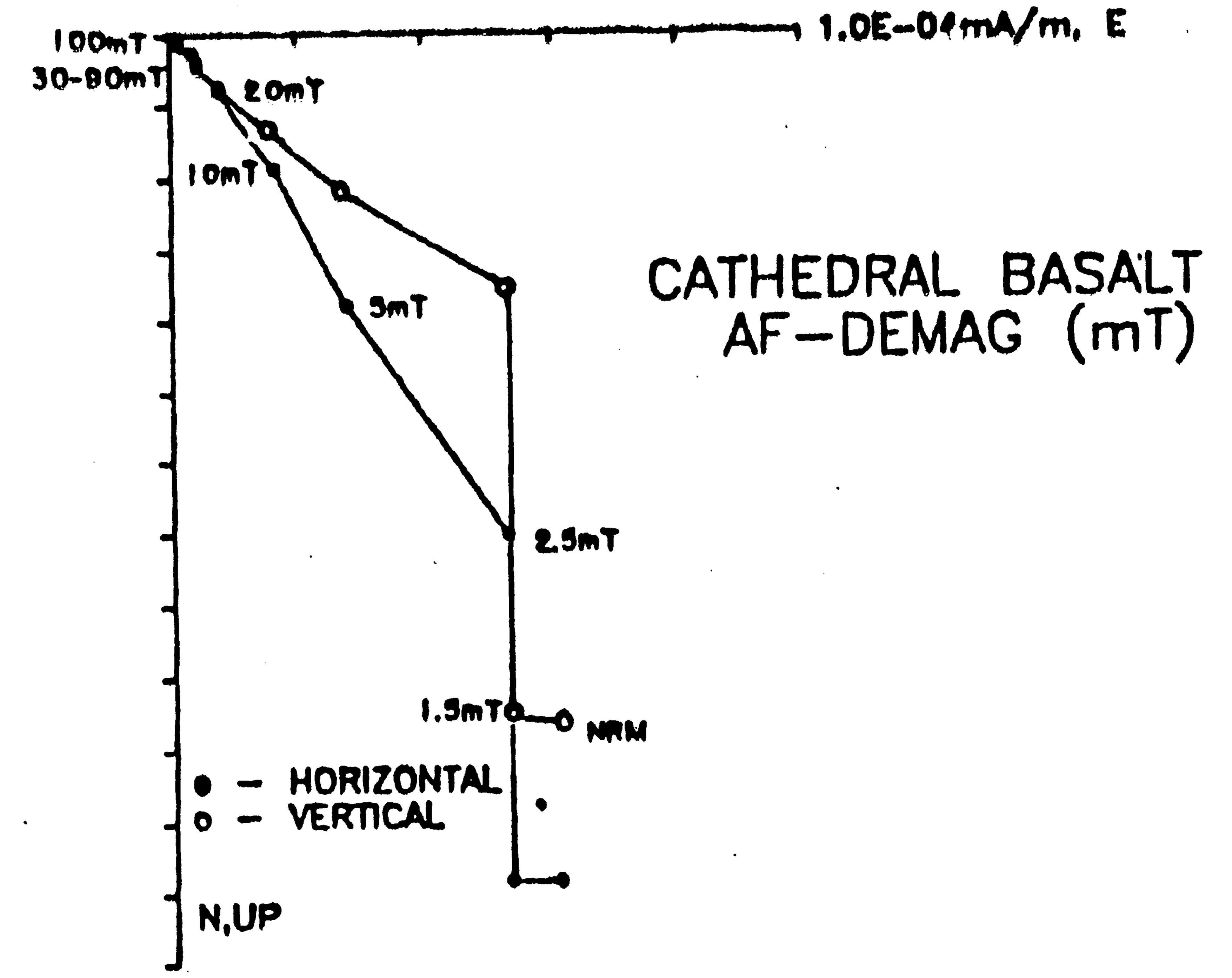
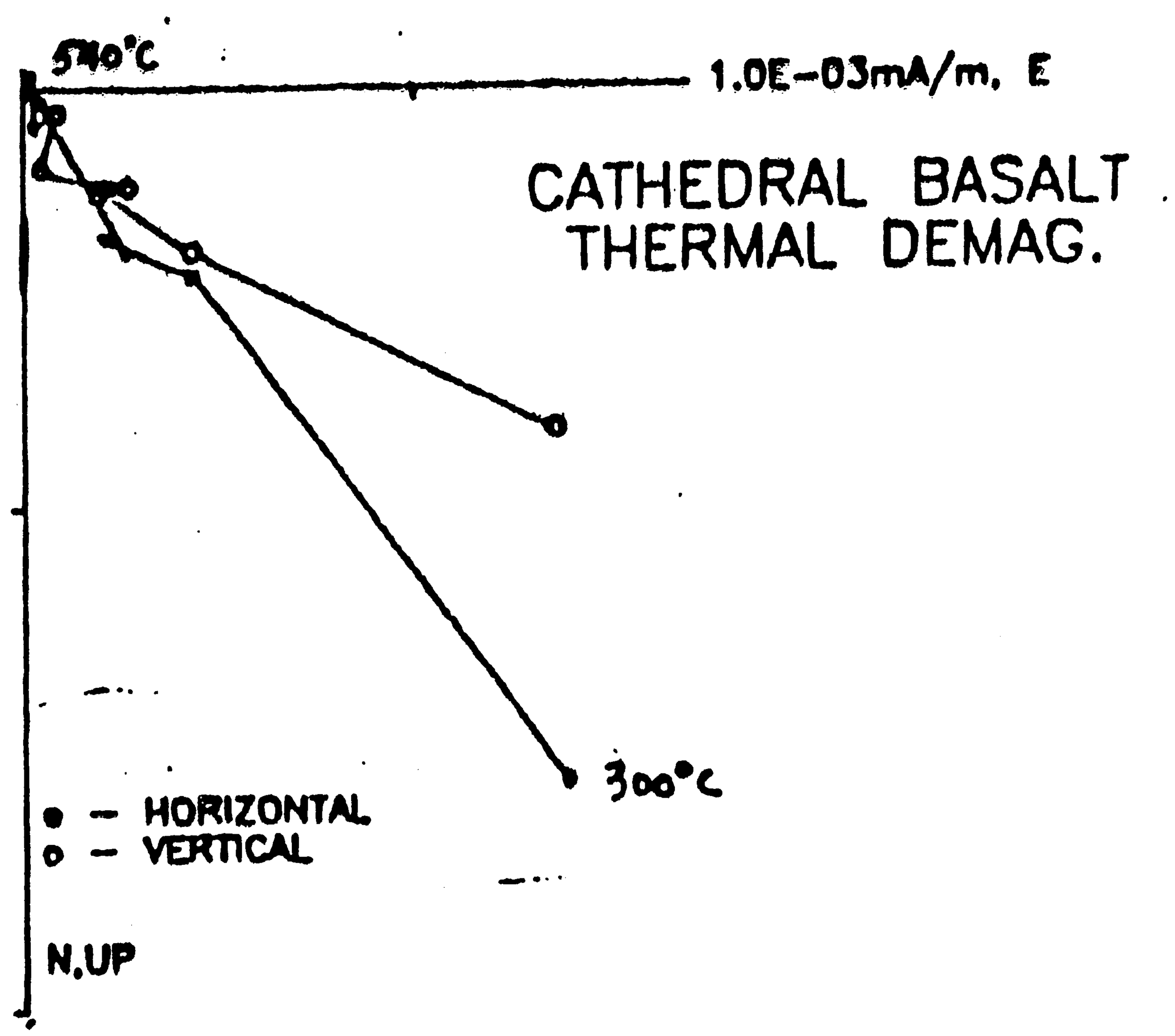


Figure 19 – Orthogonal projection of Cathedral Basalt sample. Thermal demagnetization.



