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The paleomagnetic history of the volcanic rocks of Easter Island was investigated using standard paleomagnetic techniques. The remanent magnetization of 673 specimens from the three volcanic episodes recognized on the island were measured using a spinner magnetometer. Inclinations, declinations and virtual geomagnetic poles were calculated for each flow. The majority of the samples were collected from the youngest episode, the Terevaka volcanics, which represents activity from the last 200,000 years.

The 65 flows from the Terevaka episode were used to study the Brunhes epoch on Easter Island. A mean geomagnetic pole was located at 87.4°N latitude and 204.2°E longitude. With its oval of 95% confidence, this includes the present geographic pole, as expected

for such young rocks.

Secular variation, expressed by the angular deviation of the mean virtual geomagnetic pole, was obtained for the Terevaka samples. This value, 12.8° with 95% confidence limits of 14.9° and 11.2°, is compared to other values for Brunhes age rocks. It appears to fit well onto a calculated model for the variation of angular dispersion with site latitude. It also can be related to an anomalously low region of secular variation found in the central Pacific.

Paleomagnetism and Secular Variation of Easter Island Basalts

by

Laurie Brown Isaacson

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Dr. Jack Dymond and Mr. James Clark provided field data from Easter Island as well as geochemical and geochronological results from many samples there.

My husband, Peter, must be given unmeasurable credit for assistance and moral support throughout this endeavor.

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INTRODUCTION

Paleomagnetic studies investigate the history of the earth's magnetic field. The underlying assumption to such studies is that certain rocks retain the direction and relative intensity of the ambient field at the time of their origin. For extrusive igneous rocks the field is recorded as the rocks cool from a molten lava through their Curie point. Since the time of cooling is very short on a geologic time scale, each lava flow is considered an instantaneous reading of the ancient geomagnetic field. A series of flows from one location will give an average direction of the field and a corresponding average pole position.

Studies of the ancient magnetic field over a restricted time interval are essential to the understanding of paleomagnetic events in recent earth hsitory. Easter Island consists of lava flows from several volcanic episodes spanning several million years and presents and adequate time period to study the earth's magnetic field. The location of the island close to an actively spreading ridge complex assures a young age for the extensive lava flows present there. It is possible that a detailed paleomagnetic study of such young rocks might reveal magnetic reversals and/or events known to exist in Upper Tertiary and Quaternary rocks. Also it will be possible to investigate the secular variation of the field during the time spanned by the volcanic units. Concurrent research on the geochronology and geochemistry of these same rocks greatly aids the study and provides a detailed dated history of the island's volcanism.

LOCATION AND GEOLOGY

Location

Easter Island (27°S, 109°W) is an isolated outcrop of volcanic rock in the southeast Pacific Ocean, 3700 km west of Chile. It lies on the eastern slope of the East Pacific Rise, approximately 530 km east of the ridge axis, and is part of the Sala y Gomez Ridge complex (Figure 1). It also is located at the southeastern end of the Tuamotu-Line island seamount chain. In this context the island is considered by some to be a "hot spot" or surficial expression of a mantle convection plume (Wilson, 1963; Morgan, 1973).

Geology

Easter Island is entirely volcanic in origin. Although the island has been the subject of intensive archeological studies (Heyerdal et al., 1961), the geology has only been briefly studied. Chubb (1933) and Bandy (1937) made early attempts at geologic reconnaissance of the island. Both investigators recognized the existence of three distinct episodes of volcanism, and named each for its major volcano. Figure 2 shows the regional geology of the island with the three main volcanoes: Poike, Rano Kau, and Terevaka. Baker (1966) further investigated the island, substantiated the earlier observations and

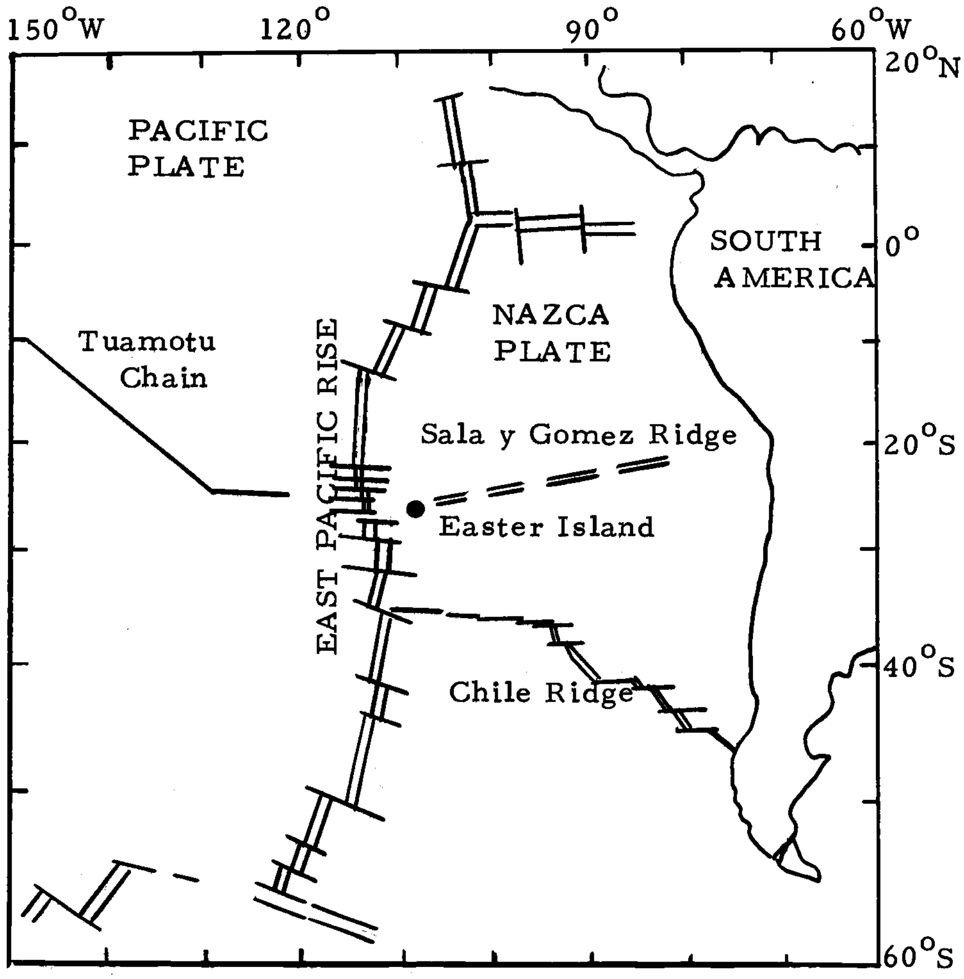

Figure 1. Index map, Southeast Pacific (after Herron, 1972a).

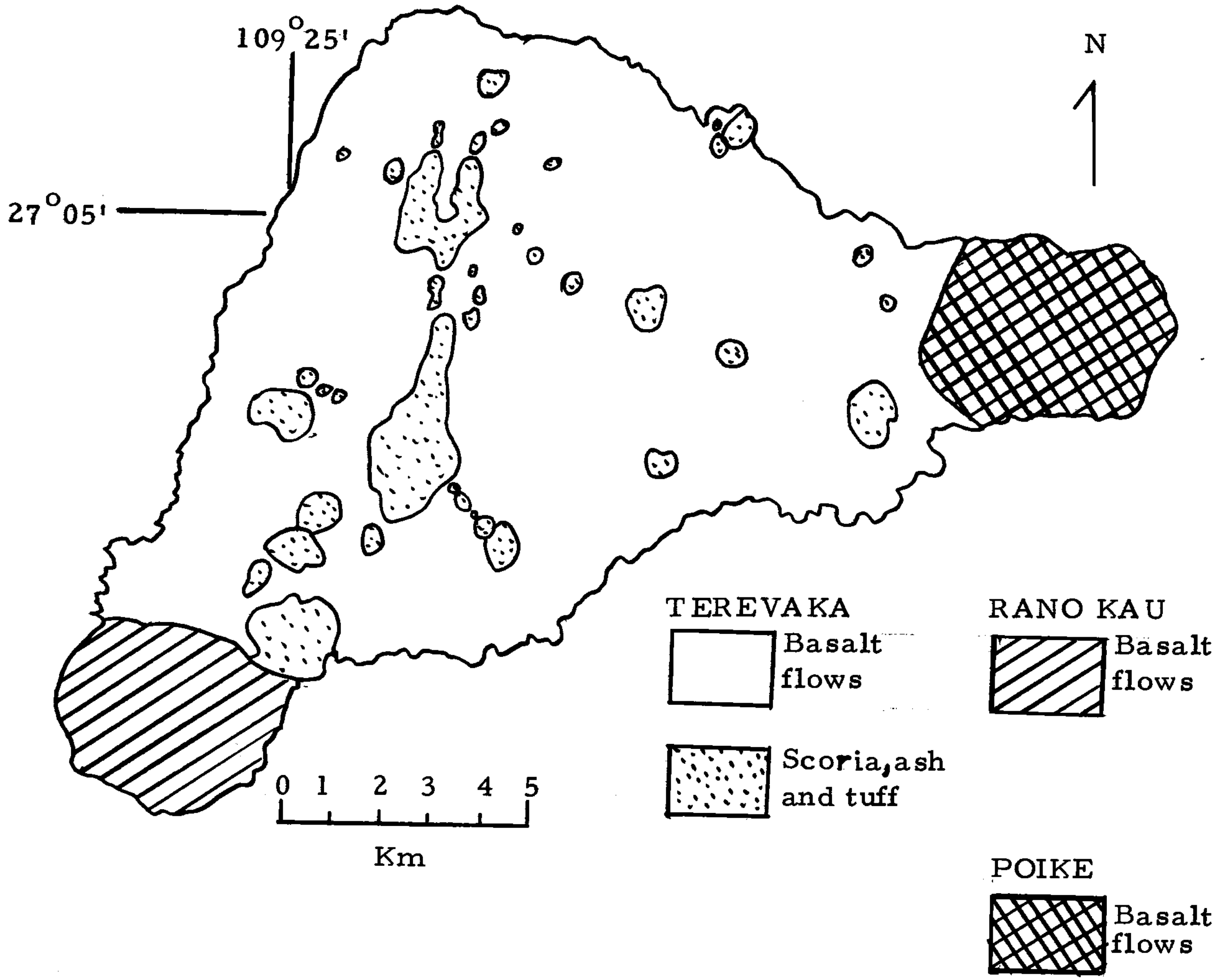

Figure 2. Geologic map of Easter Island (after Baker, 1966)

added additional information concerning the relative ages of the events. He classified Poike and Rano Kau as the older episodes, and Terevaka, covering the major part of the island, as the youngest episode.

The volcanic rocks on the island are transitional between island tholeiites and alkali basalts, with even the more basic rocks saturated in silica (J. Clark, per. comm.). The extensive number of once-active volcanic vents and pyroclastic centers, especially during the Terevaka episode, make it difficult to correlate flows around the island or futher delineate the volcanic stratigraphy without additional field work.

Age of Easter Island

Although there are no reports of volcanic activity in historical time, the island does appear to be very young (Baker, 1966) based on the unweathered appearance of many of the basalt flows. Due to the island's close proximity to the East Pacific Rise, this assumption is most consistent with plate tectonic theories. From marine magnetic data (Herron, 1972b) Easter Island is situated between anomalies two and three. Using the time scale developed by Heirtzler et al. (1968), the sea floor in the vicinity of Easter Island has a minimum age of two million years and a maximum age of five million years.

Preliminary age determinations on six hand samples from the island using potassium-argon method gave an estimated age of less than 1.0 million years (Booker _et al._, 1967).

A detailed investigation of the geochemistry and geochronology of the island is in progress (Clark and Dymond, 1974). The 30 lavas presently dated by the potassium-argon method readily identify the three episodes of volcanism recognized in field studies. Poike, the easternmost volcano, is the oldest with a date of 2.5 $\pm$0.2 million years. The southern volcano Rano Kau yields several dates, all approximately 1.0 million years. Terevaka is definitely the youngest episode on the island, with 15 flows sampled, all producing dates of 240,000 years or less. Figure 3 shows the location of the flows which have been radiometrically dated.

Cox (1969a) has established a detailed time scale for the most recent geomagnetic polarity reversals, using known paleomagnetic data and potassium-argon age dates. The three volcanic episodes on Easter Island fall into the three most recent polarity epochs. The Poike volcanics lie in the Gauss-normal epoch. The Rano Kau lavas are in the Matuyama-reversed epoch, and the Terevaka flows are in the youngest epoch, the Brunhes-normal. Since the majority of samples studied here were collected from the Terevaka region, a normal polarity is expected. However, the samples from Rano Kau should show a reversed polarity.

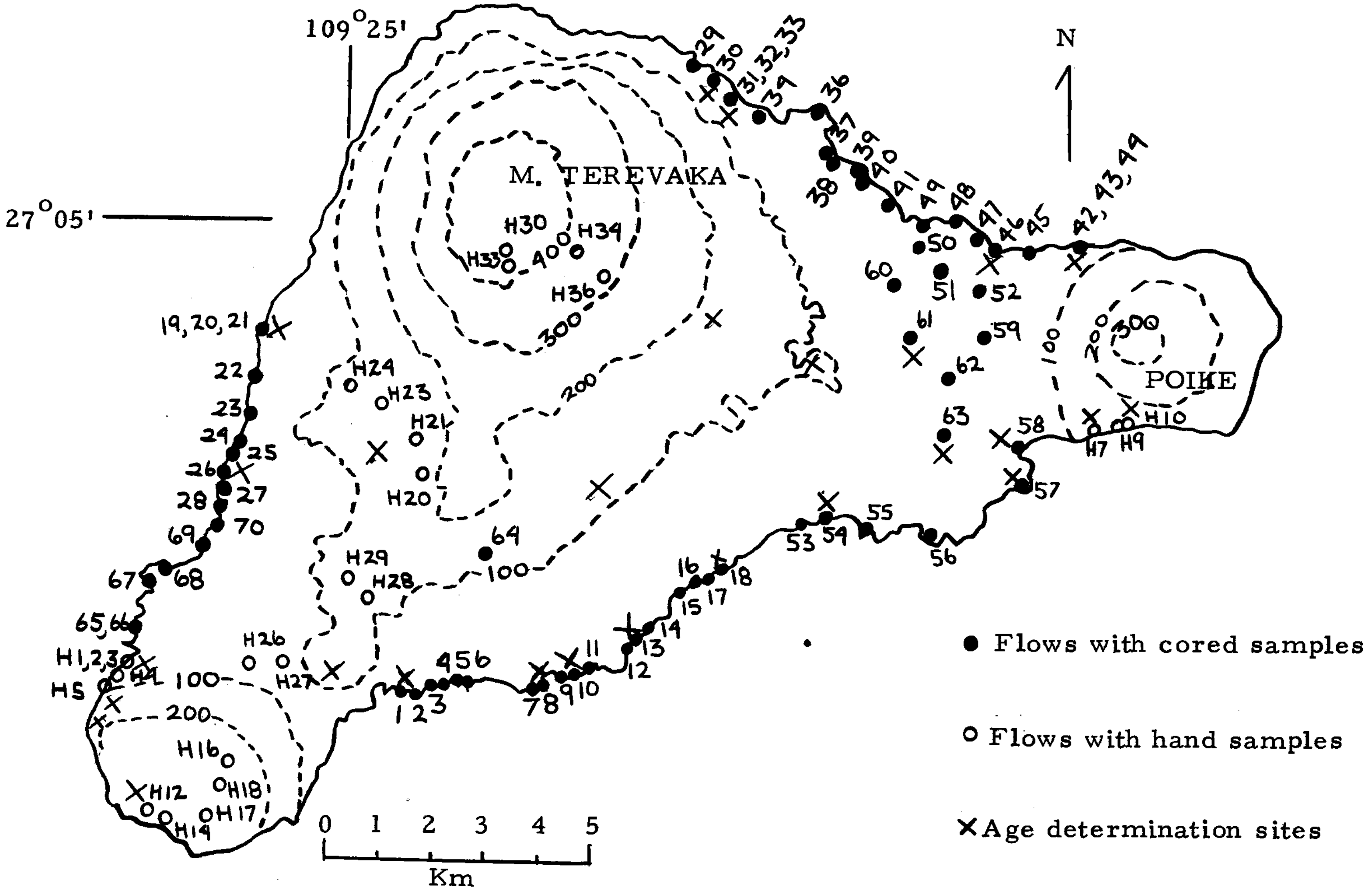

Figure 3. Sampling Sites, Easter Island.

