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PALEOSECULAR VARIATION OF THE GEOMAGNETIC FIELD IN ALASKA

A

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PALEOSECULAR VARIATION OF THE GEOMAGNETIC FIELD IN ALASKA

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ABSTRACT

Secular variation (SV) of the geomagnetic field has a time spectrum ranging from about 10 to 10^4 years. There are various mathematical methods for analysing SV leading to different field models. The multidipolar source model seems to offer more promise than spherical harmonic analysis.

Paleosecular variation measurement may be accomplished by paleomagnetic or archeomagnetic techniques. The principle difference in the two methods is one of time control. In archeomagnetic work the time sequence is usually well known and detailed temporal analysis of the magnetic field is possible. In the paleomagnetic measurement of SV time is poorly known and consequently statistical analyses are usually carried out on a series of measurements of rocks which are thought on geologic grounds to span about 10^4 years.

Successive Quaternary lava flows at sites in the Aleutian Islands, and Tertiary flows in the Wrangell Mountains of Alaska were sampled for paleosecular variation measurement. Due to limitations in the probable time span represented by the samples and statistical constraints, data at only a few sites are considered to be reliable indicators of paleosecular variation. When all the Aleutian data are combined to give greater statistical significance an angular standard deviation of $\delta = 10.8°$ is obtained. The Wrangell Mountains data give $\delta = 15.8°$.

A survey has been made of paleomagnetic literature to find suitable Cenozoic SV determinations for locations around the world. On comparing these data, there is a clear tendency for Pacific area SV to

be slightly less than that for the non-Pacific area; this feature of the SV field has also been observed historically. The difference is more pronounced in Tertiary than in Quaternary data. The present north-south asymmetry of the SV field was apparently reversed during most of Cenozoic time. The Alaskan data indicate that the Aleutian Islands, but not mainland Alaska, are within the area of low SV in the Pacific Ocean.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. SECULAR VARIATION OF THE GEOMAGNETIC FIELD

Since the early seventeenth century, it has been recognized that the geomagnetic field is essentially dipolar (Gilbert, 1600). Somewhat later, perhaps as early as 1635 (Chapman and Bartels, 1940), it was noticed by Gellibrand that the geomagnetic field was not constant but was always changing. In addition, it was found that the geomagnetic field could be resolved into dipolar and non-dipolar components. Today we know that its variation has an immense spectral range, a fact making its study especially challenging for the geophysicist. At a given point on the earth's surface, the geomagnetic field varies with a time scale running from milliseconds to periods longer than 10^6 years, or more than 16 orders of magnitude (Cox and Doell, 1964). It can be shown by spherical harmonic analysis that the more rapid variations of the geomagnetic field, those up to days and perhaps as long as the eleven year sun spot cycle (McNish, 1933; Yukutake, 1965) are due to external sources such as electric currents in the ionosphere. The remainder of the geomagnetic variation, with time scales from about ten years on up, is due to sources within the earth's core (Hide and Roberts, 1961); it is these long-term changes in the geomagnetic field which are referred to as secular variation (SV) or sometimes as the secular variation field.

Isoporic maps

At any given point on the surface of the earth, SV may be observed as slow changes in both the direction and magnitude of the geomagnetic field vector. On a world map one may plot SV as observed in the past few decades in various ways to better understand the nature of secular variation. Vestine et al. (1947) have plotted geomagnetic secular change of all the various field elements (D, H, X, Y, Z, I, and F, all of which, while not independent of each other, are concisely defined by Whitham (1967)) for four different epochs from 1912.5 to 1942.5 (Fig. 1-1); Nagata and Syono (1961) have done the same for 1955-1960. The contours on such maps connect points of equal rates of change of any of these components. These lines are called isopors and are usually in units of gamma yr^{-1} ($\gamma\ yr^{-1}$). Gaibar-Puertas (1953) has prepared similar maps for the quantity G, which was defined by Bauer (1914) as the function $G = (X^2 + Y^2 + \frac{1}{4} Z^2)^{1/2}$. G has the unique property that it is unaffected by the orientation of the geocentric dipolar component of the geomagnetic field.

Study of these isoporic maps reveals the salient features of SV. Firstly, in any given epoch there is a relatively small number (about ten) of points on the earth's surface which are surrounded by concentric closed isopors. These so-called isoporic foci represent centers of maximum or minimum SV of any of the field components. The r.m.s. value of these maxima and minima is about 50 gamma yr^{-1} with maximum rates (regardless of sign) of about 150 gamma yr^{-1} (Hide and Roberts, 1961). The sets of concentric isopors surrounding each focus cover areas of continental extent but bear no apparent relation to the continents. If isoporic maps for different epochs are compared, it is clearly evident that these isoporic foci are drifting slowly in a generally westward direction at a rate of roughly a quarter of a degree per year

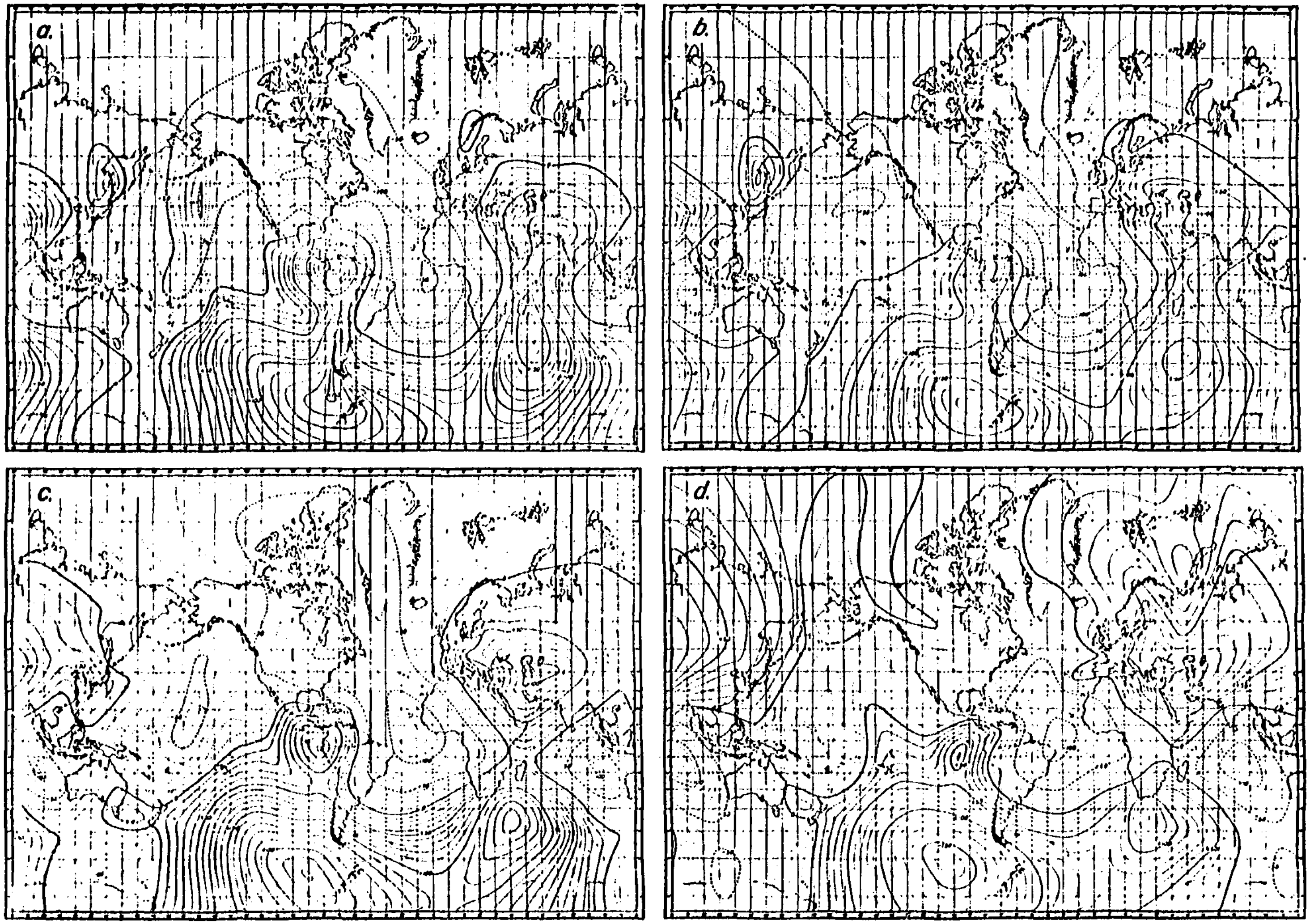


Figure 1-1. Isoporic maps showing secular change in $\gamma\ yr^{-1}$ of the vertical intensity of the geomagnetic field for the epochs (a) 1912.5, (b) 1922.5, (c) 1932.5 and (d) 1942.5 (from Vestine *et al.*, 1947)

(Runcorn, 1956). In addition, it is clear that the strength of these isoporic foci waxes and wanes with a time scale of perhaps about 100 years (Creer, 1962a). Cox and Doell (1964) point out that lifetimes of isoporic foci are more realistically estimated at 400 to 1,000 years.