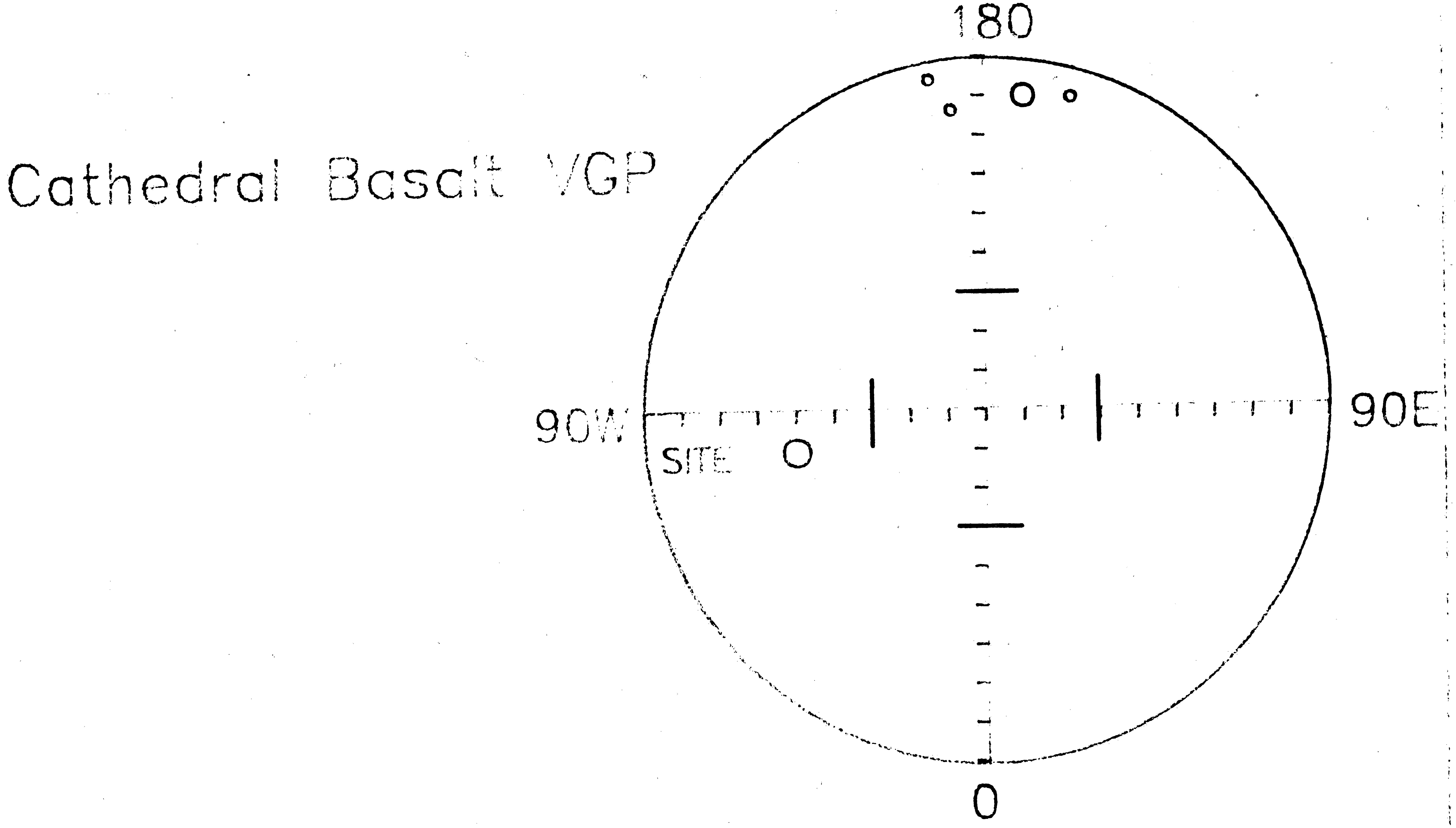


Figure 20 -- Catherdral Basalt VGP locations with unpublished location from Kodama (1985) in red.

VGP's are very near to the extreme part of a a large swing in the younger portion of the La Pilila VGP path (figure 21). The three VGP's obtained by this study may be combined to the four VGP's obtained by Kodama et al (1985b) to provide a mean VGP for the Cathedral Basalt of 9.9^{o} N, 181.59^{o} W.

Relative Paleointensity by ARM Normalization

Results from the relative paleointensity study performed on La Pilila, Railroad, and Bridge sediments are shown in figure 22. AF demagnetization of ARM in samples from each section provide results similar to AF demagnetization of NRM in samples from the same sections (figure 22). The average normalized intensity value (NRM/ARM) for La Pilila and Bridge sediments is 0.270 while that of the Railroad sediments is 0.598. The averages are unitless, as they are obtained by normalizing NRM with ARM.

A plot of relative intensity verses stratigraphic position (figure 23) shows that the the paleointensities of both the La Pilila and Bridge Section sediments are less than the paleointensity of the Railroad Section sediments. This strengthens the correlation between the early La Pilila and Bridge Section sediments. The standard deviation of the curve is 0.246, with a variance of 0.060.