EXPERIMENTAL PROCEDURES

Field Work

Donald Heinrichs, Jack Dymond, and James Clark carried out the field work in March on 1971. They spent two weeks on Easter Island collecting samples for paleomagnetic and geochemical studies.

The paleomagnetic samples were collected following procedures outlined by Doell and Cox (1965), using a gasoline powered portable drill with a diamond bit. Cores were drilled 10 to 20 cm long and 2.54 cm in diameter. These were oriented in situ using a Brunton compass and a core leveling device, consisting of a slit brass tube and an adjustable level platform. After the core is drilled, but before it is removed from the site, the tube is slipped over the core and a line is scribed down the core using a copper wire. The level and compass are used to measure the dip and aximuth of the core.

To obtain adequate data for statistical studies at least four sites per separate flow were drilled. Usually two specimens were cut from each core, with an average of eight specimens per flow obtained. Care was used to pick fresh, unweathered outcrops of rock to avoid possible problems due to weathered samples. Whenever field conditions permitted lavas were sampled in sequence. Due to the excellent outcrops found in seacliffs, and the lack of exposure in the interior of the island, most of the sampling was done along the periphery of the island. Figure 3 is a map of Easter Island showing the location of sampling sites.

The drilled rock sample is considered in a coordinate system where the Z-axis is positive down the axis of the core. X and Y are orthogonal such that the Y-axis is always horizontal and X is positive when inclined above the horizontal. In other words, the right-hand system is employed. The line scribed on the core in the field represents the Z-axis, while small hatched lines are added to represent the Y-positive direction. The dip of the core measured in the field is the plunge of the Z-axis (0^{o} to $\pm 90^{o}$). The aximuth of the core is the Y-positive direction (0^{o} to 359.9^{o}).

Due to logistical and equipment problems, it was not possible to sample all areas using the portable drill. In these locations hand samples were collected with proper notation of their orientation in the field. For outcrops sampled in this manner only one or two sites per lava flow were visited. These rock samples were later drilled in the laboratory and reoriented there to obtain the dip and azimuth of the core.

Laboratory Work

Remanent magnetization measurements were made using a 5Hz spinner magnetometer. A sample, secured in a holder on the end of a long shaft, is rotated in front of a small, highly sensitive flux-gate coil. The rotating magnetic moment of the sample produces an alternating current in the sensor. With the use of a reference magnet and coil, the phase and amplitude of the signal was determined.

The signal to be read is displayed on a digital voltmeter connected to a Lock-in amplifier. Controls on the amplifier allow for sensitivity, time constant and phase changes. The sensitivity controls vary from 1 μv to 200 mv, but settings of 1 mv to 100 mv were adequate for the rocks measured in this study. The time constant may be set from 1 msec to 300 sec; a setting of 1 sec was used exclusively here. The phase setting allows for two readings for each spin, one at 0^{o} and the other at 90^{o}.

Due to a slight but persistent drift of the magnetometer with time, it is necessary to "zero" the amplifier each day. This is done with a calibration probe inserted in the shaft. At the 0^{o} phase setting the probe should induce no output, and the calibration dial is adjusted so this is true.

The cored sample is placed in a cubic specimen holder so that each axis of the specimen is parallel to one of the holder sides. The holder is scribed with the Z and Y directions to ensure proper orientation of the sample each time. The holder is then oriented on the end of the shaft with one axis pointing vertically down (the I shaft direction), and one axis pointing horizontally along the shaft toward the motor (the II shaft direction). The sample is now "keyed" with respect to the reference signal. The 0^{o} phase reading will correspond to the vertical axis component, while the 90^{o} phase reading will be the horizontal component perpendicular to the II shaft direction, positive toward the reader (the right hand rule is still used). Although three such spins provide two readings on each component, a total of six complete spins were used to obtain four readings on each component. In this way possible inhomogeneities in the samples, magnetic anisotropy and/or possible magnetometer drift were minimized. Figure 4 lists the shaft directions and components measured for this study. The order of readings is important to ensure proper input for the computer program used to calculate the sample directions.

Magnetic cleaning experiments were carried out using an alternating field demagnetizer. This equipment consists of a variable current transmitted through a coil, creating a magnetic field in which the sample is rotated. The field can be set at any level up to 1000 oe, and then allowed to decay over a ten minute period. By this process much of the spurious or secondary elements of magnetization are randomized and stable primary magnetization remains dominant. Samples here were rotated in a four-axis tumbler, which minimizes the possibility of a preferred direction being enhanced by the alternating field.

SPIN	SHAFT DIRECTIONS		COMPONENT MEASURED	
	I	II	0^{o}	90^{o}
1	+X	-Z	+X	+Y
2	+X	+Z	+X	-Y
3	+Y	-X	+Y	+Z
4	+Y	+X	+Y	-Z
5	+Z	-Y	+Z	+X
6	+Z	+Y	+Z	-X

Figure 4. Shaft directions and measured components for spinner magnetometer.

STATISTICAL ANALYSIS

Magnetic Field Measurements

The magnetic field is a vector field and can be fully described by two angles, inclination and declination, and the field intensity. Declination is the angle between geographic north and the horizontal component of the field, inclination is the angle between the horizontal and the field vector, and the intensity is the magnitude of this field vector. From the components of the magnetic moment one can easily determine these desired angles and magnitude.

Calculations were done using an algorithm developed by Doell and Cox (1965) and further adapted by Denham (1971), dependent on the intensities M_x, M_y, and M_z and the phase angles Θ_x, Θ_y, and Θ_z. The three phase angles define three planes, which intersect to form a small error traingle. By repeated iterations this triangle is collapsed, using the intensities as weighting factors on each side. When the radius of the triangle becomes less than 0.01 degrees, the strongest vertex is chosen as the solution, with a corresponding inclination and declination. The computer program SPINNER, used to make these calculations is listed in Appendix II.

Once the inclination and declination are known at one locality, a corresponding paleomagnetic pole may be calculated using the following formulas:

$$\sin \Theta' = \sin \Theta \cos p + \cos \Theta \sin p \cos D$$

$$\sin (\phi' - \phi) = (\sin p \sin D)/\cos \Theta' \qquad (1)$$

$$\cot p = 1/2 \tan I$$

The paleomagnetic pole has the coordinates (Θ', ϕ'), the sampling locality is given by (Θ, ϕ), and I and D are the inclination and declination. These calculations are contained in the program SIMPLET (see Appendix II).

Fisherian Statistics

The analysis of paleomagnetic data calls for the investigation of a vector field over a sphere. Fisher (1953) developed a special set of statistics to deal with this problem. He simulated a Gaussian distribution in three dimensions where points on a sphere (paleomagnetic directions) were described in terms of a probability density function

$$P = \frac{K}{4\pi \sinh K} \exp (K \cos \Theta). \qquad (2)$$

Θ is the angle between individual directions and the true directions, and K is a constant called the precision parameter. K varies from K = O for perfectly random directions to K = ∞ for identical directions. Since directions from one lava flow should not be random, K is expected to be large. A best estimate for K has also been described by Fisher as:

$$K \approx k = \frac{N - 1}{N - R} \qquad (3)$$

Here N is the number of samples and R is the normalized length of the resultant vector of the N samples. A further discussion of these statistics if found in Cox and Doell (1960).

Another useful statistic presented by Fisher (1953) is α. This is the semivertical angle of a circular cone about the resultant vector R in which the true mean direction lies. For a probability level of 1 - P, α is given by:

$$\cos \alpha_{(1-P)} = 1 - \frac{N - R}{R} \left\{ (1/P)^{1/N-1} - 1 \right\} \qquad (4)$$

In paleomagnetic work P is usually taken as 0.05. Then there is 95% confidence that the cone of radius α_{95} contains the true mean direction. For α small it can be approximated by:

$$\alpha_{95} = \frac{140}{\sqrt{kN}} \qquad (5)$$

α_{95}, k and R are all calculated and output by the computer program SIMPLE1 (Appendix II).

Secular Variation Statistics

Cox and Doell (1964) show the best means of expressing secular variation to be the measure of angular standard deviation, S_T:

$$S_T^{\ 2} = \frac{1}{(B - 1)} \sum_{i=1}^{B} \delta_i^{\ 2}. \qquad (6)$$

B is the number of flows involved, and δ_i is the angle between the direction or pole of the i th lava and the mean direction or mean pole. S_T can be expressed as either the angular dispersion of directions or poles.

The total angular dispersion S_T must be corrected for various experimental and natural errors. These include within-site dispersion, between-site dispersion, and the possible presence of local geomagnetic anomalies at the time of extrusion. Cox (1969b) and Doell (1970) have developed the following method of dealing with these errors. In terms of the precision parameter k:

$$1/k_F = 1/k_T - 1/\bar{N}k_W - 1/k_A \qquad (7)$$

where k_T is the total precision parameter, k_W is the within-lava precision parameter, k_A is the percision parameter due to local anomalies at the site, $\bar{N}$ is the average number of samples per lava, and k_F is the ancient geomagnetic field precision parameter. Due to the inverse relationship between the precision parameter and angular standard deviation,

$$S = 81^{\circ}/(k)^{1/2} \qquad (8)$$

for S in degrees (Cox and Doell, 1964), equation (7) can be expressed in terms of the dispersion.

$$S_F^2 = S_T^2 - S_W^2/\bar{N} - S_A^2 \qquad (9)$$

The subscripts here are similar to the ones described for equation (7).

The within-lava precision parameter, k_W, is calculated by a two-tier analysis method outlined by Watson and Irving (1957). Here the number of samples, N_i, from the i^{th} flow are combined with the normalized resultant vector for the flow, R_i, in the equation:

$$k_W = \sum_{i=1}^{B} \frac{(N_i - 1)}{(N_i - R_i)} \qquad (10)$$

where B is the total number of lavas studied.

From a study of historic lava flows on Hawaii, Doell and Cox (1963) have estimated the angular dispersion of directions due to local anomalies to be $S_A = 1.25^\circ$. Using procedures developed by Cox (1970), Doell (1970) has expressed this deviation in terms of poles and the precision parameter as $k_A = 2100$. This value depends on the relative magnetic intensity of the lavas studied, here considered to be of the order of 10^{-3} emu/cc. A recent synthesis of the above statistical methods can be found in Ellwood _et al._ (1973).

The total precision parameter is an output of the computer program SIMPLE1. k_W is calculated with the aid of the program RVGP, given in the Appendix.

STABILITY AND RELIABILITY OF MEASUREMENTS

Stability

Paleomagnetic studies are based on the assumption that the magnetic field recorded in sampled rocks represents the earth's field at the time of original emplacement. This has been shown to be true for historical lava flows by Chevallier (1925), Nagata (1943), and Doell and Cox (1963), where comparison to observatory data is possible. When the rocks in question are older than any historical observatory data, as the case usually is, field tests and laboratory tests must be employed to validate the stability of the magnetization. The field tests (see McElhinny, 1973) require igneous contacts, magnetic reversals, fold, and/or conglomerate units. Thus, there are no applicable tests to a field area such as Easter Island, consisting only of volcanic rocks.

In this study the stability of the natural remanent magnetization was investigated by alternating field demagnetizing experiments. The stable primary magnetization measured in the laboratory is thermo-remanent magnetization (TRM), or that gained by the rock as it cools through its Curie point. This primary magnetization can be contaminated by isothermal remanent magnetization (IRM), viscous remanent magnetization (VRM) and chemical remanent magnetization

(CRM). VRM and IRM components can be removed in alternating fields of only a few hundred oersteds (McElhinny, 1973), and will be erased in demagnetized samples. The remaining magnetization can be due either to TRM or CRM, but it is hard to distinguish between the two solely from demagnetizing experiments. The fresh, unweathered aspect of the samples implied that little oxidation has occurred. This fact, along with the excellent clustering of directions obtained for many of the flows substantiated the assumption that the observed magnetization was due primarily to TRM.

Reliability

Minimum criteria for the reliability of paleomagnetic data as true indicators of the paleo-field have been proposed by Irving (1964) and McElhinny (1973). The samples studied here conform to the six stated criteria except the one demanding five (Irving) or eight (McElhinny) separate sites sampled per flow. This study had only four separate cores per flow, with two specimens cut from each core. Current work by Ellwood et al. (1973) and Watkins (1973) indicates that even for the more refined secular variation statistics, four sites per flow provide adequate data.

The most scattered flows were checked to determine if these samples represented random directions. This was done using Watson's statistical test (1956), comparing a statistical derived R to the observed R. All flows checked passed that test (i.e. directions were not random) at the 95% level except for flow 61, which was discarded from further calculations.

RESULTS

Natural Remanent Magnetization

All specimens from both cored sites and hand samples were run on the spinner magnetometer and the resulting magnetic directions calculated. For each flow, D and I for all the specimens were plotted on an equal-area stereonet projection. Figure 5 shows the direction plots for flows 37 and 45, with their respective α_{95} values. These are representative of two groups, one with the directions well-clustered (flow 37), and one with considerable scatter in the directions (flow 45).

Demagnetization

A number of flows were demagnetized in alternating fields of 50 to 200 oersteds. This was done to remove secondary unstable components of magnetization and improve the cluster of directions determining the average direction.