Spherical harmonic analysis

A more mathematical approach to analysis of recent SV is by the method of spherical harmonic analysis. Spherical harmonic analysis of the main field is outlined by Vestine (1967), and in more detail by Chapman and Bartels (1940), as well as elsewhere by others. Briefly, this entails using world-wide magnetic data to find the Gauss coefficients g_n^m, h_n^m in the expansion for the magnetic potential

$$V = a \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^{n+1} \left\{g_n^m \cos m\phi + h_n^m \sin m\phi\right\} P_n^m(\cos\theta) \qquad (1-1)$$

where a is the mean earth's radius, r is the distance from the center of the earth to the observation point (usually analysis is done at the earth's surface, so $r = a$), ϕ and θ are longitude and colatitude, respectively, and P_n^m $(\cos\theta)$ are the partially normalized spherical harmonics of Schmidt. We have omitted in (1-1) the part due to external sources which varies as $(r/a)^n$ since field contributions of external origin are generally less than one percent and therefore of the same order as the uncertainties of measurement (Vestine, 1967). The coefficient g_1^0 corresponds to an axial geocentric magnetic dipole; g_1^1 and h_1^1 correspond to geocentric dipoles oriented at right angles to each other in the equatorial plane. Higher terms correspond to geocentric magnetic quadripoles, octopoles and higher multipole terms.

Most analyses have not gone beyond the first eight terms (up to $n = m = 2$); a few (e.g. Jensen and Cain, 1962) have gone to $n = m = 6$. Beyond these terms the statistical error of measurement becomes of comparable size to the terms themselves.

By comparing the Gauss coefficients for different epochs, one can calculate their rate of change $\dot{g}_n^m$, $\dot{h}_n^m$ as a measure of the harmonic distribution of SV. Chapman and Bartels (1940) point out from these data that the spherical harmonic series for SV converges much more slowly than the main field series and so more terms must be used. This also implies that compared to the main field SV is more of a regional than a planetary phenomenon and is therefore perhaps not as amenable to spherical harmonic analysis. Recent values of g_n^m, h_n^m, $\dot{g}_n^m$, $\dot{h}_n^m$ are given in Table I-I.

Westward drift

Various efforts have been made to examine the westward drift of the geomagnetic field in greater detail than that possible by studying isoporic maps. Using the data of Vestine et al. (1947), Bullard et al. (1950) computed the westward drift of the non-dipole field between epochs 1907 and 1945 by finding the drift D such that $\Sigma\varepsilon^2$ was a minimum where

$$\varepsilon = X(\phi) - X'(\phi + D)$$

X and X' being any component of the 1945 and 1907.5 non-dipole fields respectively, and the summation being over 36 equally spaced values of longitude ϕ on a single parallel of latitude. They arrive at a westward drift averaged over all latitudes of $0.180 \pm 0.015°\ \mathrm{yr}^{-1}$ for the non-dipole field.

TABLE I-I

Spherical harmonic coefficients g_n^m, h_n^m for epoch 1960 in γ (Jensen and Cain, 1962) and secular variation coefficients $\dot{g}_n^m$, $\dot{h}_n^m$ for 1955-1960 in γ yr^{-1} (Nagata and Syono, 1961); Relative change per year is also given in yr^{-1}.

n	m	g_n^m	$\dot{g}_n^m$	$\dot{g}_n^m/g_n^m$	h_n^m	$\dot{h}_n^m$	$\dot{h}_n^m/h_n^m$
1	0	-30411.2	13.6	-.0004			
2		-1602.3	-21.5	+.0134			
3		1260.7	1.9	+.0015			
4		955.3	-4.4	-.0046			
5		-206.4	2.1	-.0102			
6		135.2	1.7	+.0126			
1	1	-2147.4	5.9	-.0027	5798.9	2.3	+.0004
2		2959.1	-1.8	-.0006	-1912.4	-16.0	+.0083
3		2029.2	-8.2	-.0040	-485.7	8.2	-.0169
4		818.5	2.7	+.0033	213.7	0.0	+.0000
5		338.4	-1.8	-.0053	7.8	1.8	+.2308
6		25.7	2.1	+.0817	30.5	-0.7	-.0230
2	2	1545.1	-0.1	-.0006	182.3	-17.1	-.0938
3		1285.7	1.1	+.0009	210.4	3.5	+.0017
4		557.0	-2.0	-.0036	-255.7	-1.1	+.0043
5		253.0	0.2	+.0008	26.0	1.7	+.0654
6		-21.5	0.1	-.0047	58.5	-0.2	-.0034
3	3	821.7	0.5	+.0006	-26.6	-6.7	+.2520
4		-335.0	-1.0	+.0030	-20.6	3.5	-.1700
5		12.9	1.0	+.0075	-97.7	-3.8	+.0389
6		-214.9	-0.3	+.0014	34.2	1.5	+.0440
4	4	276.4	-2.2	-.0080	-187.3	-2.1	+.0112
5		-125.1	-0.5	+.0040	-109.1	0.7	-.0064
6		-19.3	1.5	-.0778	2.2	-1.1	-.5000
5	5	-99.3	-0.2	+.0020	173.6	0.2	+.0012
6		-9.8	0.5	-.0510	48.0	0.7	+.0146
6	6	-166.0	-0.6	+.0036	48.4	1.0	+.0206

Bullard et al. (1950) also calculate in like manner a westward drift of 0.32 ± 0.07° yr^{-1} for SV itself (i.e. variations in the rate of change of the field). They question the significance of the difference in these quantities but present theoretical reasons why a difference could exist (cf. also Yukutake, 1970).

Yukutake (1962), in a zonal analysis of SV, expanded the magnetic potential in a Fourier series about circles of latitude λ according to

$$V(\lambda) = a \sum_{m=0}^{\infty} [G_m \cos m\phi + H_m \sin m\phi] = a \sum_{m=0}^{\infty} C_m \cos m(\phi - \phi_m)$$

where

$$G_m = \sum_{n=m}^{\infty} (\frac{a}{r})^{n+1} g_n^m P_n^m (\cos\theta) ,$$

$$H_m = \sum_{n=m}^{\infty} (\frac{a}{r})^{n+1} h_n^m P_n^m (\cos\theta) ,$$

$$C_m = \sqrt{G_m^2 + H_m^2} ,$$

and

$$\phi_m = \frac{1}{m} \tan^{-1} \frac{H_m}{G_m} .$$

He concludes that the $m = 1$ part of the field can be divided into an equatorial dipole part drifting westward at 0.1° yr^{-1} and a non-dipole part drifting at 0.2° yr^{-1} suggesting they are produced by different mechanisms. The drift velocity for the $m = 2,3$ and higher terms varies with latitude in a non-symmetric manner. Yukutake goes on to correlate longitude variations of the field along a given circle of latitude with time variations at a site on that same circle, and arrives at a mean drift velocity of 0.202° yr^{-1}, ignoring latitude or order of the harmonic.

Bullard et al. (1950) also calculated independent rates of drift of spherical harmonic components up to $n = 3$ by calculating successive phase angles, $\phi_n^m = \frac{1}{m} \tan^{-1} \frac{h_n^m}{g_n^m}$. These results are given in Table I-2.

Instead of assuming that each harmonic is drifting, Yukutake and Tachinaka (1969) separate each one into drifting and standing components by setting

$$g_n^m(t)\cos m\phi + h_n^m(t)\sin m\phi = F_n^m \cos(m\phi+\phi_n^m) + K_n^m \cos m[\phi+v_n^m(t-\tau_n^m)],$$

where the F_n^m term represents the fixed part of harmonic P_n^m, and K_n^m the part drifting with velocity v_n^m, while ϕ_n^m and $v_n^m\tau_n^m$ are phase factors. They arrive at the drift velocity values u_n^m for the P_n^m components of the main field listed in Table I-2. u_n^m depends not only on the velocity v_n^m of the drifting part but on the rate of change of the standing part of the field. Numerical examples applied to standing and drifting parts of specific isoporic foci are given by Yukutake (1970) who also presents a theoretical discussion of the matter.

The centered dipole itself, made up of the g_1^0, g_1^1, and h_1^1 terms has been found by Malin (1969) to be drifting west at 0.089 ± 0.011°yr^{-1}.

R. W. James (1968, 1969) in an expansion of the field into multipoles instead of spherical harmonics, finds the 1965 westward drift of different order multipoles ranging from 0.07 to 0.24° yr^{-1}.