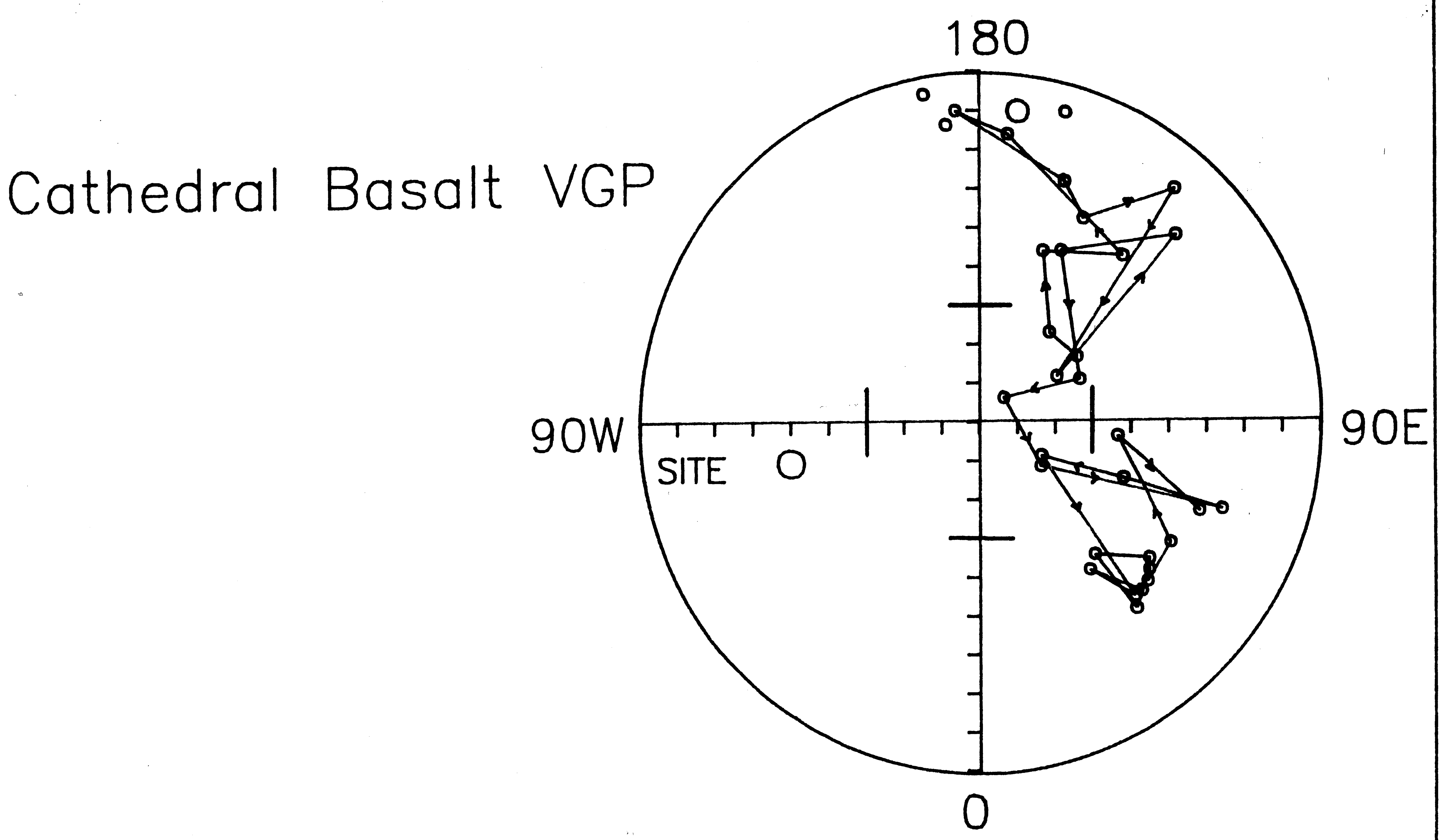


Figure 21 – Coincidence of La Pilila and Cathedral basalt VGP locations. Unpublished results from Kodama (1985) in red.

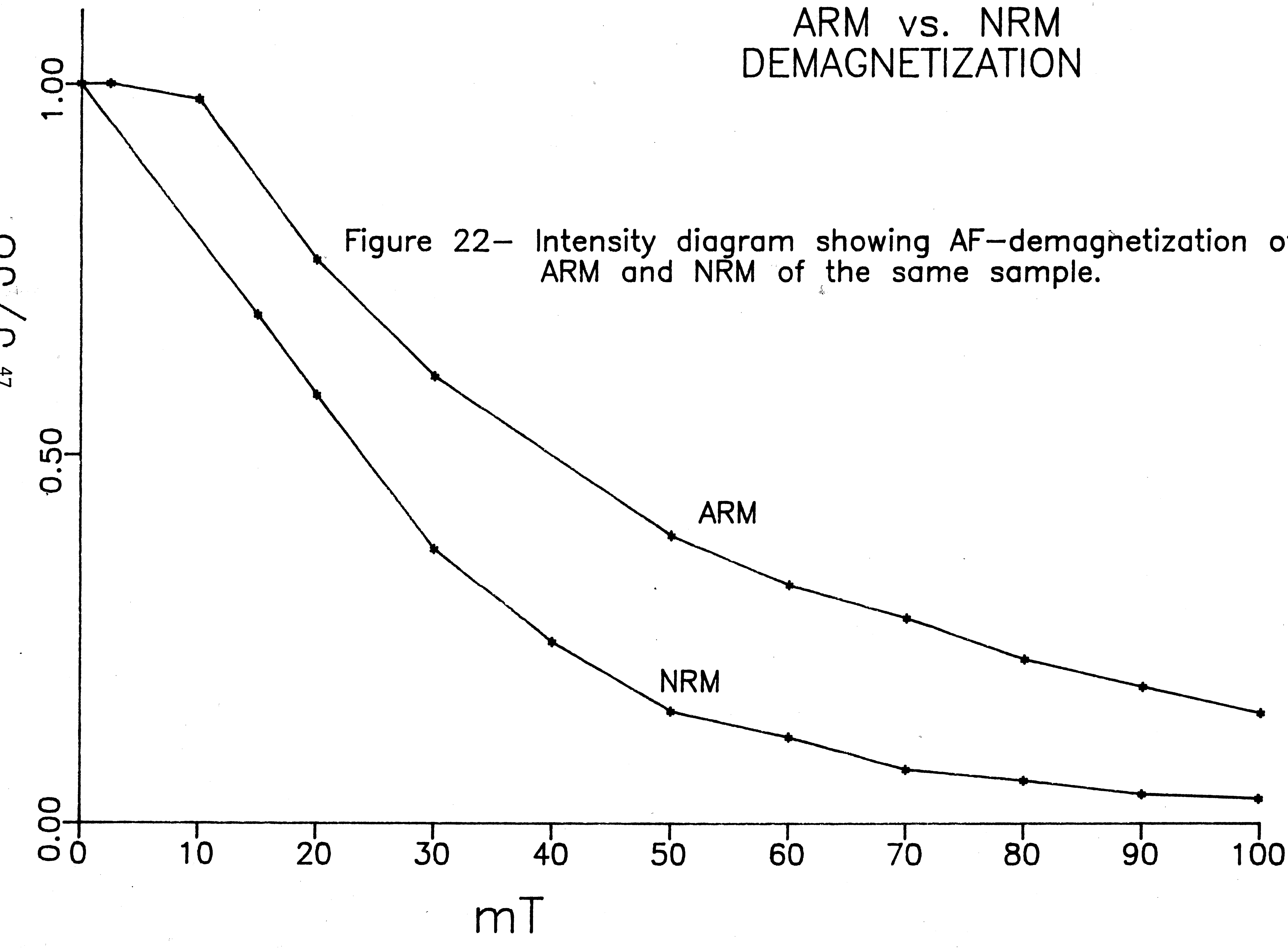


Figure 22– Intensity diagram showing AF–demagnetization of ARM and NRM of the same sample.