To obtain a suitable field level for demagnetization, the dispersion of directions was investigated following procedures by Irving et al. (1961). Two test specimens from each flow were demagnetized at levels of 25, 50, 100, 200, 400, and 800 oersteds. The demagnetizing level for the entire flow was the field at which the dispersion

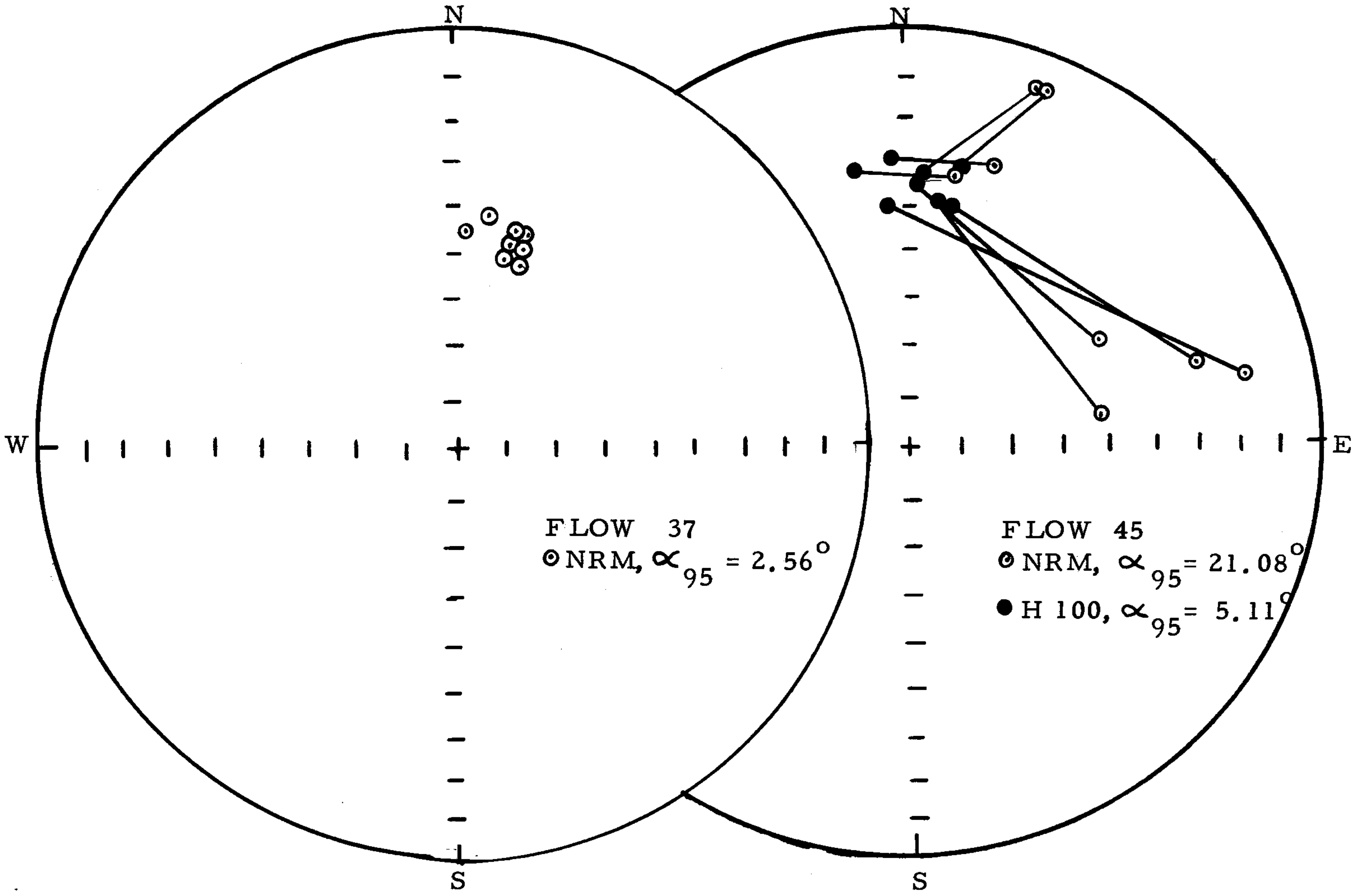

Figure 5. Stereographic projections of directions of natural remanent magnetization, Flow 37 and Flow 45.

of the directions of the two specimens was a minimum. A stability index (Bridern, 1972) was also employed, which compared the NRM vector at varying levels of demagnetization, but it proved less useful.

Figure 6 shows a typical demagnetized flow, with direction plots for the specimens, and the intensity variation at increased oersted levels. Twenty-five flows were treated in this manner, with an improved cluster of directions being obtained after cleaning.

Flow Inclinations and Declinations

The declinations and inclinations found for each sample were combined to obtain an average direction for each flow. Figure 7 is a stereographic plot of the average directions for the 65 Terevaka flows. Included on the plot are the present field directions and the axial dipole field for the latitude of Easter Island.

This data is listed in Appendix I, along with the Fisherian statistics for each flow. Also presented are the data from the other samples collected on the island. Only directions and poles are reported for flows consisting of hand samples. Due to the small number of sites sampled for these flows no attempt was made to calculate statistics or to clean these samples further. It should be noted that only four out of ten flows of the Rano Kau episode have a reversed polarity, although that is the expected result for flows of this age. Further collections and magnetic measurements are needed to clarify

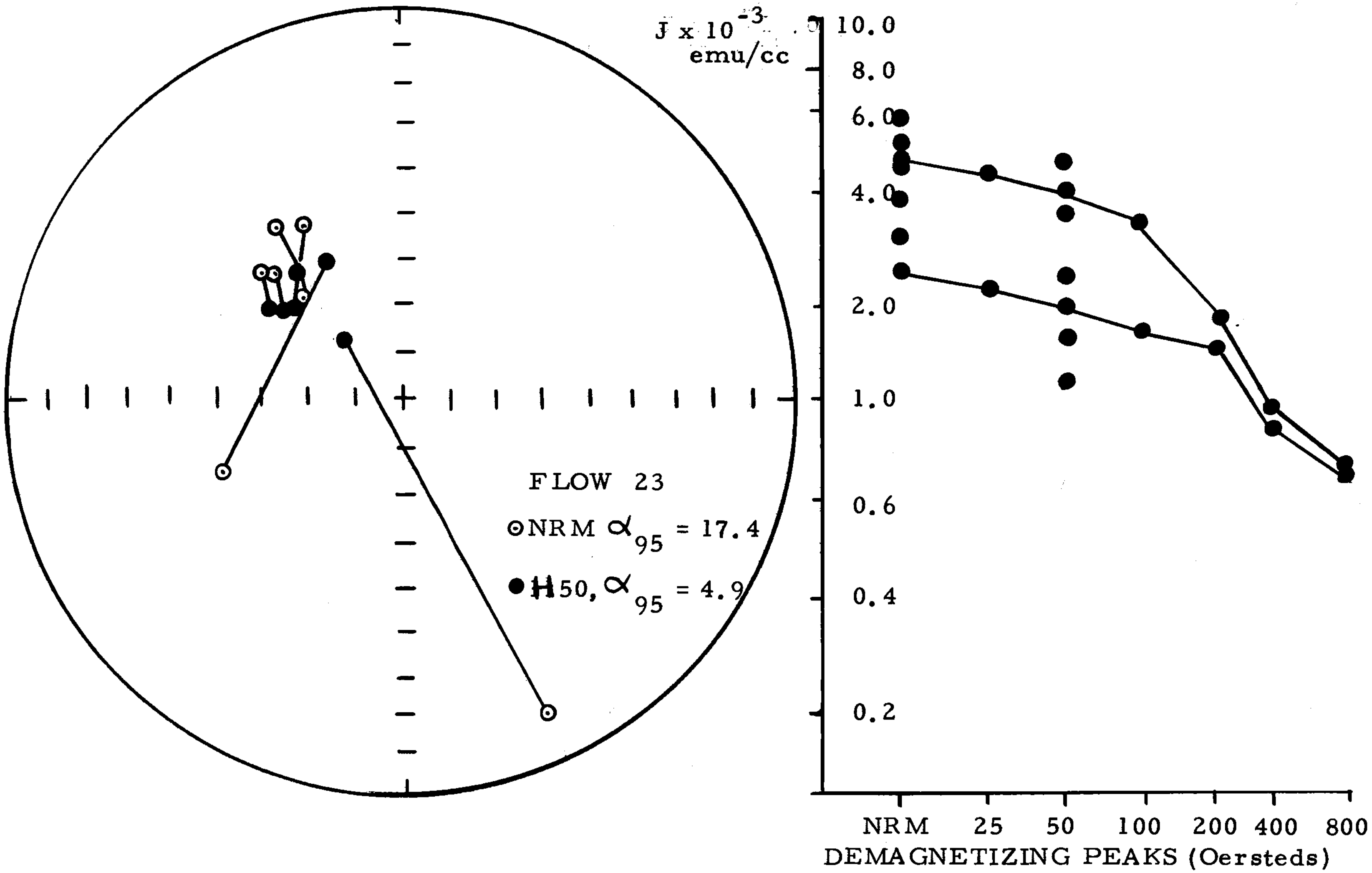

Figure 6. Sterographic projection of directions before and after demagnetization at 50 oe, and step demagnetization of Flow 23.

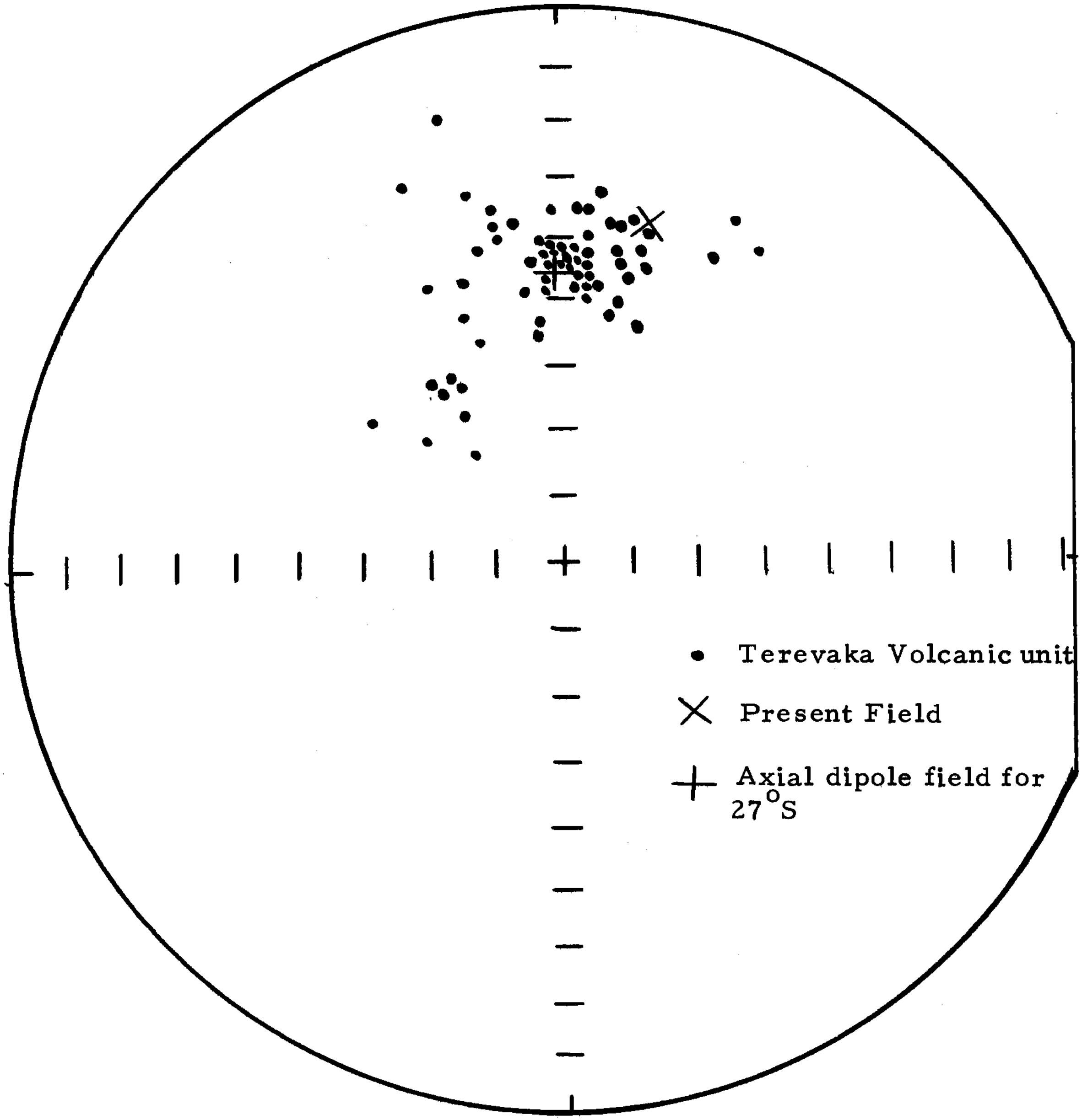

Figure 7. Stereographic projection of average declinations and inclinations for the Terevaka flows.

this problem.

Magnetic Intensities

Magnetic intensities were calculated for each specimen and an average intensity for each flow. Flow intensities ranged from .53 x 10^{-3} to 8.4 x 10^{-3} emu/cc. These values are very similar to ones reported by other investigators on Brunhes age rocks (see Cox, 1969b; Bingham and Stone, 1972)

Virtual Geomagnetic Poles

For each of the Terevaka flows a virtual geomagnetic pole (VGP) was determined from the inclination, declinations and site latitude. The term virtual geomagnetic pole is used to identify a pole calculated from one spot reading, representing only an instant in time.

The VGPs are listed in Appendix I and are shown in Figure 8 on a polar projection of the northern hemisphere. The mean VGP is designated by a cross, located at 87.4°N latitude and 204.2°E longitude. It is surrounded by the oval of confidence at the 95% level with major axis of 4.13° and minor axis 2.57°. This oval includes the present rotational pole of the earth, as is to be expected for very young rocks. Cox and Doell (1960), Irving (1964) and more recently, Opdyke and Henry (1969) have noted that the mean poles for upper Tertiary to Recent rocks are always very close to the geographic pole.

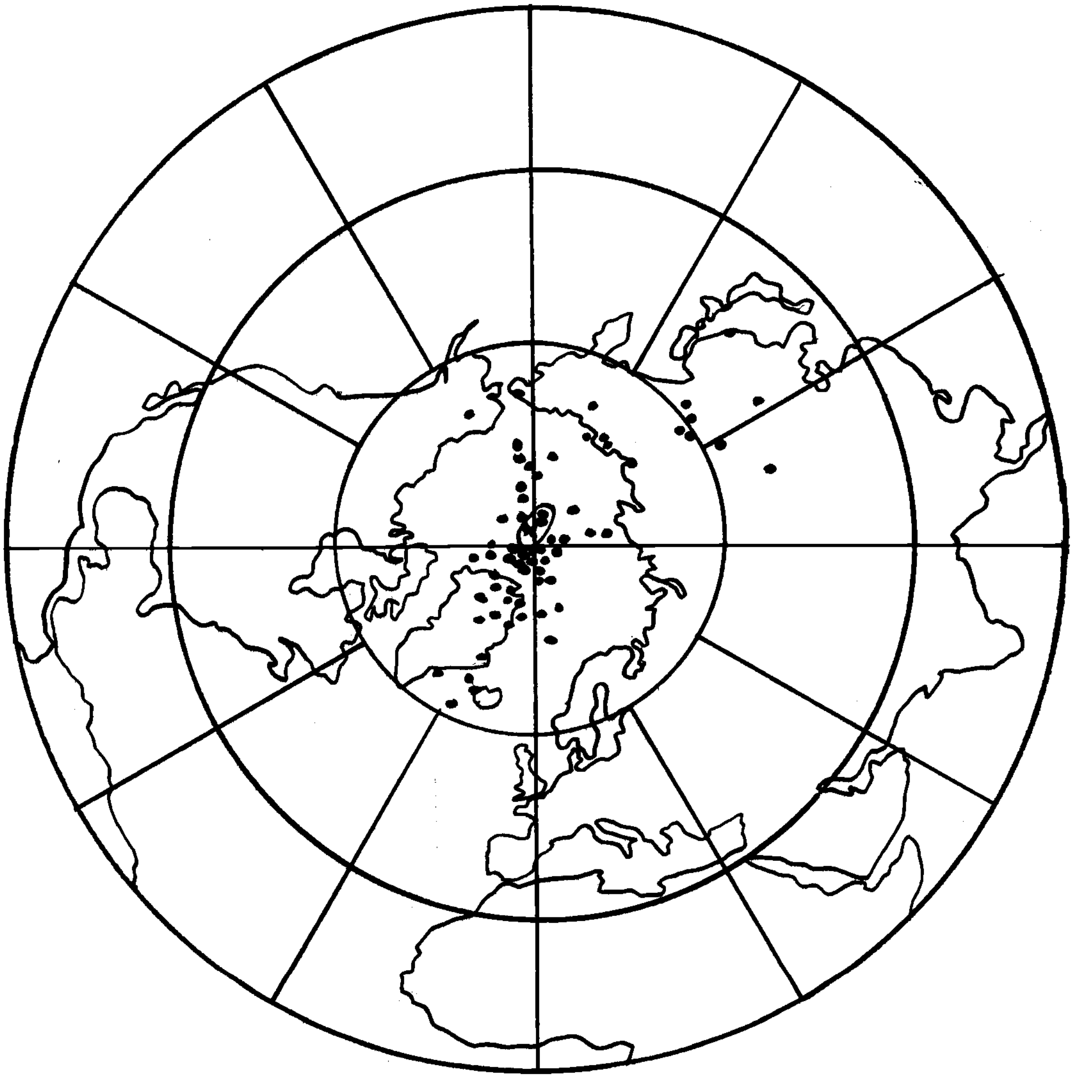

Figure 8. Virtual geomagnetic pole positions for the Terevaka flows, with the average pole position and oval of 95% confidence.