A somewhat different approach to westward drift analysis has recently come from archeomagnetism. Bucha (1969) and Bucha et al. (1970) have measured magnetic intensity from baked items at well dated

TABLE 1-2

Westward drift of geomagnetic field components in degrees yr^{-1}. Negative values indicate eastward drift.

n=1,	m=1	0.003° yr^{-1}	for 1907.5 to 1945.0, Bullard *et al.* (1950)	0.09° yr^{-1}	for 1960.0, Yukutake and Tachinake (1969)
2	1	0.235		0.16	
2	2	0.363		0.40	
3	1	-0.080		0.11	
3	2	-0.080		0.05	
3	3	0.243		0.17	
4	1			0.01	
4	2			0.01	
4	3			0.16	
4	4			0.07	
Non-dipole		0.180±0.015			
SV		0.320±0.067			

Main dipole	0.089 ± 0.011° yr^{-1}	Malin (1969)
Non-dipole up to m = 6	0.25	
Main dipole	0.1	Yukutake (1962)
Non-dipole, m = 1 only	0.2	
Mean for whole field	0.202	
Multipole components for 1965	0.07 - 0.24	James (1969)
Non-dipole	0.18	Nagata and Syono (1961)
Non-dipole	0.2	Nagata (1965)
Mean for 5000 years	0.24	Bucha (1969), Bucha *et al.* (1970)
Mean for 1000 years	0.12 ± 0.03	Burlatskaya *et al.* (1968, 1969a)

archeological sites and have been able to draw up magnetic intensity curves for the last 5000 years for Czechoslovakia, Central America, and Japan. They find a remarkable correlation between the curves, but find them out of phase with each other by a sufficient amount to give a westward drift rate of 0.24° yr^{-1}. Burlatskaya et al. (1968, 1969a, 1970) in a similar comparison of magnetic inclination recorded in bricks in Poland and Ukrainia over the last 1000 years find a westward drift of 0.12 ± 0.03° yr^{-1}. Smith and Needham (1967) comparing magnetic declination records in medieval China with archeomagnetic results from Japan for the same period also find phase differences compatable with the above data.

The large discrepancies in measured westward drift given above and compiled in Table 1-2 is a reflection not so much of the inaccuracies of its measurement, but rather of the fact that westward drift is not a simple phenomenon and its apparent magnitude depends entirely upon how one separates out the drifting part of the field.

Northwestward and outward drift of the eccentric dipole

If one separates out a best-fit dipole from the geomagnetic field, which requires using spherical harmonic coefficients up to $n = 2$, one obtains the eccentric dipole situated about 400 km from the center of the earth under a point about 10° east of the Marianas Islands (Malin, 1969). Malin finds for 1942.5 to 1962.5 that it is moving roughly northwest and outward. Vestine (1953) and Nagata and Syono (1961) find similar results. Full data is given in Table 1-3. A more complete analysis of the motion of the eccentric dipole is given with derivation of the necessary formulae by James and Winch (1967).

TABLE 1-3

Motion of the eccentric dipole.

	Malin (1969) 1942.5-1962.5	Nagata and Syono (1961) 1955-1960	Vestine (1953) 1830-1950
Westward drift	$0.29 \pm 0.05° \text{ yr}^{-1}$	$0.30° \text{ yr}^{-1}$	$0.30° \text{ yr}^{-1}$
Northward drift	$0.21 \pm 0.01° \text{ yr}^{-1}$	$0.20° \text{ yr}^{-1}$	$0.25° \text{ yr}^{-1}$
Radial velocity	$2.15 \pm 0.05 \text{ km yr}^{-1}$	2.2 km yr^{-1}	--

Dipole moment change

Another aspect of SV which has come out of spherical harmonic analysis of the geomagnetic field is a decrease in intensity of the dipole moment of the main field. At the present time this amounts to about $-0.052\% \text{ yr}^{-1}$ or -4.2×10^{22} e.m.u. yr^{-1} (Nagata, 1965). Malin (1969) notes a slight acceleration of this rate of decrease between 1942.5 and 1962.5. Archeomagnetism and historical data indicate that this rate has been approximately constant for the last 100 years and has been somewhat less during the past 2000 years (Thellier and Thellier, 1959; Nagata et al., 1963). Kitazawa (1970) used archeomagnetic data to show that a maximum value of about 1.6 times the present dipole moment was reached 2000 years ago and a minimum of 0.5 times the present moment 5500 years ago. Similar results were obtained by Nagata et al. (1963). Burlatskaya (1970) in a survey of world-wide archeomagnetic data finds a period of 7000 years in geomagnetic intensity variations; superposed on this is a smaller scale cyclic variation with a quasi-period of from 200 to 600 years.

Smith (1967, 1970) in two review papers on geomagnetic intensity studies, confirms the above results and notes a quasi-period of about

10^4 years. He concludes that dipole moment variations observed in the archeologic and geologic records are real and not due to non-dipole features or dipole wobble (see next section). Looking further back in the geologic past through paleomagnetic measurements (Chap. II), Smith notes a probable general increase in dipole moment during the last 400 million years.

Dipole wobble

In addition to drift and intensity changes of the dipole, a significant component of SV is due to a variation in direction of the main dipole, known commonly as dipole wobble. Cox and Doell (1964) estimate on the basis of present day and paleomagnetic field measurements that the variations in the direction of the main dipole have an angular standard deviation (cf. Chap. III) of about 11.5° -- this is roughly the present deviation of the dipolar field direction from the geographic pole. The characteristic time scale of the dipole wobble is probably about 10^4 years (Smith, 1970; and others) and therefore its effects are hardly directly observable on available recent records. But Kawai and Hirooka (1967) and Kawai *et al.* (1967) present archeomagnetic evidence supporting a dipole wobble in a very regular fashion having a 1,500 year period. Keimatsu *et al.* (1968) use ancient written records of auroral sightings to deduce that the dipole was inclined toward China in the 11th and 12th centuries. It seems more likely, however, that the dipole wobble is an irregular feature best treated in a statistical manner (Chapter III).

Periodicities, spectral analysis, and lifetimes of SV components

Almost since the earliest discovery of SV many attempts have been made to pick out regular periods over which the behavior of components of the field might repeat itself. Good knowledge of such periods would have obvious utility in the prediction of secular change for navigation and other purposes. Reliable measurements of the geomagnetic field have been made at only a few places for more than two hundred years. Records of inclination and declination for London and Paris which date back to the late 16th and early 17th centuries respectively indicate a period of about 480 years (Runcorn, 1956). Wehner (1928), in a study of the orientations of medieval churches whose foundations had been lined up magnetically at the time of construction, found many repetitions of a 476 year cycle. Carlheim-Gyllensköld (1896) has found a 454 year period from spherical harmonic analysis of the geomagnetic field for the years 1538 to 1885. He also found from the same data a superimposed periodicity of 1381 years. The data on which both of these studies was based would appear to be a bit too sketchy for firm conclusions. By measuring yearly average intensity values for magnetic observations in different regions of the globe Depietri (1961) finds a 55 year cycle. This result, too, appears a bit shakey. Burlatskaya *et al.* (1969b) compiled archeomagnetic results from many areas and found inclination periods in the ranges 400 - 700 years and 1000 - 1200 years.

Yukutake (1962) ran a spectral analysis on paleomagnetic results from the Narita bed, a pleistocene sedimentary formation in Japan (Nagata *et al.*, 1943, 1945 and 1949). He found periods of 700, 1200, 1800 and 7000 years predominating. He interprets these periods as being due more to westward drift than periodicity of field components themselves. However, the validity of the results is questionable, because the radiometric age determinations given by Nagata et al. (1949) lack precision.

In fact, records from more widely spaced stations clearly indicate that SV is not well represented by such periodicities on a global scale. This indicates again that SV is a regional rather than a global phenomenon.

In Table I-I, in addition to giving the Gauss coefficients g_n^m, h_n^m and their time derivatives $\dot{g}_n^m$, $\dot{h}_n^m$, we have calculated $\dot{g}_n^m/g_n^m$ and $\dot{h}_n^m/h_n^m$ giving proportional annual rates of change of each spherical harmonic component. From these values it is seen that in general all except the equatorial and axial dipole components have life times of the order of a few hundred years or less. This is in accord with the life times of isoporic foci found by comparing isoporic maps.

Origin of secular variation

Study of the geomagnetic field is one of the few ways other than through seismology that we can obtain fairly direct information about the earth's core, for it is now generally accepted that the geomagnetic field has its origin within the core (Irving, 1964; and many others). Since major changes in the geomagnetic field certainly originate within the core also, study of its secular variation has obvious utility in understanding the earth's interior (Petrova and Khramov, 1970). Many hypotheses have been proposed to explain the origin of the main geomagnetic field. The most successful have all been some sort of homogeneous dynamo (Rikitake, 1967) involving motions of a conducting fluid.

Cox (1968) reviews the dynamo models and finds instabilities sufficient to account for both the observed dipole moment variations and for the spectrum of reversed polarity intervals obtained from ocean cores, K-Ar dating and sea floor spreading data.