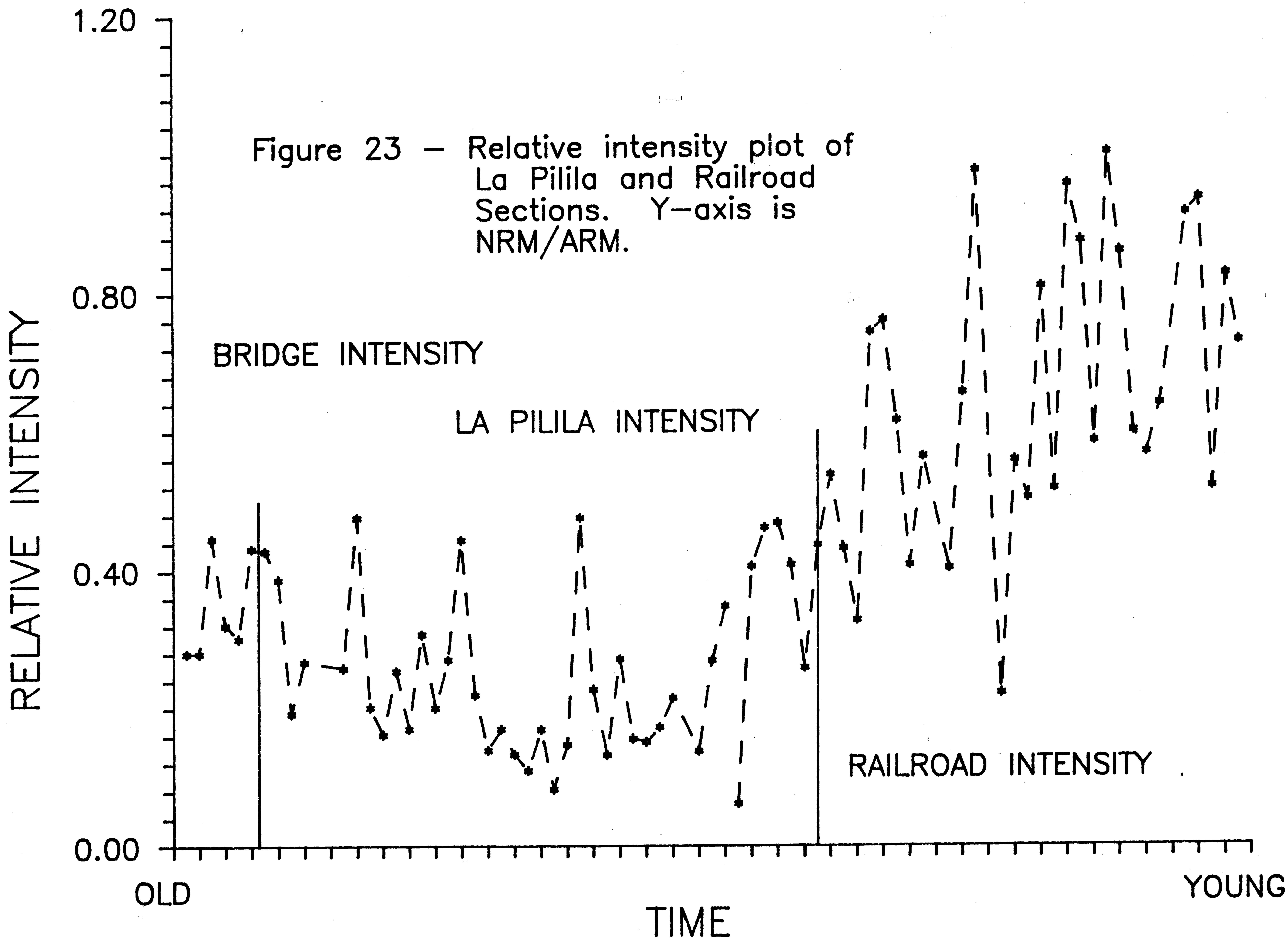


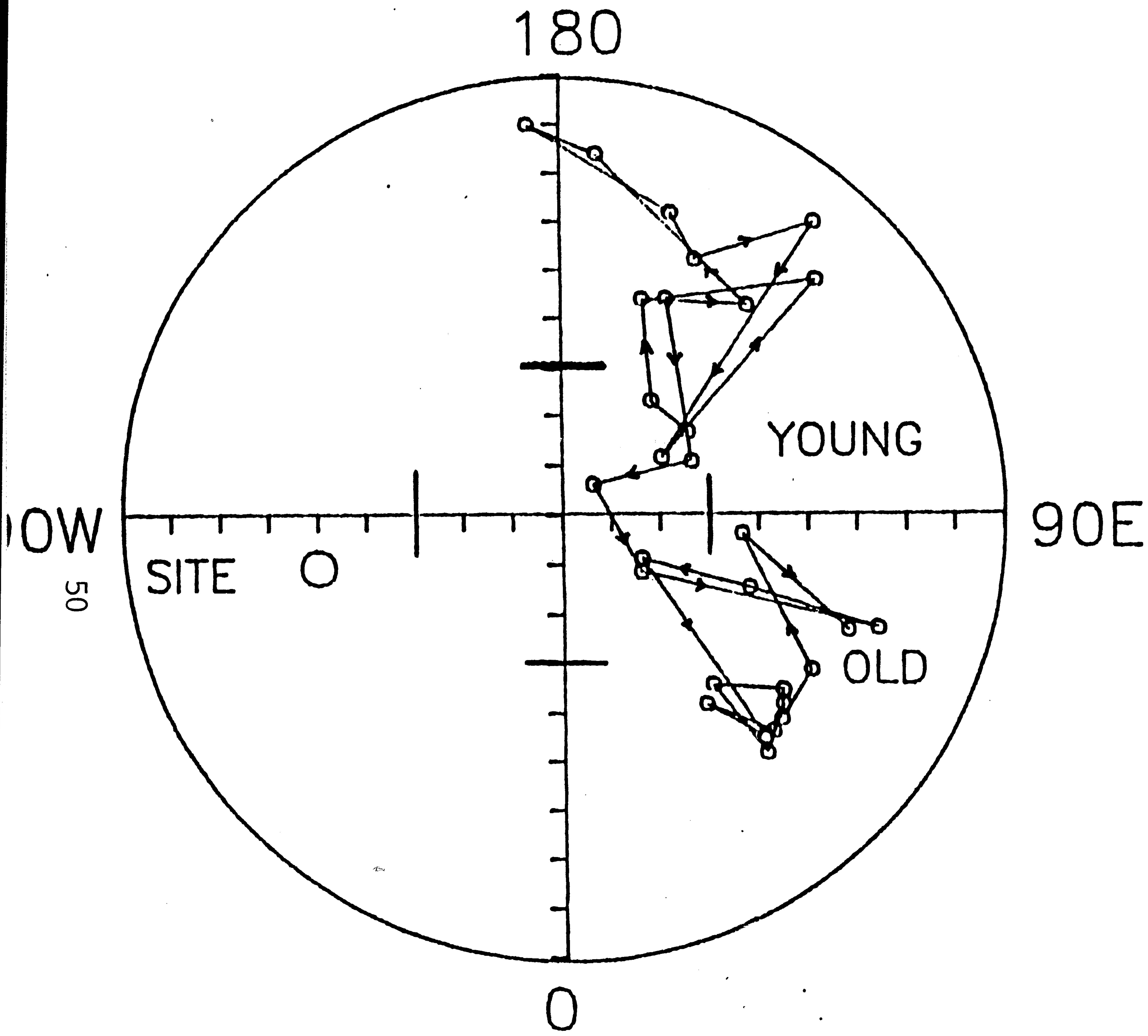
Figure 23 – Relative intensity plot of La Pilila and Railroad Sections. Y–axis is NRM/ARM.