It appears that for a time average of at least a few thousand years in the upper Tertiary the earth's field was that of an axial dipole.

Wilson (1970; 1971) has pointed out that while the average pole always occurs very close to the geographic pole, it is also usually displaced on the opposite side of the geographic pole from the source area. He proposes that this "far-side pole" position is due to a displacement of the main dipole 191$\pm$ 38 km northward along the rotation axis. The position of the mean VGP from Easter Island does not support this contention, lying slightly on the near side of the geographic pole to Easter Island. Other Southern Hemisphere data opposing Wilson's off-set theory has been presented by Watkins (1972).

Excursion of the Field

Cox, Doell and Dalrymple (1964) demonstrated the presence of short duration polarity events as part of the geomagnetic time scale. For a limited time, on the order of 10^4 years, the field reverses its polarity, then returns to the original polarity of the existing epoch. Several events in the Brunhes normal epoch have been postulated, but due to their short duration they have not been ovserved in all paleomagnetic studies of Brunhes age rocks. Three events have been found in very young rocks and sediments all dated at less than 30,000 years before present (Bonhommet and Zahringer, 1969; Morner et al. 1971; Barbetti and McElhinny, 1972). Another event is the Blake event, first observed in deep-sea sediment cores (Smith and Foster, 1969; Wollin et al., 1971) and dated between 108,000 and 114,000 years.

It is observed that occasionally a complete reversal does not occur, but the field departs from its normal vertical position for a short time and returns, never "locking-in" to the reversed position (McElhinny, 1973). Such aborted reversals are called excursions, and have been noted in recent paleomagnetic studies (Watkins and Nougier, 1973). In fact, several of the previously mentioned events may only be departures of the field and not complete reversals.

In the Easter Island data there are several flows having VGP latitudes less than 50° (Figure 8). The two lowest of these flows have VGP latitudes of 49° and 44°. These two flows are from opposite sides of the island and do not appear to be related in the field. One flow is in sequence with t other flo s, both of which have low VGP latitudes and similar VGP longitudes (see flows 32, 33, and 34, Appendix I). One of these flows has been dated by potassium argon at 127,000 ± 58,460 years. This relates the excursion observed here to the fore-mentioned Blake event, although there is not enought data to determine if the excursion is an actual reversal or simply a departure of the field from normal.

SECULAR VARIATION

Introduction

Secular variation is the change observed in magnetic field with time, both in field directions and intensitites. For variations due to internal sources, time scales of 10 to 10^4 years are likely (Cox and Doell, 1964). In looking at paleosecular variation, one is concerned with a single reading of an average value of secular variation over time. It is necessary to have a sampling sequence that covers a time interval at least several times larger than the maximum time period for the variations themselves. The Easter Island Terevaka lavas span approximately 200,000 years, and thus are able to give a reasonable average for paleosecular variation. The best method for expressing secular variation is an investigation of the scatter of points about the mean, either directions or poles (Creer et al., 1959; Cox and Doell, 1964).

Latitude Variation Models

Secular variation is a change in the earth's magnetic field. There are three main causes: variations in the intensity and direction of the non-dipole field; the wobble of the central dipole; and oscillations of the dipole (Brock, 1971). All of these causes give rise to secular variation values which vary with latitude, due to the nature of the geomagnetic field.

Several models have been proposed to explain this dependence, and have been termed models A, B, and C by Irving (1964). Model A (Irving and Ward, 1964) suggests an axial geocentric dipole of a set moment, where the secular variation is caused by a random component of fixed intensity disturbing the dipole. There is no dipole wobble in this model and all the latitude variation is caused by the dipole field latitude variance. Creer, et al., (1959) proposed model B which postulates a dipole wobble about the man dipole causing the secular variation. This is a one parameter model and non-dipole components are not considered. Model C, suggested by Cox (1962), combines the dipole wobble with non-dipole components. This model has been further expanded and is now supplanted by model D (Cox, 1970). Again both non-dipole and dipole terms affect the curve, but there also is a factor involving dipole oscillations. The angular variance for this model is found from:

$$s^2 = a^2 W_n{}^2 + b^2 W_d{}^2 \qquad (11)$$

Here a is a constant depending on the intensity of dipole oscillations, b is a constant derived from the standard deviation of the dipole wobble, and W_n and W_d are the non-dipole and dipole components given by:

$$W_n = (1 + 3\sin^2\lambda)^{-1/2}$$

$$W_d = \frac{5 + 3\sin^2\lambda}{5(1 + 3\sin^2\lambda)^2} \quad 1/2 \qquad (12)$$

λ is the latitude at which the variation is desired.

Figure 9 shows normalized latitude curves for model A, model B, W_n and W_d (after Brock, 1971). W_n and A follow the same curve, and model D will lie between W_n and W_d depending on the values of a and b.

The angular dispersion represented in Figure 9 is that determined from the scatter of paleomagnetic directions. S_T can also be expressed as the angular dispersion of virtual geomagnetic poles. Convincing evidence is given in favor of the latter by Doell (1970). The dipole wobble component causes a latitude variation in dispersions of directions, but not in the dispersions of poles (Cox, 1962; Cox, 1970). Therefore, the dipole contribution to the angular standard deviation of the VGPs is the same for all locations on the globe. The non-dipole component produces a latitude variation in dispersion of both directions and poles (Cox, 1962; Creer, 1962). Thus, by looking at dispersions of VGPs from different latitudes the dipole-wobble effects are the same, and non-dipole components cause any difference (Doell, 1970). Previously Doell (1969) has suggested 11.5° as the maximum dispersion from the dipole wobble, based on

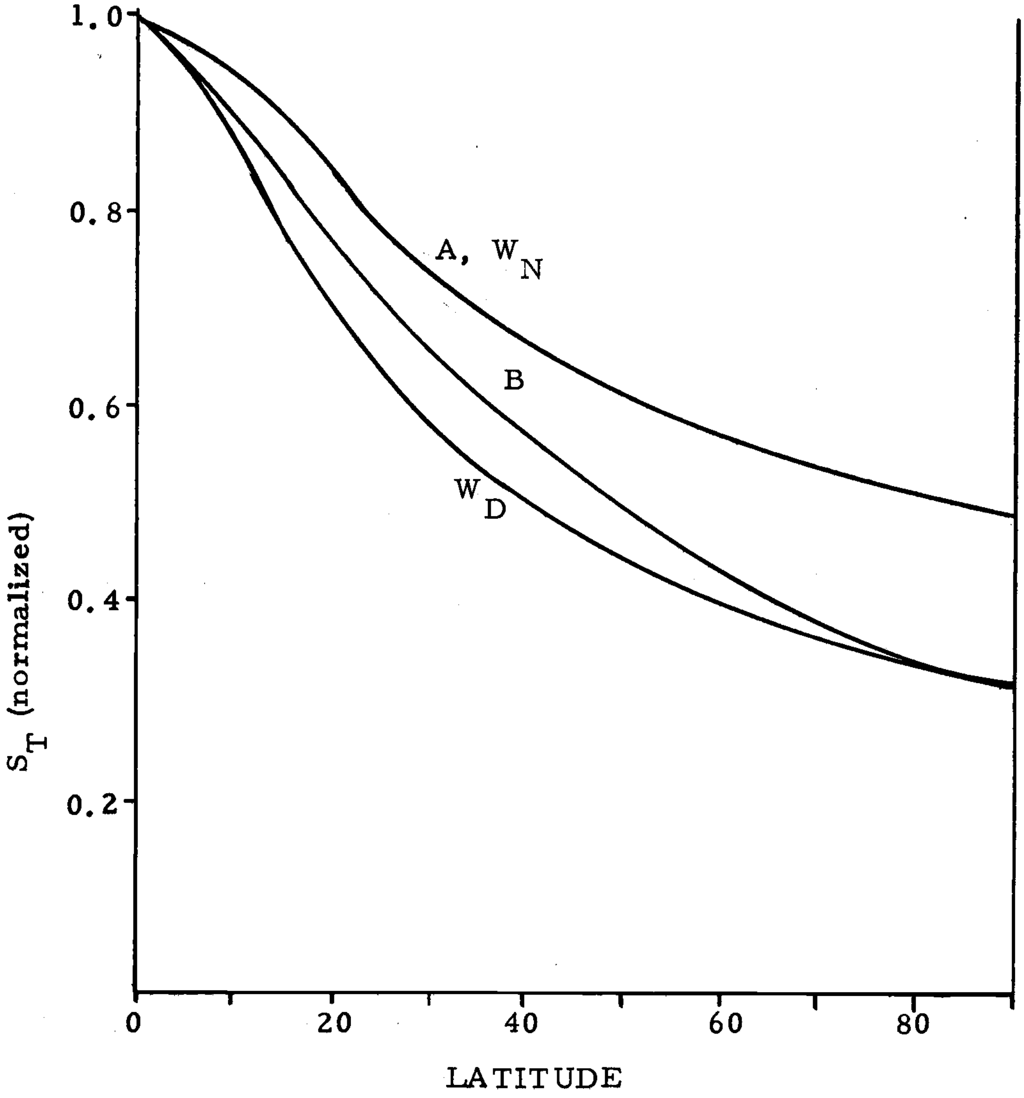

Figure 9. Normalized standard deviation of directions for models A and B, terms W_n and W_d (after Brock, 1971).

extensive studies in Hawaiian volcanics.

In addition to considering the choice of dispersion of directions or poles, one must consider the choice of relating the poles to the mean VGP or another point. As pointed put by Cox (1969b) and Doell (1970), if one accepts the geocentric dipole theory, the dispersion of poles may be calculated with respect to the present geographic pole. Since most studies of Brunhes age rocks yield mean poles not statistically different from the rotation axis (see, for example, Wilson, 1970), this is the preferred procedure.

Easter Island Secular Variation

An important consideration in determining secular variation values is the selection of data to be used. Criteria established by Cox and Doell (Cox, 1969b; Deoll, 1970; Doell and Cox, 1972) reject any data with α_{95} values greater than 9° and/or a VGP latitude of less than 50°. These investigators also require six to eight separate samples per flow. Other authors (Ellwood et al., 1973; Watkins and Nougier, 1973) discard flows with low VGP latitudes, but make no rejections on α_{95} values. A case has been made for as few as four sites per flow providing adequate results (Ellwood et al., 1973).

Figure 10 is a histogram of the α_{95} values for the 65 Terevaka flows. The great majority of the flows fall between 2° and 16°, with only 8 flows lying beyond 16°. Two sets of statistics were calculated

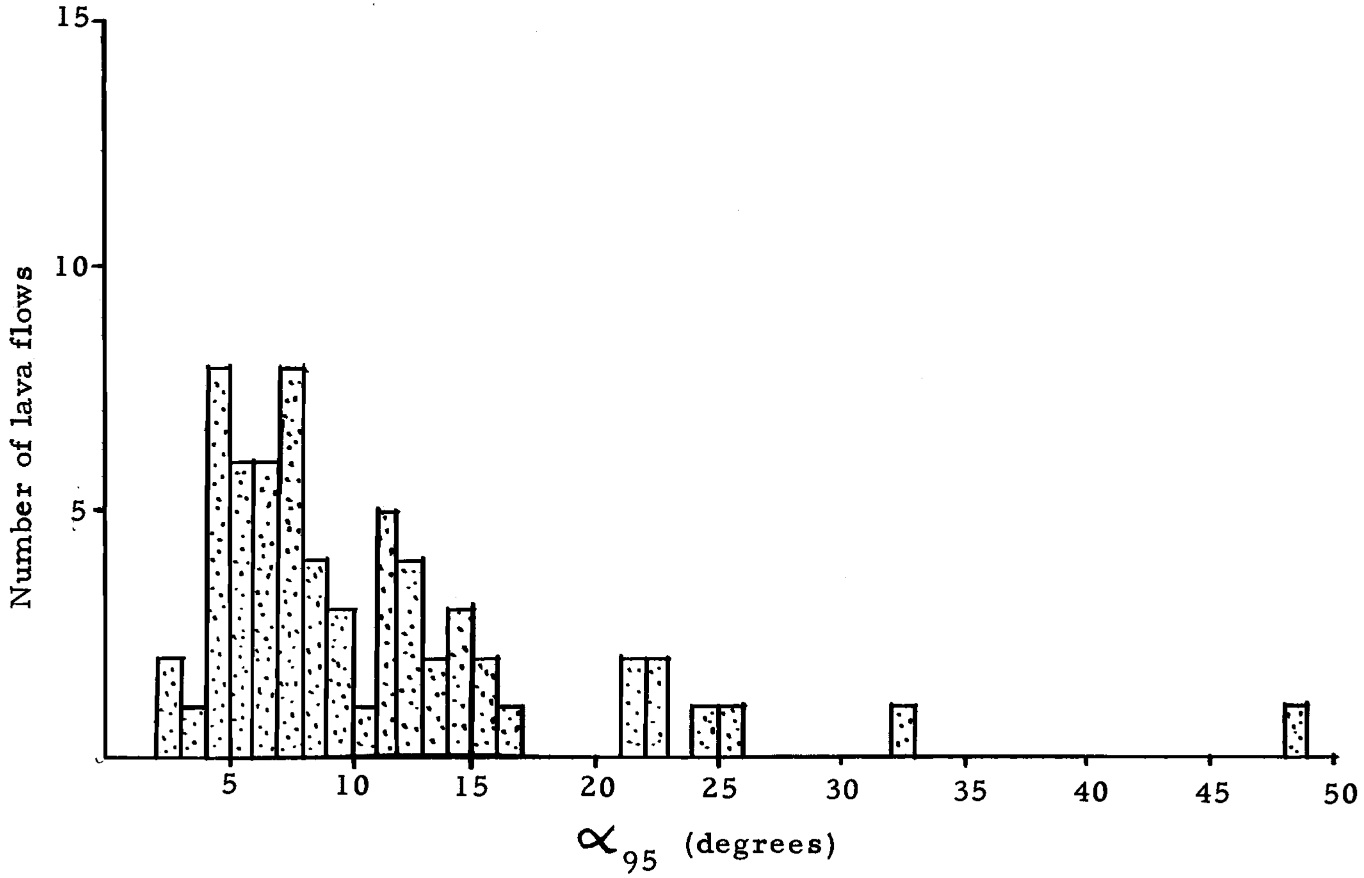

Figure 10. Histogram of α_{95} for the 65 Terevaka flows.

for the Easter Island data. One set (set A) contained only flows with α_{95} less than 10°. The other set included all the flows regardless of α_{95} values. For both sets the flows with VGP latitudes less than 50° were removed, as were any flows with less than four separate sample sites. This left 31 flows for set A and 51 flows for set B.

Following the methods outlined previously the angular standard deviation of the VGPs with respect to the geographic pole was calculated for each set. The results are presented in Figure 11. The final measure of dispersion is reported with its upper and lower 95% confidence limits (S_u and S_i) determined from tables presented by Cox 1969c).

	S_T	k_T	k_W	k_A	k_F	S_F	S_u	S_i
Set A wrt VGP	13.07	38.40	32.08	2100	56.27	10.80	13.06	9.19
wrt geogr. pole	13.09	38.31			56.07	10.82	13.09	9.23
Set B wrt VGP	15.79	26.33	19.57	2100	40.44	12.74	14.75	11.22
wrt geogr. pole	15.80	26.29			40.34	12.75	14.78	11.21

Figure 11. Secular variation statistics for Terevaka flows.