Several researchers have sought to explain the westward drift of SV by differential rates of rotation of the earth's core and mantle (e.g. Bullard et al., 1950; Richmond, 1966, 1969; also cf. the review paper of Davey, 1967). By this scheme the core, or at least its outer portion, rotates more slowly than does the earth itself, thereby carrying the gradually varying centers of secular change westward with respect to the crust where SV is observed. Bullard et al. (1950) have proposed an electromagnetic coupling mechanism between the core and mantle involving interactions between the dipole field and induced toroidal fields which helps to explain westward drift. Vestine and Kahle (1968) found a correlation between decade fluctuations in the length of the day and the westward drift of the geomagnetic eccentric dipole (the eccentric dipole is the 'best-fit' non-geocentric geomagnetic dipole (Chapman and Bartels, 1940)). If only the outer 200 km of the core is moving relative to the mantle and moves approximately with the eccentric dipole, the length of day changes are consistent with the necessary angular momentum transfer between the core and the mantle through a variable core-mantle coupling. Ball et al. (1968) refined Vestine and Kahle's

(1968) data and found a 5 to 8 year phase lag of the eccentric dipole drift curve behind the length of day variation curve which they hypothesize is due to a delay time in the transmission time of magnetic signals through the mantle; Kahle et al. (1969a,b) present new magnetic data confirming a predicted eccentric dipole drift rate decrease based on the length of day curves of Vestine and Kahle (1968) and Ball et al. (1968).

While spherical harmonic analysis is at once both a convenient and an elegant way to look at the geomagnetic field or its SV, this form of analysis has limitations for understanding the nature of the field generating mechanism. First of all, it is a mathematical fact that there is an infinitude of current systems within the earth which will produce the same equivalent magnetic field at the earth's surface (Hide and Roberts, 1961); in fact, this is an inherent difficulty with any attempt to model the field. Secondly, with increasing depth within the earth, the higher order harmonics are increased in importance while their measurement at the surface is subject to the greatest errors. Thirdly, spherical harmonic analysis tends to look at the field on a purely global scale as made up of geocentric dipoles, quadripoles, octopoles and higher multipoles while many features of the field, and especially the SV field have a more regional than global character.

It has been argued (Lowes and Runcorn, 1951; and others) that the SV field is most likely due to sources occurring within the earth's core near the core-mantle boundary rather than sources at the geocenter. Thus several attempts have been made to construct models based on current systems or dipoles situated within the outer region of the core. McNish (1940) used vertical intensity isoporic maps to deduce 13 dipoles of equal strength at depth 0.5a (the core-mantle boundary is at 0.45a; a = radius of earth) located directly beneath the isoporic foci. Lowes and Runcorn (1951) used a graphical-experimental method to arrive at 12 vertical dipoles of different magnitudes at 0.6a depth. These were not necessarily beneath isoporic foci but were mostly near them. Alldredge and Stearns (1969) using a much more analytical approach to the problem fitted 21 and 35 radial dipoles to the spherical harmonic coefficients for 1955.0 of Finch and Leaton (1957) and to the coefficients for the 1965.0 International Geomagnetic Reference Field (IAGA, 1969) respectively. The dipole sources were found to fit best at depth 0.8 a. The angular locations of the dipoles are near the maximum and minimum values of the current function

$$J = \frac{10}{4\pi} a \sum_{n=0}^{\infty} \sum_{m=0}^{n} \frac{2n+1}{n} \left(\frac{a}{r_s}\right)^{n+1} P_n^m (\cos\theta)[g_n^m \cos m\phi + h_n^m \sin m\phi]$$

which gives the current distribution required on a thin spherical shell of radius r_s to produce the observed potential (1-1) (Chapman and Bartels, 1940). A least squares fit of rates of movement and intensity changes of these dipoles was carried out to reproduce the SV field. R.m.s. residuals of 2.15 and 1.26γ yr^{-1} for the two SV fields respectively, indicate the closeness of fit.

This latest attempt to represent SV by a multidipolar model is probably the most comprehensive to date and the search for a workable field model will probably be more fruitful starting from this sort of analysis as a base, rather than using the spherical harmonic analysis approach.

II. MEASUREMENT OF SECULAR VARIATION

Using existing field measurements, we can determine the world-wide nature of secular variation with a fair amount of detail for time scales of the order of the period of time over which reliable field measurements are available, say 100 years or so. However, even 500 years which is the longest period for which there exist direct measurements of the field, and these only at a very few locations, is a short time compared with the total spectrum of SV, which is usually considered to span at least 10^4 years (Chapter I). To measure SV over a longer time than this, or for a period in the remote past, one must resort to archeomagnetic and paleomagnetic techniques, both of which utilize one or more types of remanent magnetism (Creer, 1967).

Remanent magnetism

Rocks and other objects may acquire a remanent magnetization by means of several different mechanisms. For paleomagnetic studies of rocks, this magnetism is known as natural remanent magnetism or NRM and is measureable as a vector quantity in the laboratory.

Whatever the mechanism of formation, NRM in a given rock originates in one or more of a relatively small number of magnetic minerals having ferromagnetic properties at normal temperatures. These lie predominantly within the FeO-TiO_2-Fe_2O_3 ternary system but also include such minerals as the pyrrhotites and the oxyhydroxides of iron (Irving, 1964). Details of the properties of the ferromagnetic minerals are given by Nagata (1953, 1961).

Thermo-remanent magnetism or TRM is the most important and most commonly found type of NRM. As the constituent magnetic mineral grains within a rock cool through their respective blocking temperatures, T_b, they become magnetized in the direction of the ambient magnetic field. T_b is determined mainly by particle size and crystal make-up of the magnetic minerals (Nagata, 1953). TRM is generally a very stable form of NRM, with long relaxation times, so that, barring other complications, it is preserved for periods of 10^8 or more years. TRM thus effectively 'freezes' into igneous rocks a measure of the ambient geomagnetic field at the time of their formation. Similarly, if in undergoing metamorphism a rock is heated above T_b, on cooling it will record the magnetic field at the time of the metamorphic event. In archeomagnetic studies one usually relies on TRM of pottery or bricks which have been baked to temperatures above T_b and which on cooling record the field at the time of their last firing.

Also of great importance in recording ancient field directions is chemical remanent magnetism or CRM. This type of NRM is brought on by chemical changes occuring in a rock at temperatures below T_b either by slow recrystallization of existing minerals or the formation of new magnetic minerals within the rock matrix. As mineral grains grow through their blocking diameter (Irving, 1964) they acquire a stable NRM parallel to the ambient field. CRM often has properties indistinguishable from TRM, a fact making their separation in any given rock quite difficult.

Viscous remanent magentization or VRM is a low temperature effect by means of which magnetic particles with low coercivity and/or short relaxation times gradually become magnetically oriented parallel to the ambient field at the expense of TRM or CRM previously acquired under the influence of a different geomagnetic field; this process is known as viscous decay (Irving, 1964). VRM is a statistical process based on random fluctuations in thermal energy, enabling the magnetization of magnetic domains to cross over energy barriers which they would otherwise be unable to cross. It has been shown (Nagata, 1961) that this is a time logarithmic process given by

$$J = \text{constant} + S \log t,$$

where J is the VRM acquired during time t and the magnetic viscosity coefficient S is dependent on the applied field and the rock type and varies directly with the absolute temperature. For most rock types VRM amounts to only about 2 or 3% of the TRM for periods up to 10^9 years, except at elevated temperatures (Nagata, 1961). Therefore except in extreme cases VRM has no significant bearing on the resultant remanent magnetism because it is easily removed by demagnetizing techniques (cf. below).

Both CRM and VRM are often regarded as secondary components or 'noise' on top of the original primary TRM and various techniques can be used to separate, eliminate or reduce their effects.

Sedimentary rocks can acquire an NRM by a process called detrital remanent magnetization or DRM. Minute magnetic particles become oriented by the geomagnetic field as they settle and become consolidated into sedimentary layers. Irving (1964) presents additional information on DRM. Since this process does not effect igneous rocks we shall not discuss DRM further here.

Before one can safely utilize magnetic data from any given rock or baked archeological artifact, a stability check is generally made to determine if the magnetic vector which is being measured is in fact due to primary NRM or is due to some secondary effect such as weathering, metamorphism, heating or viscous remanence. There are basically two stability tests in common use, one using successive alternating field (A.F.) demagnetization techniques, and the other using thermal demagnetization at successively higher temperatures. Both methods are described in several papers (e.g. Collinson et al. (1967); Irving (1964) has published a good summary). Both methods essentially measure the resistance of the NRM to heat or magnetically induced changes, and thus a measure of the magnetic stability is obtained.

Archeomagnetism

The archeomagnetic technique of paleo field determination, like the paleomagnetic method to be discussed below, relies on remanent magnetism to record the ancient magnetic field direction and intensity at a particular place and time on the earth's surface (Thellier and Thellier, 1959; Thellier, 1967). The principal difference between the two techniques is one of time control. In archeomagnetism the remanent magnetism is measured in bricks, tiles, potteries, or clays which have been baked by man at the time of manufacture or use, and which may be dated by means of archeologic, historic or radiocarbon techniques. Often it is possible to extract only inclination and intensity information, but not declination, as many of these items are not recoverable *in situ* where they were baked. The fact that such artifacts are orientable at all is due to the fact that bricks and tiles or pottery are normally fired in a horizontal or upright position. Sometimes historically or archeologically dated lava flows have also been used. The degree of time resolution varies greatly in archeomagnetism, generally being less precise with earlier dates. For the last 2000 or 3000 years there are many measurements with excellent historical or archeological dates of ± a few years or a few tens of years. In some areas carbon-14 dating techniques have to be used with a consequent loss in time resolution. Carbon-14 dating which is used in dating back to 50,000 years B.P. (Knopf, 1957) is usually only accurate to ± 5 or 10%, which for older material can amount to 100 years or more. Often purely archeologic methods help in further narrowing this range.