DISCUSSION

La Pilila

Our paleomagnetic results show that the La Pilila and Bridge cut sediments record high amplitude secular variation. Its amplitude is far greater than the normal range of secular variation (30^{o}) which is assumed to be 2 standard deviations of the global data set for this latitude ($40^{o}S$) (Merrill and McElhinny, 1983). The variation at La Pilila is not thought to be due to any sedimentological or sampling effect, rather, it is attributed to geomagnetic field variation during the deposition of La Pilila sediments. The best evidence for this comes from the two meter section (Kodama, 1985b) stratigraphically equivalent to the bottom of the 10 meter La Pilila Section. The results from these sections both show anomalous field directions and agree with each other within the range of the alpha-95 confidence limits (figure 24).

This anomalous geomagnetic field behavior could either be an excursion of the geomagnetic field or a portion of a polarity reversal. For this paper we will consider an excursion to be an aborted polarity transition (Hoffman, 1981). Several authors suggest certain criteria which must be met in order to consider anomalous behavior to be a geomagnetic excursion/transition. The most commonly cited criterion is that a paleomagnetic field



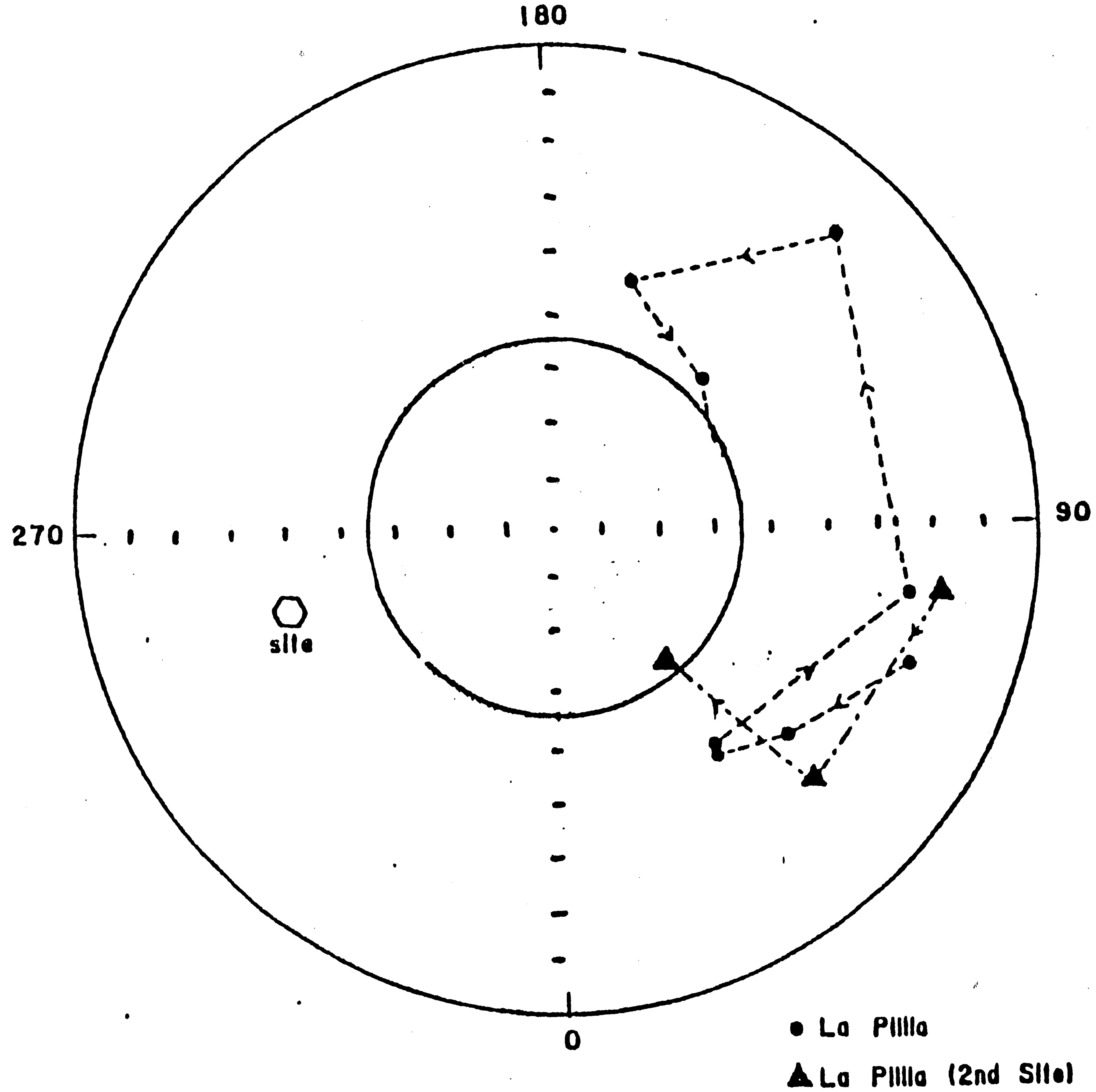


Figure 24-VGP's from this study (left) and from Kodama (1985) (right).

excursion/transition is a swing of the VGP of more than 40^{o} from the geographic pole, followed by a return of the Earth's field to one of two regular polarity states (Barbetti and McElhinny, 1976). Other types of behavior characteristic of geomagnetic excursion/transitions are noted by Doell and Cox, 1972; Hoffman, 1981; Merrill and McElhinny, 1983; and Barbetti and McElhinny, 1976. These include erratic directional movement, looping, and a reduction in remanence intensity associated with large directional motion followed by a return to regular field intensities after the excursion/transition (Hoffman, 1981; Doell and Cox, 1972; Merrill and McElhinny, 1983; Barbetti and McElhinny, 1983). Barbetti and McElhinnny (1976) also note that excursions/transitions which occur/begin during normal polarity behavior, almost exclusivly display far-sided VGP behavior. Simply stated, this means that VGP's associated with these excursions/transitions are generally found on the hemisphere opposite that which is centered around the sampling site longitude (Hoffman, 1981). This observation appears to independent of the hemisphere in which the data is collected (Barbetti and McElhinny, 1976).