Brunhes Secular Variation Versus Latitude

Doell and Cox (1972) have presented angular dispersion values for eight different paleomagnetic studies on Brunhes age volcanics. Their sampling sites include the Galapagos Islands (Cox, 1971), Hawaii (Doell, 1969, 1972 , 1972b, 1972c), western United States (unpublished data), New Zealand (Cox, 1969b), France (Doell, 1970), Alaska (Hoare et al., 1968), Iceland (Doell, 1972d), and Antarctica (unpublished data). They plot this data on an angular dispersion versus latitude diagram (Figure 12). Model D of Cox (1970) has been adapted to estimated Brunhes age geomagnetic field values. The dipole wobble, W_d, is a constant 11^{o}. The non-dipole term, W_n, is approximated by calculating the angular dispersion for the non-dipole component of the 1965 International Geomagnetic Reference Field. These two factors are combined to provide the proposed model, the upper solid line on Figure 12.

In the past several years other workers have determined additional angular dispersion values for Brunhes age rocks. These are included in Figure 12, and their sources are as follows: Comore Island (Watkins and Nougier, 1973); Reunion Island (Watkins, 1973); Amsterdam Island (Watkins and Nougier, 1973); Azores (Ellwood et al., 1973); Japan (Ozima and Aoki, 1972); Crozet Island (Watkins and Nougier, 1973); and Aleutian Islands (Bingham and Stone, 1972).

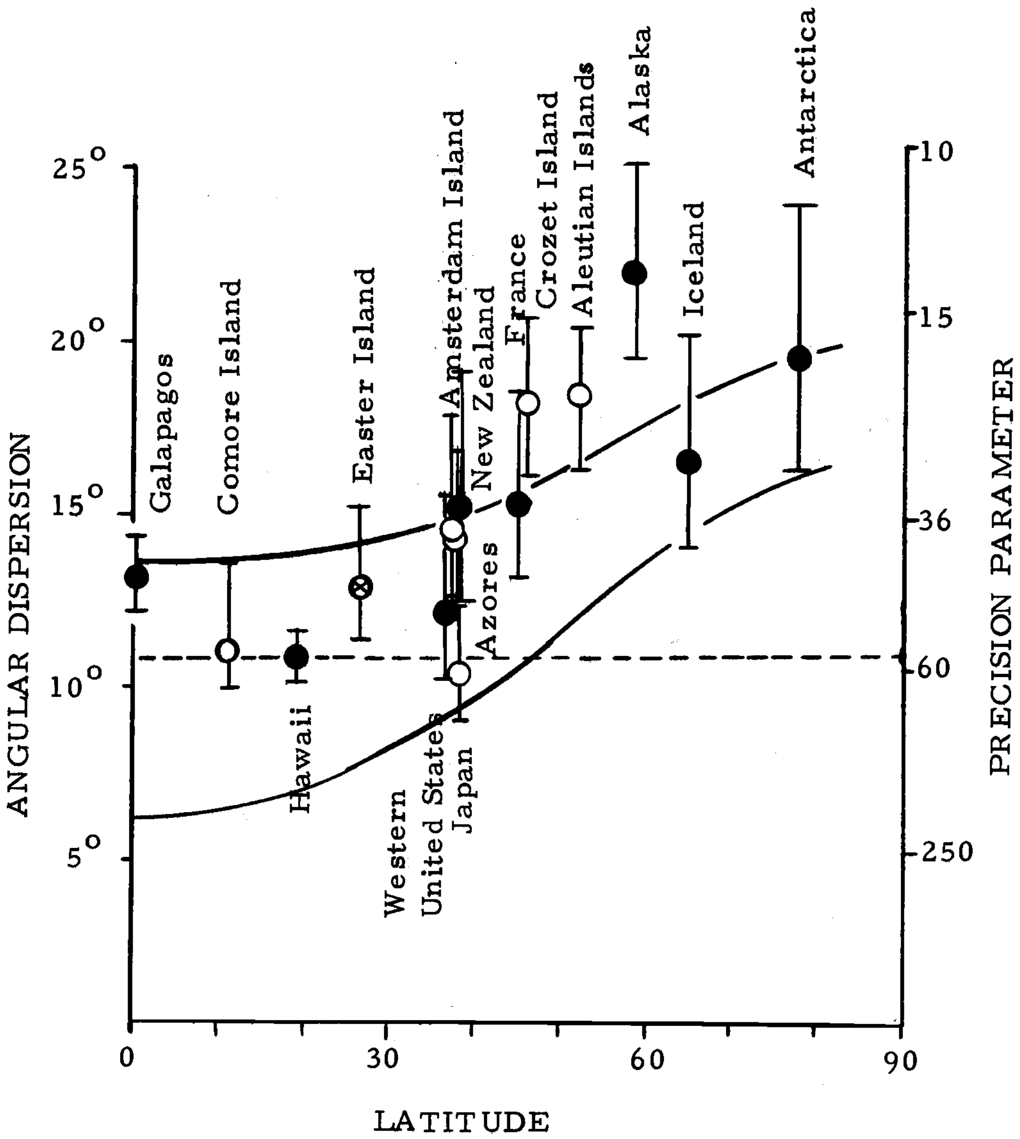

Figure 12. Angular dispersion of virtual geomagnetic poles with respect to the geographic axis.

It must be pointed out that the various studies follow different criteria in selecting the useable data, and exact comparison between results is not possible.

The Easter Island secular variation value found in this study is also plotted on the graph. It falls just below the proposed model, but with 95% confidence limits which cover a broad area on either side of the model. Even though direct comparison of all points is not possible, the general trend of the actual data is obvious. There definitely is an increase of secular variation with increasing latitude, but to use the data as support for this specific model is difficult.

To improve the data as a measure of the model's validity, one needs more paleomagnetic studies which fit the sampling criteria. There have been many studies done on Brunhes age rocks, but very few have sufficient samples and/or sites to allow for angular dispersions calculations. Since the confidence limits are directly related to the number of lavas sampled, large studies will produce narrow limits of angular dispersion.

The determination of the non-dipole part of the model is another area of question. The use of the 1965 IGRF assumes that the present non-dipole activity is representative of that in the Brunhes, but this is not necessarily so. It would be most desirable to have a better measure of the ancient non-dipole activity, and its dependence on latitude.

The problem of sampling sufficient time has been raised by Aziz-Ur-Rahman and McDougall (1973) from their studies on Norfolk and Philip Islands. They suggest that the short time spanned by many Brunhes age studies may not be long enough to accurately estimate secular variation. A minimum of 0.5 million years is proposed by them as a suitable time interval. The Easter Island data covers only half that time. A proposed subject for future study will be a secular variation investigation over the entire island. This would span at least 2.5 million years, and give an indication whether increased time produces a better estimate of secular variation.

Central Pacific Secular Variation Low

The occurrence of an extensive area of low non-dipole field intensity was observed in the central Pacific Ocean by Cox (1962) and Cox and Doell (1964). Later investigations by these authors lead to evidence that a minimum non-dipole field and minimum secular variation has persisted in the central Pacific for at least the last 0.7 million years (Doell and Cox, 1971; Doell and Cox, 1972). They postulate inhomogeneities in the lower mantle or undulations of the core-mantle boundary as possible causes of the persistently subdued non-dipole field. This low is very evident on the Brunhes angular dispersion-latitude plot (Figure 12), where Hawaii falls well below the proposed model. It is very close to the dipole wobble component, implying that little non-dipole field is present, and the observed secular variation is due to the dipole wobble only. This phenomenon is termed 'dipole window' and allows one to look at variations in the core without the complications of the non-dipole field.

An original aim of this study was to investigate the south-eastern Pacific for an extension of this low. As can be seen from Figure 12, Easter Island lies above the dipole wobble component, but below the proposed model. It appears that the Pacific secular variation low extends into the southeast, but it is certainly not as pronounced as it is around Hawaii. The Galapagos Islands in the eastern Pacific appear to be unaffected by any low variation, as they have an angular dispersion value similar to that predicted by the model. More localities in the Pacific are needed to further delineate and investigate the Pacific secular variation low.

Conclusions

The Easter Island lava flows present an excellent opportunity to investigate the nature of the geomagnetic field in the recent past. From the 65 Brunhes age flows sampled, inclinations, declinations and VGPs were calculated. The mean VGP, only slightly different from the rotation axis, was as expected for very young rocks. A possible excursion of the field was observed in four flows, and it may be related to the previously observed Blake event. A secular variation study of the lavas gave an angular dispersion of 12.8°. Although it was lower than predicted by the current model for secular variation, it was higher than the Hawaiian Islands, known to be anomalously low.

Although this study is complete for the Brunhes age rocks, it would be desirable to further sample and study the older flows on the island.

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APPENDICES

APPENDIX I

APPENDIX I

Paleomagnetic Data for Easter Island

UNIT	N	I	D	R	K	α_{95}	θ'	Φ'	EXP
				TEREVAKA EPISODE					
1	3	-34.2	32.4	2.9914	232	8.1	59.1	331.4	NRM
2	4	-38.6	26.8	3.9859	213	6.3	65.1	333.5	NRM
3	4	-43.0	356.3	3.8279	17	22.6	86.0	192.9	H200
4	4	-49.3	0.0	3.9799	149	7.6	87.0	70.8	NRM
6	4	-34.8	348.9	3.9819	165	7.2	77.0	195.9	NRM
7	4	-43.5	5.3	3.9839	186	6.8	84.9	320.5	H50
8	4	-42.3	10.5	3.9808	156	7.4	80.2	326.5	H50
9	4	-59.3	329.5	3.9381	48	13.3	61.7	125.3	H150
10	4	-54.5	339.1	3.9498	60	12.0	70.5	131.3	H100
11	4	-52.6	11.6	3.9790	143	7.7	78.3	13.9	NRM
12	3	-46.1	4.4	2.9388	33	21.9	86.1	345.5	H50
13	3	-42.3	0.2	2.9924	263	7.6	87.3	254.1	H50
14	4	-53.8	306.1	3.9253	40	14.7	43.7	137.4	H200
15	3	-36.6	12.8	2.9671	61	16.0	76.5	313.1	H200
16	4	-35.3	4.9	3.9913	344	5.0	81.1	281.9	NRM
17	4	-44.1	16.6	3.9494	59	12.0	75.1	339.0	NRM
18	3	-47.4	3.5	2.9994	3258	2.2	86.6	4.7	NRM
19	4	-46.6	3.8	3.9705	101	9.2	86.5	353.3	NRM
20	4	-44.0	5.6	3.9906	318	5.2	84.8	327.0	NRM
21	3	-53.1	354.8	2.9991	2130	2.7	82.1	103.6	NRM
22	4	-57.8	329.3	3.9930	426	4.5	61.9	128.5	NRM
23	4	-57.6	325.7	3.9915	352	4.9	59.3	130.2	H50
24	3	-46.6	5.7	2.9935	308	7.0	84.9	349.5	H50

UNIT	N	I	D	R	K	α_{95}	θ'	ϕ'	EXP
25	4	-40.7	14.9	3.9895	287	5.4	76.0	327.4	NRM
26	4	-56.3	324.3	3.9447	54	12.6	58.4	133.1	NRM
27	4	-44.7	340.6	3.9416	51	12.9	72.7	158.3	NRM
28	4	-49.5	338.2	3.9550	67	11.3	70.6	145.5	NRM
29	4	-41.2	2.6	3.9921	380	4.7	85.9	285.1	NRM
30	4	-48.9	357.9	3.9856	208	6.4	86.7	103.6	NRM
31	4	-43.1	2.6	3.9542	66	11.4	86.9	300.1	NRM
32	3	-62.1	312.6	2.9975	784	4.4	48.7	124.3	H200
33	4	-62.5	326.2	3.9865	222	6.2	58.1	119.7	NRM
34	4	-68.7	321.2	3.8440	19	21.5	51.8	108.8	H50
36	4	-37.4	10.0	3.9932	443	4.4	79.0	308.4	NRM
37	4	-45.8	14.1	3.9935	462	4.3	77.5	344.1	NRM
38	4	-48.1	352.2	3.9440	54	12.7	82.8	141.5	H50
39	4	-37.4	8.6	3.9898	293	5.4	80.1	304.0	NRM
40	4	-47.1	6.3	3.9831	177	6.9	84.3	354.2	NRM
41	4	-42.0	357.0	3.9878	246	5.9	86.1	206.5	NRM
45	4	-35.0	3.1	3.9759	125	8.3	81.7	271.2	H100
46	3	-35.6	358.3	2.9939	327	6.8	82.4	238.0	H100
47	4	-31.7	6.1	3.9753	122	8.4	78.6	281.4	NRM
48	4	-40.6	356.9	3.9812	159	7.3	85.2	214.1	H100
49	4	-30.4	27.1	3.9200	38	15.2	62.8	322.7	NRM
50	3	-30.8	345.2	2.8729	16	32.2	72.8	194.6	H400
51	4	-25.7	337.0	3.9050	32	16.6	64.6	188.1	H50
52	3	-42.8	333.7	2.9335	30	22.9	66.3	159.8	H50
53	3	-55.2	353.9	2.9824	114	11.6	80.0	100.0	H50
54	4	-16.8	344.4	3.3487	5	48.2	66.3	208.9	H100
55	4	-52.4	17.4	3.9496	60	12.0	73.9	5.6	NRM
56	4	-39.5	5.0	3.9309	43	14.1	83.5	294.6	NRM
58	4	-37.2	15.9	3.9314	44	14.1	74.2	320.1	NRM

UNIT	N	I	D	R	K	α_{95}	θ'	ϕ'	EXP
59	4	-42.4	11.0	3.9408	51	13.0	79.7	328.1	NRM
60	4	-39.9	344.8	3.7861	14	25.4	75.6	174.8	H100
61**									
62	4	-42.6	359.9	3.9658	88	9.9	87.5	247.2	H50
63	4	-44.2	1.4	3.9884	257	5.7	88.3	295.5	NRM
64	4	-49.7	12.2	3.9936	467	4.3	78.8	0.8	NRM
65	4	-43.3	355.1	3.9806	155	7.4	85.2	182.7	NRM
66	4	-36.9	352.0	3.9658	88	9.9	80.1	200.4	NRM
67	4	-41.5	1.7	3.9884	258	5.7	86.4	274.8	NRM
68	4	-36.5	348.6	3.9952	627	3.7	77.5	191.1	NRM
69	4	-48.9	5.8	3.9716	106	9.9	84.2	8.9	NRM
70	4	-37.6	348.8	3.7966	15	24.8	78.1	188.7	H200
H20	3	-41.8	309.7				44.9	11.5	
H21	2	-37.2	89.9				9.4	218.0	
H23	1	-54.8	58.9				39.7	224.1	
H24	1	-25.3	322.7				52.6	33.5	
H26	2	-34.8	206.7				-36.9	321.4	
H27	2	-21.7	311.2				41.6	28.8	
H28	2	-45.5	43.7				51.3	209.4	
H29	1	-13.5	7.7				68.4	130.7	
H30	2	-25.3	353.9				75.0	86.0	
H33	1	-14.9	77.9				14.2	200.8	
H34	2	-31.2	154.0				-39.9	256.6	
H36	1	-14.5	89.5				3.8	205.7	

RANO KAU EPISODE

UNIT	N	I	D	R	K	α_{95}	θ'	ϕ'	EXP
H1	2	-43.6	284.5				23.4	2.0	
H2	1	-32.9	305.2				39.4	17.7	
H3	1	-52.2	188.0				-29.6	297.2	