Unfortunately, archeomagnetic measurements are too thinly distributed both in time and space to extend detailed world wide analysis of SV back in time much beyond the 100 years or so for which direct measurements exist. Generally analyses have been limited to comparing archeomagnetically determined magnetic inclination or intensity curves for two or three different widely separated areas in order to study westward drift (Bucha, 1969; Bucha *et al.*, 1970; Burlatskaya *et al.*, 1968, 1969a; Smith and Needham, 1967; and Chapter I of this paper). It has also been used to study the variation in dip and declination at or near a single site to learn about dipole wobble (Kawai and Hirooka, 1967; Kawai *et al.*,1967), and to try to find periodicities in intensity, inclination or declination (Nagata *et al.*, 1963; Bucha, 1965; Watanabe, 1958; Dubois and Watanabe, 1965; Aitken *et al.*, 1964; Kovacheva-Nozharova, 1968).

Paleomagnetism

In paleomagnetism, use is made of natural remanent magnetism (NRM) in various rock types from which carefully oriented specimens are collected from in situ bed rock. An excellent summary of the paleomagnetic method and its applications is given by Irving (1964). The principal type of NRM and rock type used in SV work, and used in the present study, is thermoremanent magnetization (TRM) observed in volcanic rocks. As any rock is cooled below the blocking temperature(s) of the constituent magnetic mineral grains the ambient geomagnetic field is effectively 'frozen' into the rock. Since the time taken for even the largest lava flows to cool is generally short compared to characteristic SV times, what is recorded by a given lava flow effectively preserves an instantaneous record or spot reading of the geomagnetic field at that place and time.

Unfortunately, though the place of such a spot reading is well determined by the sampling site, the determination of the time of the reading presents a problem. Since we are interested in studying variations having between 10 and 10^4 year time scales, it would obviously be highly desirable to know the time of our spot reading to ± 10 years or at the very least to ± 10^2 years. Even relative dating of a sequence of measurements, rather than absolute dating, would be sufficient for study of SV. Radiometric dates are not generally considered reliable to the degree of accuracy required for SV analysis, even on a relative scale - one is lucky if one can date to even ± 10^4 years by these methods. If conditions are better than average one can date volcanic rocks to about ± 2% using K-Ar techniques (D. Turner, personal communication, 1971).

The time control problem doesn't arise to the same extent in most other types of paleomagnetic studies,such as those aimed at understanding continental drift and global tectonics, because the time scales of these phenomena tend to be much longer (generally greater than 10^6 or 10^7 years), and thus well within the range of standard dating techniques. Time control is, however, somewhat of a problem in detailed study of magnetic field reversals where the time scale of a reversal is thought to be as little as 1000 years.

The most promising way of handling the time problem in looking at SV is to argue on geological grounds that a particular formation was laid down in a more or less regular fashion during a period of at least about 10^4 years and to sample at regular intervals across the section (Creer, 1967). The most usual type of formation used to study paleosecular variation is a series of ancient lava flows, though some SV analyses have been done using Pleistocene to Recent glacial varves (e.g. Griffiths, 1953, 1955) and also using radial sampling of large intrusive bodies which may have taken up to 10^4 years to cool (e.g. Jaeger and Green, 1956).

An excellent example of using geological and other non-radiometric evidence to determine the time span involved in a SV analysis is Doell's (1969) study of 54 lava flows on Mauna Loa, Hawaii. He reviewed historical records since 1832 to conclude that on the average there is a summit eruption each 8 1/2 years. Then,on the basis of the lateral extent of each flow and the diameter of the summit caldera,he calculated that it would take 1100 flows to build up the 150 meters of the caldera wall which he sampled. Then his flows represent 1100 x 8 1/2 or a little more than 9,000 years.

The time resolution problem is the weakest link in modern paleosecular variation studies and is probably the primary cause for the large range of SV observed in different peoples' work.

Since the time resolution is poor, virtually all SV studies have treated the paleomagnetic results statistically, assuming that the data obtained from a given site represent a random sampling of paleo-field values. These statistics will be discussed in the following chapter.

It is generally accepted that for reliable SV measurement statistics require that a minimum of about 20 flows be sampled. This is a criterion that is only rarely met in practice. However, according to Cox (1969a) even 20 flows gives only about ± 25% reliability on the usual statistical parameters (Chap. III) at the 95% confidence level; to approach ± 5% reliability at the same confidence level one has to sample nearly 500 flows.

III. STATISTICS AND TREATMENT OF DATA

Paleopoles and virtual geomagnetic poles

A basic assumption of paleomagnetism is that when averaged over periods long enough to mean out the secular variation (about 10^4 years), the geomagnetic field is axially dipolar and is geocentric (Creer, Irving and Runcorn 1954). Using this assumption it is a simple matter to calculate from a well determined paleomagnetic vector direction after SV components have been meaned out at a given site the corresponding paleo dipole axis position using the basic equation

$$\tan I = 2 \tan\lambda, \qquad (3\text{-}1)$$

where I is the vector inclination and λ is the paleolatitude. Since the axial dipole assumtion seems to have good basis (Briden, 1968; Runcorn, 1959a, b; Creer, 1967; Opdyke and Henry, 1969; Burlatskaya *et al.*, 1969a; and others) paleopoles determined in this way probably represent true ancient geographic poles relative to the land mass being studied. However, if one takes an individual paleomagnetic direction from a given lava flow which represents a 'spot' reading of the local field, a paleopole position calculated from this reading will not in general represent the geographic or even the geomagnetic pole of that time, just as today a given magnetic vector at a point on the earth's surface doesn't necessarily correctly determine the magnetic or geographic pole due to local or regional magnetic anomalies and SV effects. Paleomagnetically determined poles which probably represent true poles because they involve time averages over 10^4 or more years we shall call paleopoles; those poles calculated from spot paleomagnetic readings are called virtual geomagnetic poles (VGP) after Cox and Doell (1960) because they probably didn't exist as true poles at all.

The statistics we shall discuss below are concerned with directions of unit vectors - that is, with points on the unit sphere. Magnitude (intensity or strength) of magnetic vectors is ignored. For the moment we may consider all statistics to apply equally well to magnetic vector directions or VGP's.

Paleomagnetic dispersion

In any series of paloemagnetic measurements a certain amount of scatter or dispersion of directions will be observed. Changes in measured direction of magnetization observed may be due to about five sources which are here briefly enumerated:

(1) Secular variation (SV) of the geomagnetic field direction appears to be characterized by periods of from 10 to 10^4 years (Cox and Doell, 1964; Chapter I, this paper) and has its source within the earth's core.

(2) Green (1958) and Cox and Doell (1964) suggest that there is a component of polar wandering of the axis of the earth and hence of the magnetic pole due to a random walk process; this would occur with a characteristic period of from 10^5 to 10^6 years.

(3) Reversals in the polarity of the magnetic field have been shown by many researchers to have occured with periods of from 10^3 to 10^6 years duration (Cox and Doell, 1964; Cox, Doell and Dalrymple, 1964; Cox, 1968; Creer and İspir, 1970). The period immediately surrounding a reversal is characterized by very widely varying field components and low intensity.

(4) There is a rapidly growing body of evidence that over much

longer periods of time (10^7 to 10^9 years) land masses of continental extent have moved about the earth's surface relative to one another ('continental drift') with consequent field variations at specific sites.

All of the above (1) through (4) represent actual changes in the field at a given location during geologic history though in (4) it is the position of the land mass rather than the field which is changing. We hasten to point out that in any given rock formation it is unlikely that any of the above except SV (1) or sometimes field reversals (3) will contribute significantly to the observed scatter, for the time scales of the other sources of variation are too long, or it is possible by other means (dating, geological evidence, etc.) to separate out their effects.

(5) Lastly, scatter or dispersion may be due to various sources of error. These sources may be conveniently divided into two categories:

(a) Experimental errors are those errors introduced directly or indirectly during the process of sample collection and measurement. These include orientation errors at various stages in the process, instrumental errors in measurement, additional components of 'soft' magnetization acquired by the sample during transit or storage, etc.

(b) Errors also occur when for one reason or another the magnetization of the rock was not formed parallel to the then existing regional field, or has since changed by the addition of secondary components. This can be due to numerous causes, including self reversal, viscous remanent magnetization, anisotropy, inclination error (in detrital remanent magnetization; cf. Chapter II), random components, etc.

Another related source of scatter in measured paleomagnetic direction is local magnetic anomalies at the time the rock was formed. Doell and Cox (1963) found for Hawaiian lava flows this source of error could amount to about 2.4°. We shall loosely call all these types of errors experimental errors. Doell and Cox (1963) have done extensive measuring of historic Hawaiian lava flows to determine the relative importance of all these sources of error.

The central problem in the present paper is to distinguish between the scatter in vector directions due to experimental error and that due to secular variation. If for each lava flow we have several measurements, the scatter within any individual flow will be due to the former source. The dispersion of flow-mean directions will be due to both sources. More or less standard analysis of variance techniques will be used to separate them.