La Pilila sediments clearly meet these criteria for geomagnetic excursions/transitions. La Pilila sediments record VGP's well over 40^{o} from the geographic pole (figure 5). VGP's from the La Pilila and Bridge cut sediments show dramatic movement and looping and when compared to the results from the Railroad cut sediments, which do not show this dramatic field movement, the La

Pilila and Bridge cut sediments display reduced paleointensities. Finally, La Pilila VGP's clearly display the far-sided behavior seen in excursions/transitions associated with a normal polarity field (Hoffman, 1981).

There are, however, some problems when the paleomagnetic behavior observed at La Pilila is considered a record of an excursion or transition of the Earth's field. Many authors (Doell and Cox, 1972; Merrill and McElhinny, 1983; Barbetti and McElhinny, 1976; Hoffman, 1981) cite uncertainties with sediment-recorded excursion or transitions. The possibility for recording inaccuracies is higher in sediments due to depositional error, such as inclination shallowing (Verosub, 1977), and/or reworking and micro-deformations of the sediments. Several observations suggest that the La Pilila and Railroad sediments are not plagued by these problems. The fresh nature, continuity of beds, AMS results (Kodama et al, 1985a) which show that Railroad Section sediments' depositional fabric is a primary fabric, and within horizon agreement between sample directions suggests that there has been no reworking of the sediments. The redeposition experiments done by Kodama et al (1985a) which indicate that these sediments are capable of recording steep inclinations, suggest that the Railroad sediments' record of the geomagnetic field is accurate. Because the magnetic behavior, as well as the appearance, of La Pilila sediments are very similar to the Railroad cut sediments, we suggest that these results are also indicative of the depositional fabric of the La Pilila sediments.

Railroad, Bridge, Section Results.

Unlike the La Pilila Section, the Railroad Section sediments record VGP's which are just at the edge of the accepted range for secular variation of 30^{o} at 40^{o} latitude, and display near-sided behavior (figure 10). The pole appears to have been at a still stand during the deposition of these sediments as evidenced by the tight grouping of VGP's. Results obtained by Kodama (1985a and 1986) agree with this interpretation.

Results obtained by Kodama et al. (1985b) from horizons stratigraphically below the Railroad Section, but above the Bridge Section, show a moderate swing in declination (30^{o}) (figure 11) from north to northwest. This directional movement is similar in character to that seen in the La Pilila sediments. There is, however, no coincidence between these directions and the La Pilila or Bridge directions.

The Bridge Section sediments, on the other hand, show the rapid movements seen in the La Pilila sediments. Relative paleointensity data available for these samples show reduced field intensities with respect to the Railroad sediments. The importance of the Bridge Section results is in their relationship to results from the La Pilila section. The VGP path of Bridge

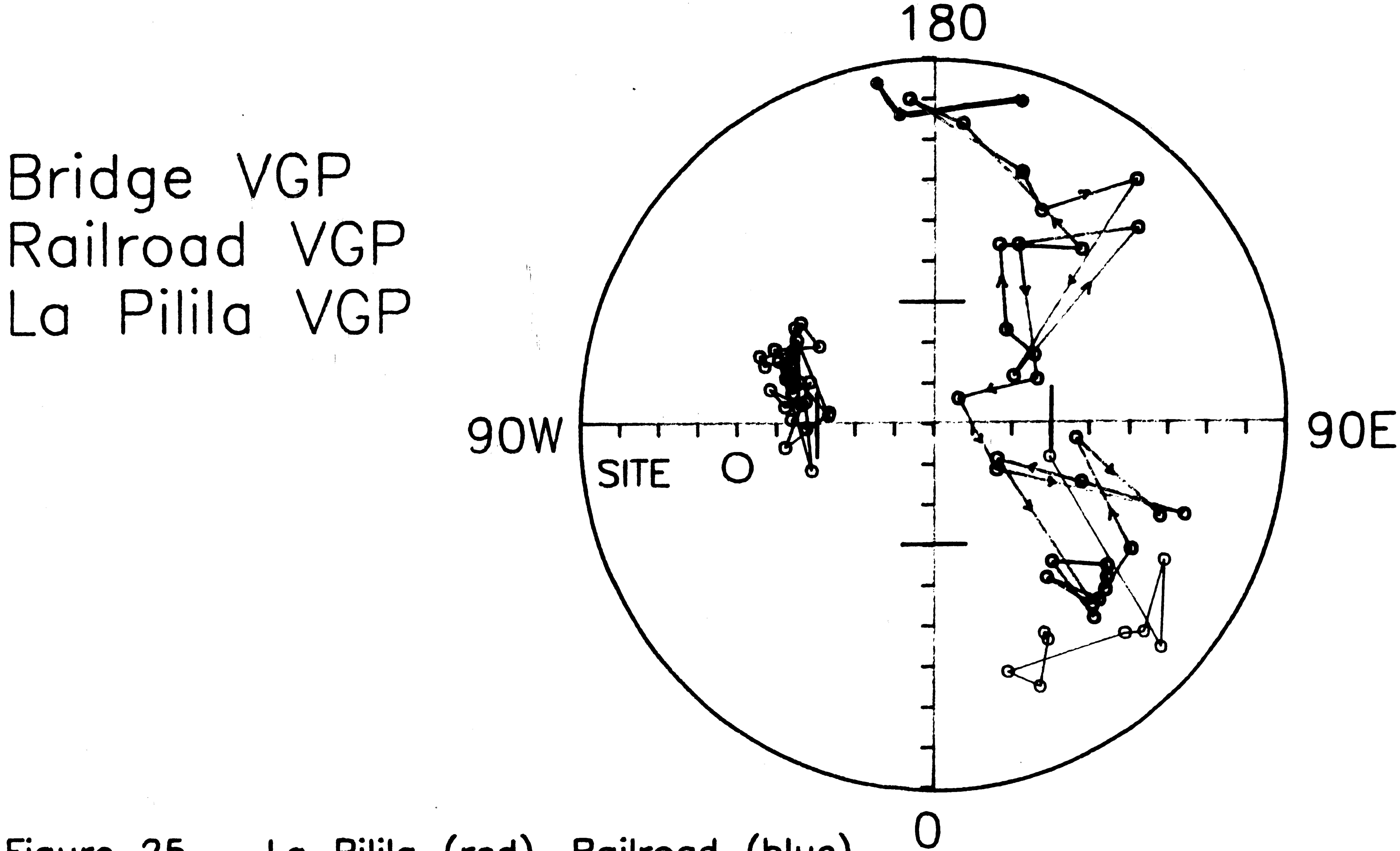


Figure 25 – La Pilila (red), Railroad (blue), Bridge (green), and Cathedral Basalt (purple) VGP projection. Northern hemisphere projection.