UNIT	N	I	D	R	K	α_{95}	Θ'	Φ'	EXP
H4	2	-43.6	36.1				57.3	201.5	
H5	2	-37.6	196.2				-39.3	309.1	
H12	1	17.1	290.6				13.9	37.1	
H14	3	-39.8	217.5				-28.4	329.2	
H16	2	-38.4	152.1				-34.2	257.7	
H17	2	-26.3	319.2				49.8	30.4	
H18	1	-17.0	277.5				10.6	15.0	
				POIKE EPISODE					
42	5	-48.0	13.1				79.3	212.0	
43	4	-25.7	4.9				75.7	128.9	
44	4	-16.3	354.3				70.6	93.7	
57	4	-48.2	358.1				87.4	327.3	
H7	2	-43.0	121.4				-13.2	236.6	
H9	1	-40.9	313.2				47.8	13.5	
H10	1	-49.3	324.9				59.2	5.2	

N, number of separate cores per flow
I, inclination in degrees below the horizontal
D, declination in degrees
R, length of the resultant vector
K, precision parameter
α_{95}, radius of the cone of 95% confidence about the resultant vector
Θ', latitude in degrees of the VGP
Φ', longitude in degrees of the VGP
EXP, level at which remanent magnetization was measured

** flow gave random results, discarded

Easter Island Collection Numbers listed inclusively per flow

Unit	Collection Numbers	Unit	Collection Numbers
1	EC-123 - EC-126	53	EC-364 - EC-367
2	EC-127 - EC-130	54	EC-368 - EC-371
3	EC-131 - EC-134	55	EC-372 - EC-375
4	EC-135 - EC-138	56	EC-376 - EC-379
6	EC-143 - EC-146	58	EC-384 - EC-387
7	EC-147 - EC-150	59	EC-388 - EC-391
8	EC-151 - EC-154	60	EC-392 - EC-395
9	EC-155 - EC-159	61	EC-396 - EC-399
10	EC-160 - EC-163	62	EC-400 - EC-403
11	EC-164 - EC-167	63	EC-404 - EC-407
12	EC-168 - EC-170	64	EC-408 - EC-411
13	EC-171 - EC-173	65	EC-416 - EC-419
14	EC-174 - EC-177	66	EC-420 - EC-423
15	EC-178 - EC-181	67	EC-424 - EC-427
16	EC-182 - EC-185	68	EC-428 - EC-431
17	EC-186 - EC-189	69	EC-432 - EC-435
18	EC-190 - EC-193	70	EC-436 - EC-439
19	EC-195 - EC-198	H20	EH-82 - EH-84
20	EC-199 - EC-202	H21	EH-87 - EH-88
21	EC-204 - EC-207	H23	EH-93 - EH-94
22	EC-208 - EC-211	H24	EH-95
23	EC-212 - EC-215	H26	EH-99 - EH-100
24	EC-216 - EC-219	H27	EH-101 - EH-102
25	EC-220 - EC-223	H28	EH-104 - EH-105
26	EC-224 - EC-227	H29	EH-106 - EH-107
27	EC-228 - EC-231	H30	EH-108 - EH-109
28	EC-232 - EC-235	H33	EH-114 - EH-115
29	EC-236 - EC-239	H34	EH-117 - EH-118
30	EC-240 - EC-243	H36	EH-121 - EH-122
31	EC-244 - EC-247	H1	EH-13 - EH-14
32	EC-248 - EC-251	H2	EH-15
33	EC-252 - EC-255	H3	EH-19
34	EC-256 - EC-259	H4	EH-21 - EH-22
36	EC-261 - EC-264	H5	EH-23 - EH-24
37	EC-265 - EC-268	H12	EH-53 - EH-54
38	EC-269 - EC-272	H14	EH-57 - EH-59
39	EC-273 - EC-276	H16	EH-64 - EH-65
40	EC-277 - EC-280	H17	EH-66 - EH-67
41	EC-281 - EC-284	H18	EH-68
45	EC-317 - EC-320	42	EC-304 - EC-308
46	EC-321 - EC-324	43	EC-309 - EC-312
47	EC-325 - EC-328	44	EC-313 - EC-316
48	EC-329 - EC-332	57	EC-380 - EC-383
49	EC-333 - EC-336	H7	EH-38 - EH-39
50	EC-337 - EC-340	H9	EH-43
51	EC-341 - EC-344	H10	EH-45 - EH-46
52	EC-345 - EC-348		