Fisher statistics

Most paleomagnetic analysis is carried out assuming that the data have approximately the Fisher (1953), or Fisherian, 'spherical normal' distribution of points on a sphere, which has an angular probability density

$$P d\Omega = \frac{\kappa}{4\pi \sinh \kappa} e^{\kappa \cos \theta} d\Omega, \qquad (3\text{-}2)$$

where θ is the angle between the preferred direction and an observation. This distribution is equivalent to the Gaussian error function of one dimensional theory. Since an azimuthal angle ϕ does not appear it is clear this is an axially symmetric distribution. For $\kappa \neq 0$ and $< \infty$ it can be seen that the density decreases away from the preferred direction. For $\kappa = 0$ the points are uniformly distributed; i.e., there is no preferred direction. The larger κ is, the more tight the distribution. κ corresponds to the reciprocal of the variance of the Gaussian distribution. Runcorn (1967) points out that the Fisher distribution is valid only if all vectors are unit vectors or at best equal in intensity. Fisher has shown that if the true mean vector is unknown the best estimate κ of the precision parameter κ is given by

$$\cosh k - \frac{1}{k} = \frac{R}{N},$$

or for $k > 3$ with good accuracy by

$$k = \frac{N - 1}{N - R}, \qquad (3\text{-}3)$$

where R is the length of the vector sum of N unit vectors whose directions correspond to the data points of the sphere. Paleomagnetic data by no means always have a Fisherian distribution, but Watson and Irving (1957) have presented data which show that if the rocks possess stable magnetization, the directions will hold reasonably close to Fisher statistics; if they have unstable components they do not conform to the distribution. Thus use of the statistic k does not necessarily imply that the data are Fisherian, but is used as a convenience and nonetheless serves as a useful yardstick for comparing data.

If there are several sources of scatter occuring at the same statistical level with Fisher parameters k_1, k_2, k_3, ... they add according to the relation

$$\frac{1}{k_T} = \frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3} + \dots \qquad (3\text{-}4)$$

where k_T is the total scatter observed (Runcorn, 1957).

Angular standard deviation

Another statistic we shall use is

$$\delta = \cos^{-1} \frac{R}{N} , \qquad (3\text{-}5)$$

the angular standard deviation (Wilson, 1959). There is some confusion in the literature as to what is called the angular standard deviation factor, and under what circumstances. We will make an attempt to resolve this confusion. δ as in (3-5) is analogous to the standard deviation of a planar distribution and is in no way dependent on whether or not we have a Fisherian distribution. Just as for a planar distribution the standard deviation is that value within which 68% of the data lie *if* it is a normal distribution, so also for a spherical distribution the angular standard deviation is that angle within which 63% of the data lie *if* the distribution is Fisherian (Runcorn, 1960; Larochelle, 1968). The discrepency in these percentages is due to spherical distortion of the Gaussian normal distribution.

Runcorn (1957), Creer, Irving and Nairn (1959), Creer (1962b), Irving (1964), Doell and Cox (1963), and Cox (1969b) and others use the statistic

$$\Delta = \sqrt{\frac{2}{k}} \text{ radians} = \frac{81}{\sqrt{k}} \text{ degrees}, \qquad (3\text{-}6)$$

which is the angular standard deviation for large N if the distribution is Fisherian (some confusion has arisen in notation in that different authors have used the symbols s, S, ξ, σ, θ_o, θ_{63}, Ψ_o and δ along with amost as many different appellations to designate that which we call Δ after Creer (1962a and 1967)). Δ is derived from (3-5) by Wilson (1959) by setting

$$\frac{R}{N} = \cos\delta \approx 1 - \frac{1}{2}\delta^2,$$

or

$$\delta_{rms} = \sqrt{\frac{2(N-R)}{N}}. \qquad (3\text{-}7)$$

If we assume N ≈ N-1 (a questionable assumption) then

$$\delta_{rms} = \sqrt{\frac{2}{k}} = \Delta.$$

An alternate derivation comes from Cox and Doell (1964) by starting from the beginning and taking the angular standard deviation to be the RMS value of the individual deviations from the mean,

$$\delta = \sqrt{\frac{\sum_{i=1}^{n} \delta_i^2}{N-1}} \approx \sqrt{\frac{2(N-\Sigma\cos\delta_i)}{N-1}} = \sqrt{2\,\frac{N-R}{N-1}} = \sqrt{\frac{2}{k}} \qquad (3\text{-}8)$$

where δ_i is the angle between the i^{th} observation and the mean direction.

In statistics there is often a confusion between the $N^{-1/2}$ or $(N-1)^{-1/2}$ factors appearing in relations such as (3-7), and (3-8). This arises because sometimes it is unclear whether dispersion is being measured about the true mean or the measured mean of the quantity under consideration. In the former case there are N degrees of freedom for N measurements; in the latter there are only N-1 since the mean itself is determined by the N measurements. Generally, but not always, in paleomagnetic work the mean is unknown so that the N-1 factor is appropriate. $N^{-1/2}$ can be considered approximately equal to $(N-1)^{-1/2}$ only for N larger than 10 or so. Thus it would appear that statistically equation (3-5) should be written

$$\delta = \cos^{-1}\frac{R}{N-1}.$$

However, for many sets of data this would give an imaginary δ since $\cos\delta$ would be greater than unity.

Thus we are left with two somewhat inconsistent angular standard deviations, both of which we retain for the sake of comparision with other people's work. Henceforth we designate

$$\delta = \cos^{-1} \frac{R}{N} \qquad (3\text{-}5)$$

and

$$\Delta = \sqrt{\frac{2}{k}} \qquad (3\text{-}6)$$

and acknowledge the fact that only for large N are they sometimes equal. However, we shall find that in practice δ and Δ usually differ only by a small amount, even for quite small N (cf. Tables 5-1 and 5-2 in Chapter V). Watson (1966) makes the point that it is a mistake to attempt to define an angular standard deviation at all, for k is much easier to handle statistically than δ or Δ. The equation for addition of angular standard deviations arising from several sources corresponding to equation (3-4) for k is

$$\delta_T = [\delta_1^2 + \delta_2^2 + \delta_3^2 + \ldots.]^{1/2} \qquad (3\text{-}9)$$

Cox (1962). This applies equally to δ or to Δ.

Confidence limits

All the above statistical quantities k, δ, Δ are measures of the dispersion of a set of vectors. That is, they are measures of the true scatter in an infinite population of vector directions from which N are sampled, rather than indications of the precision or accuracy of the measuring process. They do not necessarily change with more measurements (increasing N) as do such factors as the radius of the 95% circle of confidence,

$$\alpha_{95} = \cos^{-1}\left\{1 - \frac{N-R}{R}\left[\left(\frac{1}{1-0.95}\right)^{\frac{1}{N-1}} - 1\right]\right\} \approx \frac{140}{\sqrt{kN}} \text{ degrees} \qquad (3\text{-}10)$$

(Fisher, 1953) and a similar expression for α_{63} (the expression relating α_{95} to k is valid only for Fisherian distribution and small α; this expression is not used in our analysis). These parameters measure how accurately the measured mean represents the true mean, and as such will generally become smaller the larger N is. Since in SV work we are generally interested in the dispersion of a group of vectors rather than the mean itself we shall be more concerned with dispersion than precision parameters.

Analysis of variance

Thus far we have been considering the statistics of N independent observations of direction all observed at the same hierarchical level of statistics. If we are sampling a series of lava flows, each of which represents a 'spot' reading of the geomagnetic field, in order to study the SV we will want to take several samples from each flow to minimize experimental error. Thus for each 'flow mean' direction there will be associated a certain 'within flow' scatter k_ω or δ_ω. As a measure of secular variation we will find the scatter of these flow means, k_T or δ_T. However, this flow mean scatter is the total scatter due both to the experimental errors of the within flow scatter (k_ω or δ_ω) and the between flow scatter (k_β or δ_β), which is presumably due solely to SV. To sort out one source from the other we shall use the two tier analysis of Watson and Irving (1957), which is explained more fully by Watson (1966) as merely being an analysis of variance carried out on a sphere. The more general principles of analysis of variance are given by Panofsky and Briar (1963). Larochelle (1967, 1968) uses a slightly different analysis of variance scheme, but as the results only differ slightly, and for the sake of comparison with other work we will follow the scheme of Watson and Irving. Accordingly we may draw up Table 3-1.

TABLE 3-1

Analysis of variance table for 2-tier analysis after Watson and Irving (1957). See text for details.

Source	DF (degrees of freedom)	SS (Sum of squares)	MS (mean square)	Expectation of mean square
Between flows	$2(B-1)$	$\Sigma R_i - R$	$(\Sigma R_i - R)/2(B-1)$	$\frac{1}{2}(\frac{1}{k_\omega} + \frac{\overline{N}}{k_\beta})$
Within flows	$2[\Sigma(N_i - 1)]$	$\Sigma(N_i - R_i)$	$\Sigma(N_i - R_i)/2\Sigma(N_i - 1)$	$\frac{1}{2k_\omega}$
Total	$2(N-1)$	$N-R$		

where B = number of flows,

N_i = number of cores in i^{th} flow,

$N = \sum_{i=1}^{B} N_i$,

R_i = length of resultant of N_i unit vectors from i^{th} flow,

R = length of resultant of all N unit vectors from B flows,

and $\overline{N} = \frac{1}{B-1}(N - \frac{\Sigma N_i^2}{N})$ = weighted average of the N_i.