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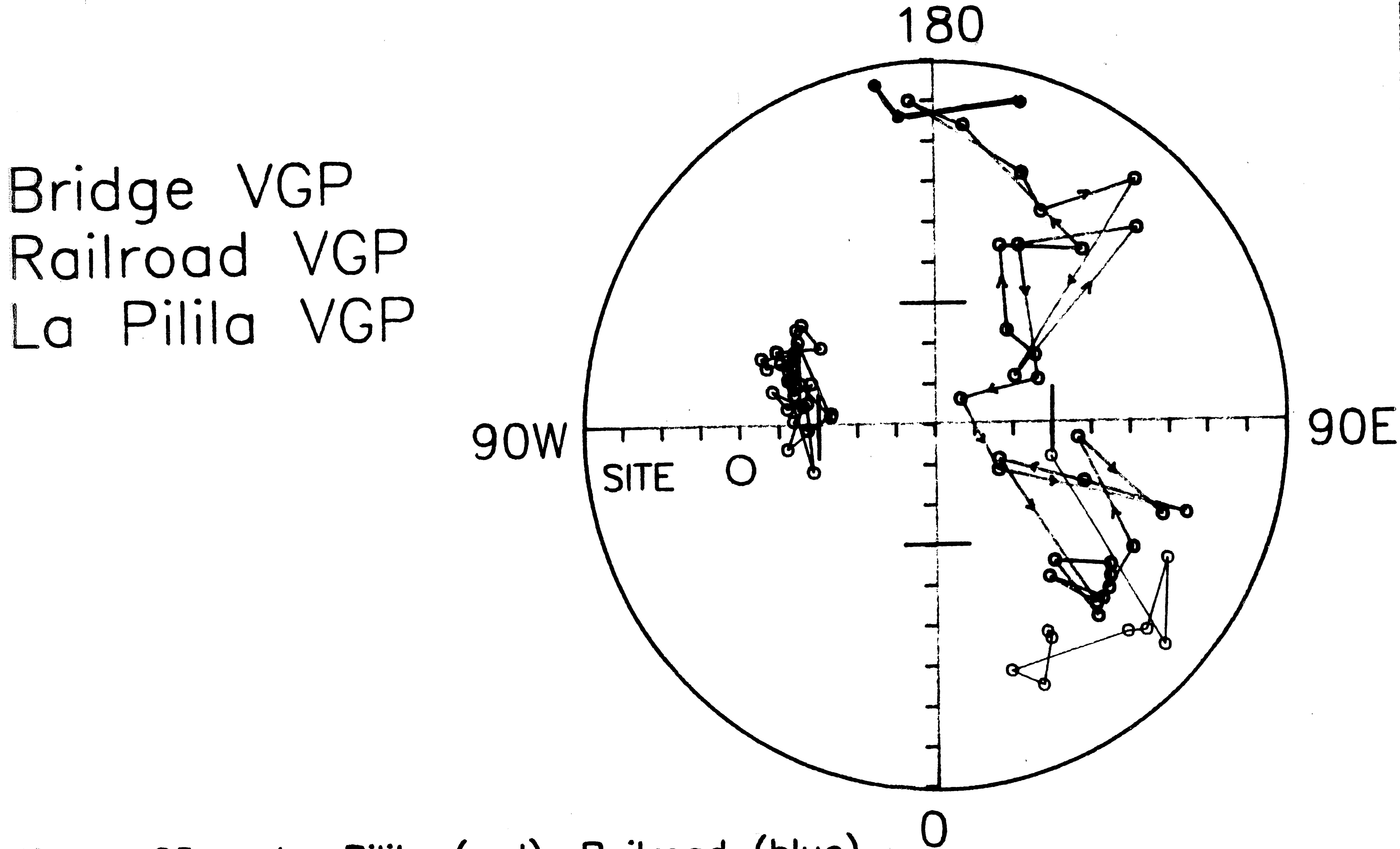

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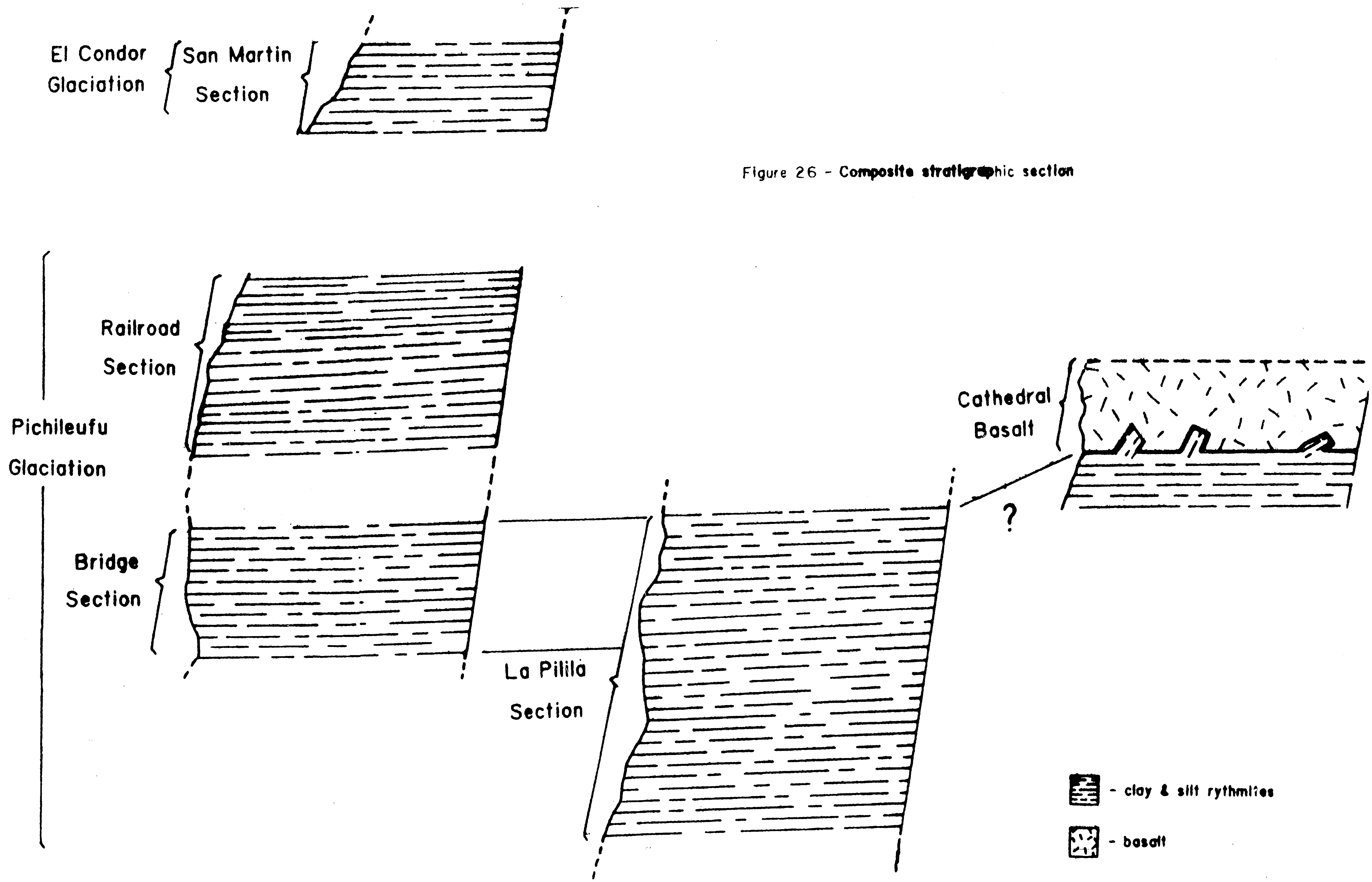