APPENDIX II

Computer programs

SPINNER

SIMPLET

RVGP

```
      PROGRAM SPINNER
C
C         **********SPINNER**********
C
C        DECEMBER 14, 1970   STANFORD UNIVERSITY, DEPT. OF GEOPHYSICS
C        CHARLES R. DENHAM, AFTER SHERM GROMME OF USGS
C
C        PURPOSE
C                 PROGRAM SPINNER IS A DATA REDUCTION PROGRAM FOR
C                 SPINNER MAGNETOMETER MEASUREMENTS.  THE PROGRAM
C                 ACCEPTS BOTH SLOW AND FAST SPINNER TYPE DATA.
C                 IT DETERMINES THE BEST MAGNETIC DIRECTION AND
C                 MOMENT IMPLIED BY THE SPINNER DATA, AND COMPUTES
C                 SEVERAL STATISTICAL PARAMETERS.
C
C        REFERENCE
C                 THE ALGORITHM FOR THIS PROGRAM IS GIVEN IN DOELL
C                 AND COX, (1965), MEASUREMENT OF THE REMANENT MAG-
C                 NETIZATION OF IGNEOUS ROCKS, U.S. GEOLOGICAL SURVEY
C                 BULLETIN 1203-A.
C
C        COMPATIBILITY
C                 SPINNER IS DESIGNED FOR STANFORD#S IBM SYSTEM 360/67
C                 WATFIV FORTRAN 4 COMPILER.
C
C        UPDATING THE PROGRAM
C                 ALL SIGNIFICANT CHANGES MADE IN THIS PROGRAM AFTER
C                 OCTOBER 11, 1970, SHOULD BE NOTED HERE.  WRITE A FEW
C                 COMMENTS, INDICATE THE DATE, AND ADD 1 TO THE
C                 UPDATE INTERNALLY STORED IN THE PROGRAM.
C
C                 UPDATE=1               ORIGINAL USGS FAST-SPINNER
C                                        PROGRAM, CIRCA 347 B.C.
C                 UPDATE=2               READS AND USES SLOW-SPINNER
C                                        TYPE DATA ONLY.  1969.
C                 UPDATE=3               READS AND USES SLOW- AND FAST-
C                                        SPINNER TYPE DATA.  WRITES
C                                        OUTPUT ON PRINTER,
C                 UPDATE=4               PROGRAM ADAPTED TO OSU
C                                        CDC SYSTEM, INPUT AND OUT-
C                                        PUT POSSIBLE VIA TELETYPE,
C                                        JULY,1973.
C
C        SLOW-SPINNER CALIBRATION CONSTANT
C                 CALIB     IN EMU PER VOLT INPUT TO THE ITHACO
C                           353 PHASE-SENSITIVE DETECTOR 81 AMPLIFIER
C
C        DESCRIPTION OF PARAMETERS
C
C                 INPUT NAMES COMMON TO SLOW- AND FAST-SPINNER DATA
C                           ID          IDENTIFICATION OF THE MEASURED
C                                       SAMPLE. IF ID IS THE WORD
C                                       #RESIDUAL  #, THE MEASUREMENTS
C                                       ARE THE SLOW-SPINNER RESIDUAL.
C                                       THE RESIDUAL WILL BE SUBTRACTED
C                                       FROM ALL FOLLOWING SLOW-SPINNER
C                                       DATA, UNTIL NEW RESIDUAL DATA IS
C                                       ENCOUNTERED.
C                           AL          ALPHA, AZIMUTH OF THE +Y AXIS
```

```
C                                      (HORIZONTAL) OF THE SAMPLE
C                                      IN A RIGHT-HANDED XYZ COORDINATE
C                                      SYSTEM.  IN DEGREES.
C                              BE      BETA, THE PLUNGE OF THE +Z AXIS
C                                      (POSITIVE DOWNWARD) (DEGREES)
C                              V       VOLUME OF THE SAMPLE
C                                      (CUBIC CENTIMETERS)
C                              STR     AZIMUTH OF THE STRIKE OF THE
C                                      BED, TO THE RIGHT OF THE DIP
C                                      DIRECTION.
C                              DIP     DIP OF THE BED (POSITIVE=DOWN)
C                                      (EXAMPLE:  A BED WHICH STRIKES
C                                      N30W AND DIPS 45E WILL HAVE
C                                      STR=150. AND DIP=45. OR
C                                      STR=330. AND DIP=-45.)
C                              IEXP    IDENTIFICATION OF THE EXPERIMENT
C                              INF     ANY ADDITIONAL INFORMATION
C
C          INPUT FORMAT
C                 FREE-FORMAT.  SEPARATE THE DATA BY ONE COMMA AND/OR
C                 ONE OR MORE BLANKS.
C                 ANY NUMBER OF DATA PER CARD.  THE COMPUTER
C                 READS ITEMS UNTIL IT FINDS ENOUGH TO
C                 SATISFY THE PROGRAM REQUIREMENTS.  THE NEXT
C                 READ STATEMENT WILL READ A NEW SET OF MEASUREMENTS.
C
C                 FAST SPINNER INPUT NAMES
C                              EXTRA   A DUMMY NUMBER, NEEDED TO GIVE
C                                      THE FAST-SPINNER INPUT THE SAME
C                                      NUMBER OF ITEMS AS THE SLOW-
C                                      SPINNER INPUT.  IT IS NOT
C                                      USED IN THE COMPUTATIONS.
C                              P(M,L)  PHASE (DEGREES)
C                              RM(M,L) MAGNITUDE (EMU)
C
C                 SLOW SPINNER INPUT NAMES
C                              SCALE   SENSITIVITY SETTING OF THE
C                                      ITHACO 353 PHASE-SENSITIVE
C                                      DETECTOR B-1 AMPLIFIER, IN
C                                      MICRO-VOLTS.
C                              SPIN(M,L,1), SPIN(M,L,2)
C                                      IN-PHASE (0) AND OUT-OF-PHASE (9
C                                      COMPONENTS, RESPECTIVELY, ON A M
C                                      SCALE OF -10 TO +10 VOLTS.
C
C                 SLOW-SPINNER RESIDUAL INPUT NAMES
C                              RESID(M,L,1),RESID(M,L,2)
C                                      IN-PHASE AND OUT-OF-PHASE COMPON
C                                      OF THE RESIDUAL
C
C         THE DATA CARDS.....
C         THE DATA FOR EACH MEASURED SPECIMEN IS INPUT TO THE SPINNER
C         PROGRAM IN THE FOLLOWING ORDERS.....
C
C         SLOW-SPINNER DATA.....SPECIMEN OR RESIDUAL
C                ID,AL,BE,V,STR,DIP,IEXP,INF,SCALE,SPIN(X,Y,0),
C                SPIN(X,Y,90),SPIN(X,-Y,0),SPIN(X,-Y,90),
C                SPIN(Y,Z,0),SPIN(Y,Z,90),SPIN(Y,-Z,0),
C                SPIN(Y,-Z,90),SPIN(Z,X,0),SPIN(Z,X,90),
```

```
C                   SPIN(Z,-X,0),SPIN(Z,-X,90)
C
C                   IF ID IS THE WORD ≠RESIDUAL ≠, THE SLOW-SPINNER
C                   MEASUREMENTS ARE THE RESIDUAL.
C
C            FAST-SPINNER DATA
C                   ID,AL,BE,V,STR,DIP,IEXP,INF,EXTRA,PHASE(X,Y),
C                   MAGNITUDE(X,Y),PHASE(X,-Y),MAGNITUDE(X,-Y),
C                   PHASE(Y,Z),MAGNITUDE(Y,Z),PHASE(Y,-Z),
C                   MAGNITUDE(Y,-Z),PHASE(Z,X),MAGNITUDE(Z,X),
C                   PHASE(Z,-X),MAGNITUDE(Z,-X)
C
C            EACH SPECIMEN≠S INPUT DATA MAY BE SPREAD OVER AS MANY OR
C            FEW CARDS AS THE USER DESIRES, SO LONG AS THE PROPER ORDERING
C            OF THE INPUT ITEMS IS MAINTAINED.  DO NOT PUT DATA FROM TWO
C            DIFFERENT SPECIMENS ON THE SAME CARD.
C
C                    OUTPUT NAMES
C                              ID          SAME AS INPUT ID
C                              I           INCLINATION (DEGREES)
C                              D           DECLINATION
C                              J           MAGNETIC MOMENT PER UNIT VOLUME
C                                          (EMU/CC)
C                              M           TOTAL MAGNETIC MOMENT (EMU)
C                              A           AN ANALOGUE OF THE RADIUS OF THE
C                                          ERROR TRIANGLE FORMED BY THE THR
C                                          GREAT CIRCLES DEFINED BY THE PHA
C                                          ANGLES
C                              MM          THE ROOT-MEAN-SQUARE OF THE DIFF
C                                          BETWEEN THE SIX MEASURED MAGNETI
C                                          INTENSITIES AND THE IDEAL INTENS
C                                          THAT WOULD BE EXPECTED IF THE SA
C                                          ACTED AS AN IDEAL DIPOLE WITH MO
C                                          M AND THE DIRECTION OF MAGNETIZA
C                                          CALCULATED.  MM IS TAGGED IF IT
C                                          0.05 (5 PERCENT OF M)
C                              2 DEL(I)    PHASE-ANGLE INCONSISTENCY BETWEE
C                                          FORWARD AND BACKWARD SPINS FOR E
C                                          PLANE.  OUTPUT AND TAGGED IF EXC
C                                          4.9 DEGREES
C                              M DIFFERENCE(I)
C                                          INTENSITY INCONSISTENCY BETWEEN
C                                          FORWARD AND BACKWARD SPINS FOR E
C                                          PLANE.  OUTPUT AND TAGGED IF EXC
C                                          5.0 PERCENT OF M
C                              IFLAG       IF 2 DEL(I) AND/OR M DIFFERENCE(
C                                          AND/OR MM EXCEED THEIR RESPECTIV
C                                          TOLERANCE LIMITS, IFLAG=*.  OTHE
C                                          IFLAG=BLANK.
C                              IEXP        SAME AS INPUT IEXP
C                              INF         SAME AS INPUT INF
C                              N           WEIGHTING-FACTOR EXPONENT FOR CC
C                                          THE ERROR-TRIANGLE.
C                              L           NUMBER OF ITERATIONS TO CONVERGE
C                                          ERROR-TRIANGLE TO 0.01 DEGREES R
C                              UPDATE      REFERS TO CHANGES WHICH HAVE BEE
C                                          IN THIS PROGRAM SINCE OCTOBER 11
C                                          SEE NOTES ABOVE.
C
```

```
C         REMARKS CN CUTPUT INFORMATION
C                   THE FOLLOWING ARE NOT OUTPUT ON CARDS
C                            2 DEL(I)
C                            M DIFFERENCE(I)
C                            INF
C                            N
C                            L
C
C         SUBROUTINES AND FUNCTION SUBPROGRAMS SUPPLIED
C                   ATAN9(Y,X,A)          PERFORMS THE SAME DUTY AS THE FL
C                                         ATAN2(Y/X).  A=ATAN2(Y/X), WHERE
C                                         BETWEEN -PI AND +PI RADIANS.
C                                         USAGE      CALL ATAN9(Y,X,A)
C
C         SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C                   SIN(X)
C                   COS(X)
C                   SQRT(X)
C                   ATAN(X)
C                   SIGN(X,Y)
C                   ABS(X)
C                   THESE ARE ALL STANDARD FUNCTIONS, AVAILABLE ON
C                   WATFIV AND AERO-ASTRO≠S SDS SYSTEM.
C
C         METHOD
C                   EACH OF THE THREE MAJOR PLANES (XY,YZ,ZX) OF THE SAM
C                   ORIENTATION SYSTEM HAS BEEN MEASURED TWICE.  THE AVE
C                   PHASE AND INTENSITY FOR THE MAGNETIC COMPONENT LYING
C                   EACH PLANE IS CALCULATED.  THE THREE PHASE ANGLES AR
C                   USED TO GENERATE A TRIANGLE-OF-ERROR ON A SPHERE (AS
C                   ONE WERE USING A STEREONET), WITHIN WHICH LIES THE C
C                   MAGNETIC DIRECTION.  THE TRIANGLE IS CONVERGED, USIN
C                   THREE INTENSITIES AS WEIGHTING-FACTORS.  THE STRONGE
C                   PLANES ARE GIVEN MORE CONFIDENCE THAN THE WEAKEST ON
C                   (≠≠CONFIDENCE≠≠ = INTENSITY**N, WHERE N=2 INITIALLY,
C                   AND N=6 MAXIMUM.)  ONCE THE ERROR-TRIANGLE HAS COLLA
C                   TO 0.01 DEGREES RADIUS, THE STRONGEST VERTEX IS CHOS
C                   AS THE PREFERRED DIRECTION INDICATED BY THE SPINNER
C                   MAGNETOMETER MEASUREMENTS.
C
C     BEGIN THE MAIN PROGRAM SPINNER
C
      INTEGER UPDATE
      CHARACTER ISTAR,IFLAG
      CHARACTER IBLANK
      REAL ID1,ID2,IEXP,INF
      DIMENSION P(2,3),PA(3),RM(2,3),RMA(3),CM(3),DS(2,3),W(3),
     1DEL(3)
      DIMENSION SPIN(3,2,2),RESID(3,2,2),RSPIN(3,2,2)
      UPDATE=4
      ISTAR=1H*
      IFLAG=IBLANK=1H
      CALIB=1.12
      RCF=57.2957795
C
C      .   WRITE HEADING AND OUTPUT UPDATE AND CALIB
C
      WRITE (61,4001)
 4001 FORMAT(30X,≠PROGRAM SPINNER≠,//)
```

```
      WRITE (61,4002) UPDATE
 4002 FORMAT(≠ PROGRAM MODIFICATION NUMBER = UPDATE =≠,I2)
      WRITE (61,4003) CALIB
 4003 FORMAT(≠ SLOW-SPINNER-CALIBRATION CONSTANT =≠,F4.2,≠ EMU/VOLT≠)
C
C          INITIALIZE THE SLOW SPINNER RESIDUAL
C
      RESIDA=0.
      DO 3 L=1,3
      DO 3 M=1,2
      DO 3 N=1,2
      RESID(L,M,N)=0.0
    3 CONTINUE
C
C           READ THE INPUT DATA, AS IF IT WERE FROM THE
C           SLOW-SPINNER
C
      WRITE (61,8001)
 8001 FORMAT(≠PTTY INPUT AT 10≠)
   10 READ(60,7001) ID1,AL,BE,V,STR,DIF,IEXP,INF,
     1SCALE
 7001 FORMAT(A8,2(F4.1),F4.2,2(F4.1),2A8,F3.0)
      READ(60,7002) ((SPIN(L,M,1),SPIN(L,M,2),M=1,2),L=1,3),ID2
 7002 FORMAT(12(F4.2),A8)
      IFLAG=IBLANK
      IF(ID1.EQ.ID2) GO TO 12
      WRITE (61,4011)
 4011 FORMAT(≠-SAMPLES OUT OF ORDER≠)
      CALL EXIT
C
C           WRITE A HEADING
C
   12 WRITE (61,4014)
 4014 FORMAT(//////////)
      WRITE (61,4004)
 4004 FORMAT(≠ IDENTIFICATION      ALPHA      BETA    VOLUME    STRIKE
     1     DIP      EXPERIMENT     ADDITIONAL INFORMATION≠)
C
C           IS THE DATA FAST-SPINNER TYPE^
C
      SUM=0.
      DO 21 L=1,3
      DO 21 M=1,2
      SUM=SUM+SPIN(L,M,1)+SPIN(L,M,2)
   21 CONTINUE
      IF(SUM.GT.200.) GO TO 5003
      GO TO 5705
C
C           THE DATA IS REALLY FAST-SPINNER TYPE.
C           MAKE APPROPRIATE ADJUSTMENTS.
C
 5003 DO 23 L=1,3
      DO 23 M=1,2
      P(M,L)=SPIN(L,M,1)
      RM(M,L)=SPIN(L,M,2)
   23 CONTINUE
C
C           WRITE THE FAST-SPINNER DATA
C
```

```
      WRITE (61,5301) ID1,AL,BE,V,STR,DIP,IEXP,INF
 5301 FORMAT(≠ ≠,A8,4X,5(0PF10.1),5X,A9,6X,A48,/)
      WRITE (61,4008)
 4008 FORMAT(18X,≠(+X,+Y SPIN)≠,6X,≠(+X,-Y SPIN)≠,6X,≠(+Y,+Z SPIN)≠,6X,
     1≠(+Y,-Z SPIN)≠,6X,≠(+Z,+X SPIN)≠,6X,≠(+Z,-X SPIN)≠)
      WRITE (61,4007)
 4007 FORMAT(≠ FAST-SPINNER:  PHASE  MAGNITUDE  PHASE  MAGNITUDE  PHASE
     1 MAGNITUDE  PHASE  MAGNITUDE  PHASE  MAGNITUDE  PHASE  MAGNITUDE≠)
      WRITE (61,5303) ((P(M,L),RM(M,L),M=1,2),L=1,3)
 5303 FORMAT(≠ MEASUREMENTS:≠,6(0PF7.1,1PE11.2))
      GO TO 2009
C
C           WRITE THE SLOW-SPINNER DATA
C