The significance of the between flow dispersion may be judged by using an F-ratio test on the mean squares. If there is no significance we are forced to ignore between flow variation due to SV and assume it is all due to experimental errors; i.e. $k_\beta = \infty$. In fact, of course, this may not be strictly true but whatever SV component is present in the scatter will be irrevocably buried in the errors. In any case it should be possible to place an upper limit on the scatter attributable to SV. A complete numerical example of the use of this method is given by McElhinny (1967).

The method of Watson and Irving (1957) is, strictly speaking, only valid if the within-flow scatter is constant from flow to flow. McElhinny (1967) points out that the method may still be used if the data is Fisherian and the product k_iN_i is approximately constant where k_i is the Fisher parameter of the i^{th} flow. Though our data will rarely strictly satisfy these criteria, in the absense of a better statistical scheme we shall make use of it anyway as a useful measure of between-flow scatter, and for comparison with other results.

An alternative method of removing the effect of within-flow scatter from the scatter of flow means should also be mentioned. Taking δ_t to be the measured dispersion of flow means and δ_ω to be the RMS value of the within flow dispersions δ_i of the B flows, one may write

$$\delta_\beta^2 = \delta_t^2 - \frac{\delta_\omega^2}{B} , \qquad (3\text{-}11)$$

where δ_β may now be considered to represent the between-flow dispersion after removal of within-flow effects. δ_β is thus a measure of the true dispersion of field directions during extrusion of the flows in question.

This method has the advantage of simplicity but lacks the built-in assurance of a significance test. However, Creer and Sanver (1970) in analyzing 21 sets of data by both equation (3-11) and the two-tier analysis of Watson and Irving (1957) found an almost negligible difference of only 0.7 ± 0.5° between them.

IV. PALEOSECULAR VARIATION MEASUREMENTS IN ALASKA

Techniques

The methods and equipment used in this study are similar to those used by others and are adequately described in the literature (e.g. Collinson et al., 1967). Our particular system is explained by Cameron (1970) and Cameron and Stone (1970).

Cores were taken with an air cooled chain saw motor powered coring drill using a water cooled 2.54 cm diameter stainless steel coring bit with diamonds set in a phosphor-bronze matrix on the cutting edge. The drill is similar to that described by Doell and Cox (1967).

Cores were oriented using a slotted copper tube which fits over the core while it is still attached to bedrock. A brass wire slid down the slot records the fudicial line on the core itself. A Brunton compass is fitted to a moveable platform at the top of the tube. Absolute orientation in space of each core was achieved by sun compass readings.

In the laboratory, cores were cut into 1 cm or 2.1 cm discs before measurement in a 5 Hz spinner magnetometer (Foster, 1966) or in a few cases with an astatic magnetometer.

Orientation errors both in the field and final positioning in the measuring apparatus are thought to be on the average < 2°, in line with Doell and Cox (1963). Errors arising from the measurement itself are rarely as much as 5°.

Following Doell and Cox's (1963) suggestion that 6 cores per flow was an optimum number in terms of balancing statistical advantage against logistical difficulty, we took 5 or 6 cores per flow (rarely as few as 3 or 4 per flow, and on occasion as many as 11 or more).

To ensure adequate representation of the magnetic field direction recorded by a given flow, an attempt was made to spread the sampling sites within the flow laterally over 50 meters or more. In practice, due to weather, terrain, outcrop limits or time, this was only rarely possible and 20 or 30 meters is perhaps a better estimate of lateral spread. An attempt was also made to sample at equal vertical intervals within any flow but likewise logistical considerations often prevented this. Cores were taken only from rocks which were in situ and one could be certain no local rotation or slumping had occurred.

Stability tests and magnetic cleaning were accomplished by successive alternating field (A.F.) demagnetizations. Samples were tumbled about two mutually perpendicular axes within a slowly decreasing 60 Hz field.

Final directions and VGP's taking core and bedding orientation into account were calculated using an IBM 360-40 electronic digital computer. Results were hand plotted on a Wulff stereographic projection. Statistical parameters were calculated using the same computer.

Potassium-argon (K-Ar) whole rock age determinations were carried out on a few hand samples from almost all the sites by Geochron Laboratories, Inc. and Mobil Research and Development Corporation.

Sampling sites

Suitable sequences of lava flows for paleosecular variation measurements were sampled on three islands in the Aleutian Island chain, and at one site in the Wrangell Mountains (Fig. 4-1). Field work was

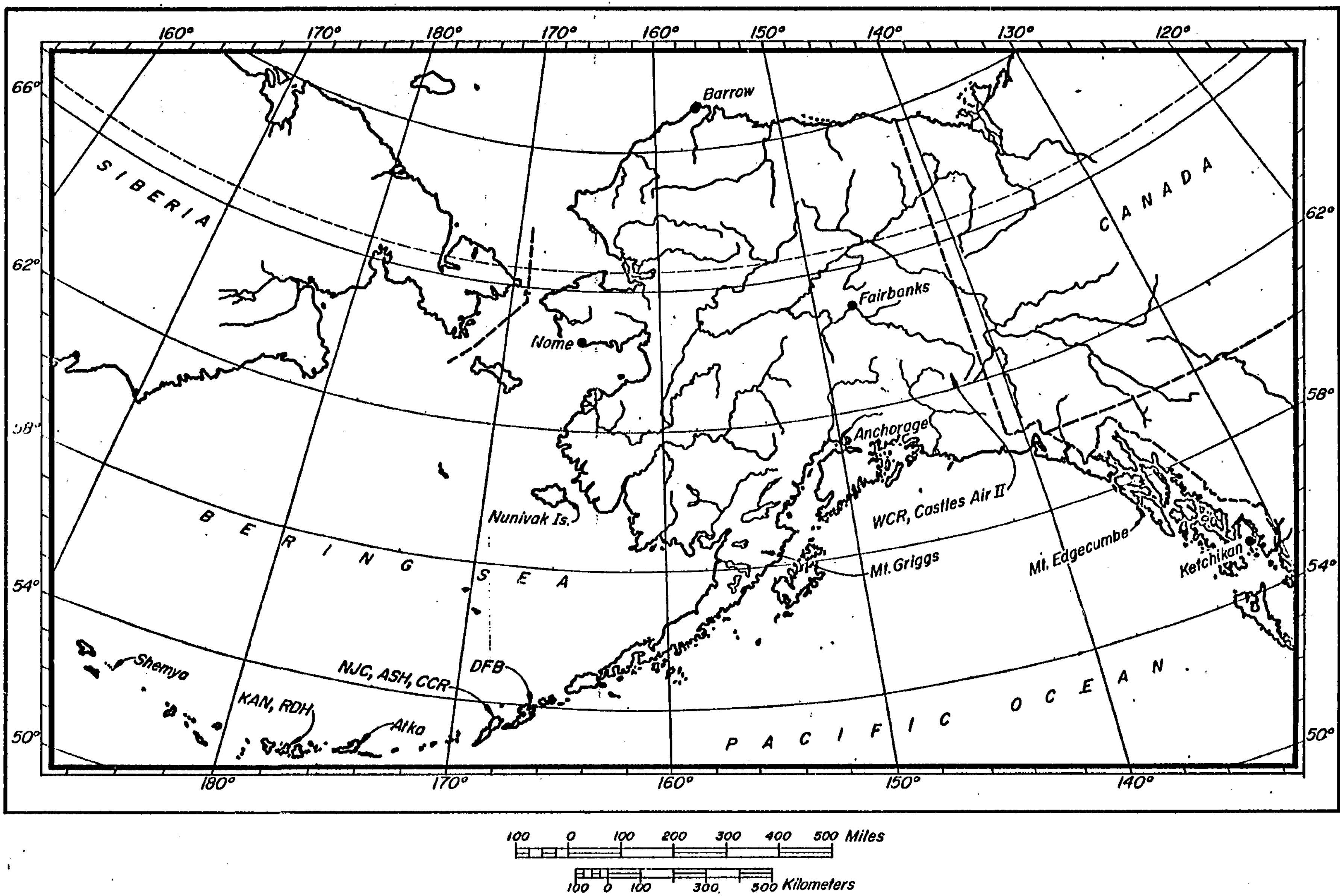


Figure 4-1. Location map of paleosecular variation measurement sites in Alaska.

done during the summers of 1967, 1968 and 1969. Samples collected at a few other Alaskan sites were also used in combined statistical analysis.

The overall geology of the Aleutian Islands has been outlined by Coats (1956b), Cameron (1970) and Cameron and Stone (1970). A resumé of geophysical work in and around the Aleutian Islands has been compiled by Stone (1968). A series of reconnaissance surveys of individual islands was published in the late 1950's by the U.S. Geological Survey in several sections of Bulletin 1028.