Figure 26 - Composite stratigraphic section

Section sediments coincides with the early portion of the La Pilila VGP path, suggesting that the Bridge Section sediments were deposited at the same time as the lower part of the La Pilila Section. The result is the stratigraphic section presented in figure 26. Given this composite section, the interpretation of Railroad sediments recording the middle of an excursion/transition made by Kodama et al (1985a) is probably not correct. The Railroad sediments appear to record the end of an excursion/transition, rather than the middle.

While all these sediments are considered to be of Pichileufu age by glacial geologists, our paleomagnetic data can give a detailed correlation of the sections we have sampled. The La Pilila sediments are clearly the oldest of the three sections. The Bridge Section sediments are sychronous with the early portion of the La Pilila sediments and the Railroad Section sediments are the youngest of the three. The amount of time represented by these three sections is uncertain, as the rhythmic layering has not been determined to be annual. It has been reported that excursions of the geomagnetic field last on the order of 10^3 years (Fuller et al, 1979; Barbetti and McElhinny, 1976). If these sediments record an aborted reversal, the amount of time required to deposit the entire stratigraphic section should be on the order of 10^{3-104} years, making the interpretation of rhythmites as annual layering possible.

San Martin Results

San Martin sediments are known to be the youngest of all sediments sampled. The VGP's obtained from the sediments fall within the range of normal secular variation, indicating the presence of normal field conditions during the deposition of the San Martin sediments. Whether San Martin sediments record an interim period of the excursion recognized in the Bridge and La Pilila sediments or a portion of the secular variation path of the present geomagnetic field has not been determined. A precise age of the San Martin sediments would be neccessary to compare their paleomagnetic record to existing data.

Field Behavior

The VGP path for the composite stratigraphic section constructed by this study is seen in figure 25. The Pichileufu sediments are believed to record an excursion or a polartiy transition of the geomagnetic field. During the excursion/transition, the field appears to be moving rapidly and is lower in intensity than the near stable polarity field. The data show clockwise and counterclockwise looping fo the VGP's when they are at low latitudes. Although we did not observe true normal or reversed polarity behavior of the field earlier or later than this excursion/transition, one possibility is that we have observed either a R-N transition or a N-N excursion. This

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Cathedral Basalt

The Cathedral Basalt was radiometrically dated and paleomagnetically sampled to provide an absolute age for the excursion/transition recorded by La Pilila/Bridge cut sediments. Since the Cathedral Basalt had originally been reported to overlie and incorporate sediments of the oldest glaciation in the Quillen Valley north of the field area (Evenson, personal communication), it was hoped that the VGP's from the Cathedral Basalt would coincide with the VGP path of La Pilila/Bridge cut sediments. The Cathedral Basalt VGP's do coincide with the younger portion of the La Pilila VGP path which is almost 90^{o} from the geomagnetic pole (figure 21). The basalt was dated by $^{40}Ar/^{39}Ar$ methods to be 19.14 (+/-0.17) my old. This would suggest an Early Miocene age for the sediments, however, this is not consistent with their fresh nature. Hoffman (1979) reports that records of successive transitions are well- constrained in longitude and the field does often return to similar positions in successive reversals. Valet and Laj (1981) see similar behavior in records of successive geomagnetic reversals in western Crete. In light of these studies, the Cathedral Basalt could have recorded an Early Miocene transition of the geomagnetic field. The behavior recorded in La Pilila/Bridge cut sediments is then a later transition, or aborted transition, which followed a similar path. Currently, glacial geologists are investigating the relationship between the Cathedral Basalt and the glacial sediments in the Quillen Valley. The date is also undergoing scrutiny. The Cathedral Basalt is included in the composite stratigraphic section (figure 26) derived from this study, however, the precise relationship is uncertain.

CONCLUSIONS

The La Pilila and Bridge cut sediments appear to record an excursion/transition of the geomagnetic field during the Pichileufu glacial age. The erratic movement and looping of the VGP along with reduced relative paleointensities are indicative of an excursion/transition. The validity of this excursion/transition is fairly certain, based on its record in widely separated sections.

Based on paleomagnetic and stratigraphic evidence, it has been determined that La Pilila sediments are the oldest of the sites sampled. The Bridge Section coincides with the older portion of the La Pilila Section as evidenced by the coincidence of their paleomagnetic signals. The Railroad Section is the youngest of the three, recording paleomagnetic directions near the expected ADP direction.

During the excursion/transition recorded by these sediments, the field behavior is characterized by dramatic looping and reduced field intensities at times when the magnetic vector is over 40^{o} from the expected ADP direction. Field intensity increases again when the magnetic field returns to within 40^{o} from the expected field direction. During periods of rapid motion of the field, as seen in La Pilila and Bridge sediments, the VGP's are observed to be far-sided. Conversely, during periods of relative quiescence or stillstand of the field, the VGP's are found to be near-sided. Paleomagnetic signals from the Cathedral Basalt indicate that the field may have returned to the same equatorial location during successive excursions/transitions for, at least, the last 19 million years. Whether the Pichileufu sediments record an excursion of the geomagnetic field or a portion of a transition is not certain without sampling of sediments stratigraphically above and below the Pichileufu sediments.

An attempt to provide an absolute age of the sediments and the excursion/transition was unsuccessful. The uncertainty surrounding the Cathedral Basalt date and its relationship to sediment sites sampled, makes absolute dating of the paleomagnetic signal difficult, if not impossible.

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David Bufo received a B.S. from Lafayette College in 1985. He is currently living and working in Denver, Colorado.