 5705 WRITE (61,5301) ID1,AL,BE,V,STR,DIP,IEXP,INF
      WRITE (61,4005)
 4005 FORMAT(≠ SLOW-SPINNER:  SENSITIVITY    +X      +Y      +X      -Y
     1 +Y      +Z      +Y      -Z      +Z      +X      +Z      -X≠)
      IF(ID1.NE.8HRESIDUAL) GO TO 5704
      RESIDA=9999.
      WRITE (61,4012)
 4012 FORMAT(≠ ****RESIDUAL≠)
      WRITE (61,5703) SCALE,((SPIN(L,M,1),SPIN(L,M,2),M=1,2),L=1,3)
      GO TO 5805
 5704 WRITE (61,5703) SCALE,((SPIN(L,M,1),SPIN(L,M,2),M=1,2),L=1,3)
 5703 FORMAT(≠ MEASUREMENTS:≠,F6.2,12F7.1)
 5805 CONTINUE
C
C          CONVERT SLOW SPINNER DATA TO EMU
C
      DO 2002 L=1,3
      DO 2002 M=1,2
      DO 2002 N=1,2
      SPIN(L,M,N) = SPIN(L,M,N)*SCALE*CALIB
      SPIN(L,M,N) = SPIN(L,M,N)*.001
 2002 CONTINUE
C
C          SET THE SLOW SPINNER RESIDUAL
C
      IF(ID1.NE.8HRESIDUAL) GO TO 2001
      DO 4016 L=1,3
      DO 4016 M=1,2
      DO 4016 N=1,2
      RESID(L,M,N)=SPIN(L,M,N)
 4016 CONTINUE
      GO TO 10
C
C      CORRECT SLOW SPINNER DATA FOR RESIDUAL
C
 2001 IF(RESIDA.NE.9999.) GO TO 2005
      DO 4018 L=1,3
      DO 4018 M=1,2
      DO 4018 N=1,2
      SPIN(L,M,N)=SPIN(L,M,N)-RESID(L,M,N)
      RSPIN(L,M,N)=SPIN(L,M,N)*10.**6/(SCALE*CALIB/10.)
 4018 CONTINUE
      WRITE (61,5707) SCALE,((RSPIN(L,M,1),RSPIN(L,M,2),M=1,2),L=1,3)
 5707 FORMAT(≠ CORR. FOR RESIDUAL:≠,F7.0,2X,12F7.3)
C
```

```
C          CONVERT SLOW SPINNER DATA TO PHASE AND INTENSITY
C
 2005 DO 2003 L=1,3
      DO 2003 M=1,2
      RM(M,L) = SQRT(SPIN(L,M,1)**2 + SPIN(L,M,2)**2)
      CALL ATAN9(SPIN(L,M,2),SPIN(L,M,1),P(M,L))
      P(M,L)=P(M,L)*RCF
      IF(P(M,L).GE.0.0) GO TO 2003
      P(M,L)=P(M,L)+360.
 2003 CONTINUE
C
C          BEGIN THE MAIN BODY OF THE SPINNER PROGRAM
C
 2009 WRITE (61,4020)
 4020 FORMAT(//)
      SUM=0.0
      DO 15 I=1,2
      DO 15 J=1,3
   15 SUM=P(I,J)+RM(I,J)
      IF(SUM)999,999,116
C
C          AVERAGE THE TWO PHASE READINGS FOR EACH PLANE
C          AND COMPUTE 2 DEL(I)
C
  116 DO 149 J=1,3
      IF((P(1,J)+P(2,J))-270.)128,120,120
  120 IF((P(1,J)+P(2,J))-450.)122,122,128
  122 PA(J)=(360.+P(1,J)-P(2,J))/2.
      DEL(J)=ABS(180.-(P(1,J)+P(2,J))/2.)
      GO TO 140
  128 DEL(J)=(P(1,J)+P(2,J))/2.
      IF(DEL(J)-180.)134,134,132
  132 DEL(J)=360.-DEL(J)
  134 PA(J)=(P(1,J)-P(2,J))/2.
      IF(P(1,J)-P(2,J))138,140,140
  138 PA(J)=360.+PA(J)
  140 IF(PA(J)-180.0)144,144,142
  142 PA(J)=PA(J)-360.0
  144 IF(DEL(J)-4.9)149,149,146
C
C          2 DEL(I) TOO LARGE. FLAG IT.
C
  146 WRITE (61,200)    J,DEL(J)
  200 FORMAT(≠ ≠,        7X,≠2 DEL(≠,I1,≠) =≠,0PF7.2,≠ DEGREES≠)
      IFLAG=ISTAR
  149 CONTINUE
C
C          AVERAGE THE TWO INTENSITY READINGS FOR EACH PLANE
C          AND COMPUTE M AND J
C
      DO 212 I=1,3
  212 RMA(I)=(RM(1,I)+RM(2,I))/2.
      RMT=SQRT((RMA(1)**2+RMA(2)**2+RMA(3)**2)/2.)
      RJ=RMT/V
C
C          COMPUTE THE WEIGHTING-FACTORS FOR CONVERGING THE ERROR-TRIANGL
C
      N=2
  220 RMI=(((1./RMA(1))**N)+((1./RMA(2))**N)+((1./RMA(3))**N))
```

```
      DO 224 I=1,3
  224 W(I)=((1./RMA(I))**N)/RMI
C
C          COMPUTE M DIFFERENCE(I)
C
      DO 240 J=1,3
      DRM=ABS(RM(1,J)-RM(2,J))
      DNRM=DRM/RMT*100.
      IF(DNRM-5.00)240,238,238
C
C          M DIFFERENCE(I) TOO LARGE.  FLAG IT.
C
  238 WRITE (61,201)J,DNRM
  201 FORMAT(≠ ≠,≠M DIFFERENCE(≠,I1,≠) =≠,0PF7.2,≠ PERCENT OF M≠)
      IFLAG=ISTAR
  240 CONTINUE
C
C          CONVERGE THE ERROR TRIANGLE
C
      Q=0.
      R=0.
      S=0.
      IF(W(1)-W(2))320,318,318
  318 IF(W(1)-W(3))326,330,330
  320 IF(W(3)-W(2))322,326,326
  322 Q=1.
      GO TO 332
  326 R=1.
      GO TO 332
  330 S=1.
  332 WI=(Q*W(2))+(R*W(3))+(S*W(1))
      WJ=(S*W(2))+(Q*W(3))+(R*W(1))
      WK=(R*W(2))+(S*W(3))+(Q*W(1))
      TI=(Q*PA(2))+(R*PA(3))+(S*PA(1))
      TJ=(S*PA(2))+(Q*PA(3))+(R*PA(1))
      TK=(R*PA(2))+(S*PA(3))+(Q*PA(1))
C
C          INITIALIZE A
C
      A=0.
C
C          ITERATE UP TO 13 TIMES TO GAIN CONVERGENCE
C
      DO 514 L=1,13
      RMJ=COS(TJ/RCF)
      RNJ=SIN(TJ/RCF)
      RNK=COS(TK/RCF)
      RLK=SIN(TK/RCF)
C
C          NO STRONG INTERSECTION^  FLAG AND GO TO NEW INPUT DATA
C
      IF(RNJ*RNK)920,420,420
  420 F=1./(SQRT(1.+(((RLK)**2)*((RNJ)**2))/((RNK)**2)))
      RL=F*RLK*RNJ/RNK
      ZM=F*RMJ
      RN=F*RNJ
      G=SQRT((RL*RL)+(ZM*ZM))
C
C          ERROR-TRIANGLE CONVERGED TO ZERO DEGREES RADIUS^
```

```
C
      IF(G)431,532,431
  431 CALL ATANS(ZM,RL,TI1)
      TI1=TI1*RCF
      AM=1.0
      IF(TI-TI1)440,438,438
  438 AM=0.0
  440 TI2=TI-TI1+AM*360.0
      U=1.0
      IF(TI2-180.0)446,446,448
  446 U=-1.0
  448 TI3=(U+1.0)*360.0/2.0-U*TI2
C
C          ERROR-TRIANGLE CONVERGED TO LESS THAN 0.01 DEGREES RADIUS^
C
      IF(G*TI3-0.07)532,532,452
  452 TI4=TI2*(1.0-WI)+0.5*(1.0+U)*WI*360.0
      TI5=TI4+TI1
      TI6=TI5
      IF(TI5-180.0)462,462,460
  460 TI6=TI5-360.0
  462 IF(L-1)464,464,476
  464 DJ=SIGN(1.0,(RNK*RLK))
      IF(RLK)470,468,470
  468 DJ=SIGN(1.0,(RNK*COS(TI6)))
  470 DK=SIGN(1.0,(RNJ*RMJ))
      IF(RMJ)476,474,476
  474 DK=SIGN(1.0,(RNJ*SIN(TI6)))
  476 TJ1=TJ+TI3*U*DJ*WJ
      TK1=TK+TI3*U*DK*WK
      TJ2=TJ1
      IF(TJ1+180.0)484,484,486
  484 TJ2=TJ1+360.0
  486 IF(TJ1-180.0)490,490,488
  488 TJ2=TJ1-360.0
  490 TK2=TK1
      IF(TK1+180.0)494,494,496
  494 TK2=TK1+360.0
  496 IF(TK1-180.0)500,500,498
  498 TK2=TK1-360.0
C
C          COMPUTE A
C
  500 AT=0.5*(WJ+WK)*U*TI3
      A=A+AT
      TI=TI6
      TJ=TJ2
  514 TK=TK2
C
C           INCREASE THE WEIGHTING-FACTOR EXPONENT N AND
C           TRY AGAIN FOR CONVERGENCE
C
      N=N+1
C
C          NO CLOSURE^  FLAG AND GO TO NEW INPUT DATA
C
      IF(N-6)220,220,910
C
C           ERROR-TRIANGLE HAS CONVERGED SATISFACTORILY
```

```
C           BEGIN THE FINAL PHASE OF THE PROGRAM
C
  532 FL=S*RL+R*ZM+Q*RN
      FM=Q*RL+S*ZM+R*RN
      FN=R*RL+Q*ZM+S*RN
      A=ABS(A)
C
C          COMPUTE MM
C
      CM(1)=RMT*SQRT(FL*FL+FM*FM)
      CM(2)=RMT*SQRT(FM*FM+FN*FN)
      CM(3)=RMT*SQRT(FN*FN+FL*FL)
      RMMS=0.0
      DO 566 I=1,2
      DO 566 J=1,3
      DS(I,J)=(CM(J)-RM(I,J))*(CM(J)-RM(I,J))
  566 RMMS=RMMS+DS(I,J)
      RMM=(1.0/(2.449*RMT))*SQRT(RMMS)*100.
      IF(RMM-5.00)610,572,572
C
C           MM TOO LARGE. FLAG IT.
C
  572 WRITE (61,202)
  202 FORMAT(≠0≠,≠MM GREATER THAN 5.0 PERCENT OF M≠)
      IFLAG=ISTAR
C
C          PERFORM ALPHA AND BETA CORRECTIONS
C
  610 SB=SIN(BE/RCF)
      CB=COS(BE/RCF)
      SA=SIN(AL/RCF)
      CA=COS(AL/RCF)
      BB=(FL*SB)+(FN*CB)
      X= (FM*CA)+(BB*SA)
      Y= (FM*SA)-(BB*CA)
      Z= (FN*SB)-(FL*CB)
C
C          COMPUTE I AND D
C
      XXYY=SQRT(X*X+Y*Y)
      CALL ATAN9(Z,XXYY,FI)
      FI=FI*RCF
      CALL ATAN9(Y,X,FD)
      FD=FD*RCF
      IF(Y)632,634,634
  632 FD=360.0+FD
  634 CONTINUE
C
C          SEPARATE THE PRINCIPAL-PARTS AND EXPONENTS OF J AND M
C
      DO 726 I=1,12
      KJ=(-(I-1))
      IF(RJ-1.0)726,728,728
  726 RJ=RJ*10.0
  728 CONTINUE
      DO 736 I=1,12
      KMM=(-(I-1))
      IF(RMT-1.0)736,738,738
  736 RMT=RMT*10.0
```

```
  738 CONTINUE
C
C          PRINT THE ANSWERS, SHORT (USGS) FORMAT
C
      WRITE (61,4010) N,L
 4010 FORMAT(≠0WEIGHTING-FACTOR EXPONENT = N =≠,I2,/,
     1≠       NUMBER OF ITERATIONS = L =≠,I2)
      WRITE (61,4006)
 4006 FORMAT(≠0SOLUTION:≠)
      WRITE (61,6002) ID1,IFLAG,FI,FD,A,RJ,KJ,RMT,KMM,RMM,IEXP,LPDATE
 6002 FORMAT(≠ ≠,A8,A1,≠I=≠,0PF5.1,≠ D=≠,F5.1,≠ A=≠,F4.1,≠ J=≠,F4.2,
     1≠E≠,I2,≠ M=≠,F4.2,≠E≠,I2,≠ MM=≠,F5.1,≠%≠,A9,≠MOD≠,I1)
C
C           WRITE THE ANSWERS ON CARD, SHORT (USGS) FORMAT
C
      WRITE(7,6003) ID1,IFLAG,FI,FD,A,RJ,KJ,RMT,KMM,RMM,IEXP,INF
 6003 FORMAT(A8,A1,≠I=≠,F5.1,≠ D=≠,F5.1,≠ A=≠,F4.1,≠ J=≠,F4.2,≠E≠,
     1I2,≠ M=≠,F4.2,≠E≠,I2,≠ MM=≠,F5.1,≠%≠,A9,A8)
C
C          PERFORM STRIKE AND DIP CORRECTIONS
C
      IF(DIP)1701,10,1701
 1701 SSN=SIN(STR/RCF)
      SCS=COS(STR/RCF)
      DIP=-DIP
      DSN=SIN(DIP/RCF)
      DCS=COS(DIP/RCF)
      CX=X*(SCS*SCS+SSN*SSN*DCS)+Y*SSN*SCS*(1.0-DCS)-Z*DSN*SSN
      CY=X*SSN*SCS*(1.0-DCS)+Y*(SSN*SSN+SCS*SCS*DCS)+Z*SCS*DSN
      CZ=X*SSN*DSN-Y*DSN*SCS+Z*DCS
      CXXYY=SQRT(CX*CX+CY*CY)
      CALL ATAN9(CZ,CXXYY,CFI)
      CFI=CFI*RCF
      CALL ATAN9(CY,CX,CFD)
      CFD=CFD*RCF
      IF(CY)1702,1703,1703
 1702 CFD=360.0+CFD
C
C          PRINT THE ANSWERS CORRECTED FOR STRIKE AND DIP
C          SHORT (USGS) FORMAT
C
 1703 WRITE (61,6102) ID1,IFLAG,CFI,CFD,RJ,KJ,IEXP,LPDATE
 6102 FORMAT(≠0≠,A8,A1,≠I=≠,F5.1,≠ D=≠,F5.1,7X,≠ J=≠,F4.2,≠E≠,I2,
     1≠ STR&DIP CORRECTED≠,≠%≠,A9,≠MOD≠,I1)
C
C           WRITE THE ANSWERS ON CARD, CORRECTED FOR
C           STRIKE AND DIP, SHORT (USGS) FORMAT
C
      WRITE(7,6103) ID1,IFLAG,CFI,CFD,RJ,KJ,IEXP,INF
 6103 FORMAT(A8,A1,≠I=≠,F5.1,≠ D=≠,F5.1,7X,≠ J=≠,F4.2,≠E≠,I2,
     1≠ STR&DIP CORRECTED %≠,A9,A8)
      GO TO 10
C
C          FLAGS FOR NO REASONABLE SOLUTION
C
  910 WRITE (61,204)
  204 FORMAT(≠0NO CLOSURE:  CHECK INPUT DATA FOR MISTAKES≠)
      GO TO 10
  920 WRITE (61,205)
  205 FORMAT(≠0NO STRONG INTERSECTION:  CHECK INPUT DATA FOR MISTAKES≠)
      GO TO 10
  999 STOP
      END
```

```
        OS3 FORTRAN  VERSION 3.12           04/05/74  1436

              SUBROUTINE ATAN9(Y,X,A)
      C
      C           SUBROUTINE ATAN9(Y,X,A) PERFORMS THE STANDARD IBM
      C           FUNCTION A=ATAN2(Y/X), WHERE A LIES BETWEEN -PI AND +PI
      C           RADIANS
      C
              RCF=57.2957795
              IF(X)3001,3002,3003
         3001 A=ATAN(Y/X)+SIGN(180.,Y)/RCF
              GO TO 3009
         3002 IF(Y)3004,3005,3006
         3004 A=-90./RCF
              GO TO 3009
         3005 A=0.
              GO TO 3009
         3006 A=90./RCF
              GO TO 3009
         3003 A=ATAN(Y/X)
         3009 CONTINUE
              RETURN
              END

 NO ERRORS FOR ATAN9
LENGTH OF SUBPROGRAM        00113
```

```
      PROGRAM SIMPLE1
C     XZOX$EN:SIXPPXVTES VECTOR AVERAGE, POLE, AND FISHER STATISTICS.
C     COMPARISON WITH FLOWAVER:  SIMPLE1 DOES NOT COMPUTE WITHIN-FLOW
C     AVERAGES OR CL.  INSTEAD, THE ANGULAR STANDARD DEVIATION IS
C     APPROXIMATED BY SA=SQRT(2./K).  ALSO THE QUANTITY
C     RA=ARCOS(R/N) IS COMPUTED.
C     INPUT DATA:  IDENTIFICATION, EXPERIMENT, SITE LATITUDE, SITE
C     LONGITUDE, INCLINATION, DECLINATION, INTENSITY.
C     IN ADDITION, SEPARATE EACH FLOW WITH A CARD HAVING ≠END.DATA≠
C     IN COLUMNS 1-8.
C     SETS CAN ALSO BE SEPARATED BY THE CARD CONTAINING THE
C     IDENTIFICATION, EXPERIMENT, AND SITE LOCATION, WHICH MUST HAVE A
C     BLANK IN COLUMN 1.
C     NORMALLY, USE SPINNER CARDS FOR INPUT.
C     OUTPUT DATA:  IDENTIFICATION, EXPERIMENT, SITE LATITUDE, SITE
C     LONGITUDE, AVERAGE INCLINATION, AVERAGE DECLINATION, POLE
C     LATITUDE, POLE LONGITUDE, N, R, KAPPA, ANGULAR STANDARD
C     DEVIATION, AVERAGE INTENSITY, STANDARD DEVIATION OF INTENSITY,
C     DELTA(M), DELTA(P), AND RA.
C     THE OUTPUT FORMAT IS SIMILAR TO THAT OF FLOWAVER.
      DIMENSION CARD(20)
      INTEGER CARD
      CHARACTER COL1
      REAL IDENT,END1,EXPER,AI,AD,AJ
      EQUIVALENCE (CARD,END1,COL1)
      RCF=57.29577
      PI=3.14159
C     OUT7=≠PUNCH≠
      WRITE (61,50)
   50 FORMAT(≠ PROGRAM SIMPLE1: VECTOR AVERAGING AND POLES..........≠)
    5 N=0
      XSUM=YSUM=ZSUM=SUMJ=SUMJJ=0.
      WRITE (61,49)
   49 FORMAT(1H0)
      WRITE (61,52)
   52 FORMAT(≠ INPUT CARDS..........≠)
      IF(COL1.EQ.1R ) GO TO 17
   10 READ(5,11) CARD
   11 FORMAT(20A4)
      IF(EOF(5)) CALL EXIT
      IF(N.NE.0.AND.COL1.EQ.1R ) GO TO 20
   17 WRITE(61,12) CARD
   12 FORMAT(≠ ≠,20A4)
      IF(COL1.EQ.1R ) DECODE(70,13,CARD) IDENT,EXPER,SLA,SLO
   13 FORMAT(10X,A5,5X,A4,6X,2F10.2)
      IF(COL1.EQ.1R ) GO TO 10
      IF(END1.EQ.≠END.DATA≠) GO TO 20
      DECODE(45,14,CARD) AI,AD,AJ
C  14 FORMAT(11X,F5.0,3X,F5.0,10X,E7.0)
   14 FORMAT(5X,F5.1,3X,F5.1,2X,F8.5)
C  14 FORMAT(   T39,F6.0,T49,F6.0/T61,E8.0) FOR SIMPLE1 OUTPUT AVERAGES.
      N=N+1
      XSUM=XSUM+COS(AI/RCF)*COS(AD/RCF)
      YSUM=YSUM+COS(AI/RCF)*SIN(AD/RCF)
      ZSUM=ZSUM+SIN(AI/RCF)
      SUMJ=SUMJ+AJ
      SUMJJ=SUMJJ+AJ*AJ
      GO TO 10
   20 IF(N.EQ.0) GO TO 5
```

```
      R=SQRT(XSUM*XSUM+YSUM*YSUM+ZSUM*ZSUM)
      AD=ATAN2(YSUM,XSUM)*RCF
      IF(AD.LT.0.) AD=AD+360.
      FN=N
      AI=ASINF(ZSUM/FN)*RCF
      AJ=SUMJ/FN
      IF(N.EQ.1) GO TO 35
      STDJ=SQRT((FN*SUMJJ-SUMJ*SUMJ)/FN/(FN-1.))
      IF(R.GE.FN) GO TO 35
      FK=(FN-1.)/(FN-R)
      FPRN=(1.0-(FN-R)*(.05**(1./(1.-FN))-1.)/R)
      IF(ABS(FPRN).GT.1.0) GO TO 35
      AL95=ACOSF(FPRN)*RCF
   24 IF(SLA.EQ.0.0.AND.SLO.EQ.0.0) GO TO 45
      P=ATANF(2./TANF(AI/RCF))
      IF(P.LT.0.) P=P+PI
      PLA=ASINF(SIN(SLA/RCF)*COS(P)+COS(SLA/RCF)*SIN(P)*COS(AD/RCF))
      BETA=ASINF(SIN(P)*SIN(AD/RCF)/COS(PLA))
      PLO=(PI-BETA+SLO/RCF)*RCF
      IF(COS(P).GE.SIN(SLA/RCF)*SIN(PLA)) PLO=(SLO/RCF+BETA)*RCF
      IF(PLO.GE.360.0) PLO=PLO-360.0
      PLA=PLA*RCF
      DELM=AL95*SIN(P)/COS(AI/RCF)
      DELP=0.5*AL95*(1.+3.*COS(P)**2)
      SA=SQRT(2./FK)*RCF
      RA=ACOSF(R/FN)*RCF
   25 WRITE (61,54)
   54 FORMAT(≠ OUTPUT INFORMATION..........≠)
      WRITE(61,26) IDENT,EXPER,SLA,SLO,AI,AD,PLA,PLO
   26 FORMAT(≠ 1 ≠,A5,1X,A4,≠ SLA=≠,F6.2,≠ SLO=≠,F6.2,≠ AI=≠,F6.2,
     1≠ AD=≠,F6.2,≠ PLA=≠,F6.2,≠ PLO=≠,F6.2)
      WRITE(61,27) IDENT,EXPER,N,R,FK,AL95,SA,AJ,STDJ
   27 FORMAT(≠ 2 ≠,A5,1X,A4,≠ N=≠,I3,≠ R=≠,F9.5,≠ K=≠,F7.2,≠ AL=≠,F5.2,
     1≠ SA=≠,F5.2,≠ AJ=≠,  E8.2,≠ SJ=≠,  E8.2)
      WRITE(61,28) IDENT,EXPER,DELM,DELP,RA
   28 FORMAT(≠ 3 ≠,A5,1X,A4,≠ DELM=≠,F5.2,≠ DELP=≠,F5.2,≠ RA=≠,F5.2)
      WRITE(61,29) IDENT,AI,AD,AJ,N,EXPER
   29 FORMAT(≠ ≠,A7,≠ AV I=≠,  F5.1,≠ D=≠,F5.1,8X ,≠J=≠,  E8.2,
     110X,≠N=≠,I3,4X,A4)
      WRITE (7,39) IDENT,AI,AD,AJ,N,EXPER
   39 FORMAT(A5,6X,F5.1,3X,F5.1,10X,E7.2,4X,I3,4X,A4)
      WRITE (7,59) IDENT,PLA,PLO,AJ,N,EXPER
   59 FORMAT(A5,6X,F5.1,3X,F5.1,10X,E7.2,4X,I3,4X,A4,≠    VGP≠)
C     IF(OUT7.NE.≠PUNCH≠) GO TO 5
C     WRITE(7,76) IDENT,EXPER,SLA,SLO,AI,AD,PLA,PLO
C  76 FORMAT( ≠1 ≠,A5,1X,A4,≠ SLA=≠,F6.2,≠ SLO=≠,F6.2,≠ AI=≠,F6.2,
C    1≠ AD=≠,F6.2,≠ PLA=≠,F6.2,≠ PLO=≠,F6.2)
C     WRITE(7,77) IDENT,EXPER,N,R,FK,AL95,SA,AJ,STDJ
C  77 FORMAT( ≠2 ≠,A5,1X,A4,≠ N=≠,I3,≠ R=≠,F8.5,≠ K=≠,F7.2,≠ AL=≠,F5.2,
C    1≠ SA=≠,F5.2,≠ AJ=≠,1PE8.2,≠ SJ=≠,1PE8.2)
C     WRITE(7,78) IDENT,EXPER,DELM,DELP,RA
C  78 FORMAT( ≠3 ≠,A5,1X,A4,≠ DELM=≠,F5.2,≠ DELP=≠,F5.2,≠ RA=≠,F5.2)
C     WRITE(7,79) IDENT,AI,AD,AJ,N,EXPER
C  79 FORMAT(A7,≠ AV≠,T12,≠I=≠,F5.1,≠ D=≠,F5.1,T35,≠J=≠,1PE8.2,
C    1T55,≠N=≠,I3,T64,A4)
      GO TO 5
   35 AL95=SA=RA=DELM=DELP=FK=100000.$STDJ=-1.00
      GO TO 24
   45 PLA=PLO=100000.
      GO TO 25
      END
```