Kanaton Ridge, Kanaga Island (KAN). The geology of northern Kanaga Island in the Andreanof Island group of the Aleutians is outlined by Coats (1947, 1956a).

Kanaton Ridge (KAN) forms the caldera rim of ancient Mount Kanaton, a broad shield volcano constructed, according to Coats, during late Tertiary and early Quaternary time. However, a K-Ar date run on a sample taken a few feet above the top flow cored, gave a date of only 0.18 ± 0.09 m.y. It is composed of a sequence of nearly horizontal basalt and andesite flows which are weathered only enough to make finding *in situ* outcrops suitable for paleomagnetic sampling a little difficult.

Eight flows were sampled in June 1968 from between 1500 and 2000 feet altitude on an eastward trending ridge just outside the ancient caldera rim, about 1.5 km east of the lake, which is 3 km southeast of Kanaga Volcano (the sampling site is near military grid point DH505930 or at approximately 51°54'N., 182°54'E.). Between 3 and 11 cores per flow were drilled but only one flow had less than 6 cores drilled. The flows are numbered 1 through 8 from the lowest exposure upward to near the top of the ridge.

Three 1 cm discs were cut from each core and stability tests were run on selected discs from each flow. On the basis of these tests, which indicated that most unstable components had been removed by 380 oe peak A.F. demagnetization (Figure 4-2a, b), one disc (the middle one) from each core was demagnetized at 380 and 760 oe. As the former field clearly gave the lower scatter only these values were used in the analysis.

Flow 8 of the KAN series presented somewhat of a problem as both magnetically low dip and magnetically reversed cores were present. It was finally decided after studying the field notes denoting exact locations of cores that we had inadvertantly sampled two flows, the one being normal with low dip and high scatter and the other being reversed with low dip but very small scatter. They both have considerably lower magnetic intensity than the remaining flows. These flows have been designated 8A and 8B respectively.

Due to low magnetic dips and intensities of samples from these flows it is presumed that they were extruded while the geomagnetic field was undergoing a reversal and therefore represent a period of unstable field behavior (Momose, 1963; Lawley, 1970; Goldstein _et al_., 1970; Ito and Fuller, 1970; Creer and İspir, 1970). Though it is impossible to tell from the limited exposures which flow is the older it seems likely that flow 8A which is normal predates reversed flow 8B because of the stable sequence of normal flows below. In any case, since flows 8A and 8B represent abnormal field behavior they have been omitted

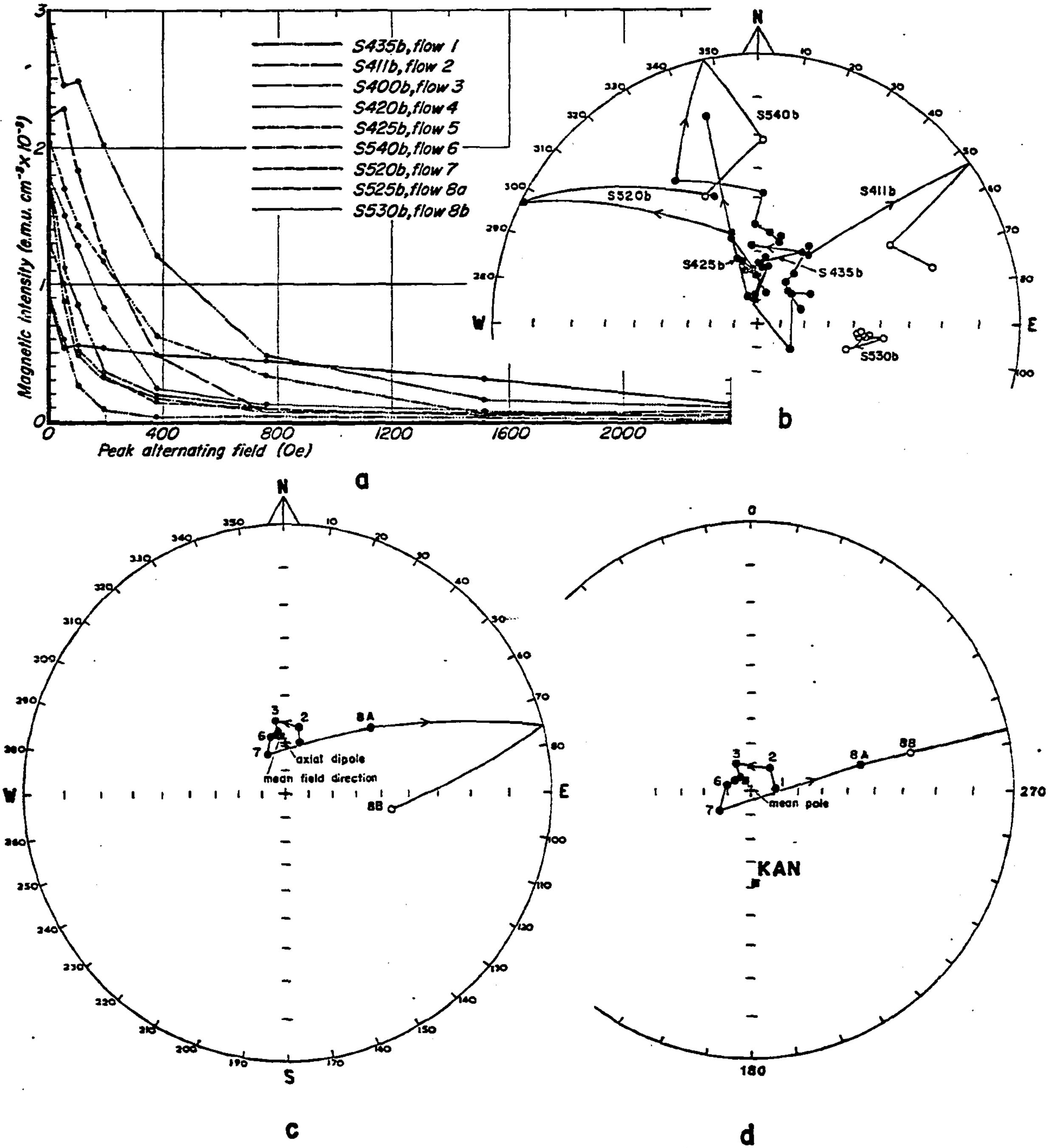


Figure 4-2. Paleomagnetic data for Kanaton Ridge, Kanaga Island (KAN). (a) Magnetic intensity and (b) vector directions of pilot samples during A.F. demagnetization. Arrows point toward higher fields. Sample numbers are indicated. (c) Flow mean magnetic vectors. Flow numbers are indicated; arrows point toward younger flows. (d) Corresponding flow mean VGP's. Mean data from Table 4-1. North seeking poles (north VGP's) are plotted on Wulff stereonets with solid circles indicating lower (north) hemisphere and open circles indicating upper (south) hemisphere.

from the statistical analysis.

The magnetic reversal of flow 8B gives us an additional handle on the age of the KAN sequence. The only field reversals reported within the Bruhnes Normal Polarity Epoch or within the last 700,000 years (Cox and Dalrymple, 1967; and others) are the Blake Event dated by carbon-14 methods at between 108,000 and 114,000 years ± 10% (Smith and Foster, 1969) and the Laschamp Event dated by C-14 methods at about 8,000 years (Bonhommet and Babkine, 1967; Bonhommet, 1970) and by K-Ar methods at less than 20,000 years (Bonhommet and Zäringer, 1969). However, Denham and Cox (1970) present independent fairly conclusive evidence that no geomagnetic field reversal occurred between 30,000 and 12,000 years ago.

The age for the KAN sequence reported above is actually the mean of two whole rock K-Ar age determinations run on the same sample by Mobil Research and Development Corporation which were listed as 0.24 ± 0.08 and 0.13 ± 0.09 m.h. This gives a total range of 40,000 to 320,000 years. However, this range merely reflects the precision of the laboratory technique and a somewhat greater actual range may be expected. Thin section examination of the rock shows it to be a basalt with microphenocrysts of labradorite, augite and olivine while the ground mass contains plagioclase and clinopyroxene microlites, glomeroporphritic aggregates of clinopyroxene, and opaques (B.N. Chatterjee, personal communication, 1969). The rock appears to be not unsuitable for K-Ar age dating (D. Turner, personal communication, 1971).

Thus given the possible errors on all age determinations, it seems that in the KAN section we have probably recorded the Blake Reversal

Event, though it is possible that the Laschamp Event has been recorded instead, if indeed they are separate events. The possibility of a large scale magnetic field excursion should not be entirely ruled out, as the Kanaton reversal is not exact, but is only about 120° away from the mean of the normal flows (Figure 4-2c).

The remaining seven flows have vector directions and VGP's fairly tightly distributed ($k=136$ and 58 respectively) about the axial dipole field direction and the geographic pole respectively (Table 4-1 and Figure 4-2c,d). The number of flows is too small to ascertain much about the distribution, but it is not too far from being axially symmetric. A clear serial correlation from one flow to the next is evident indicating that perhaps these 7 flows were extruded fairly rapidly and do not represent the full spectrum of secular variation.

The standard two tier analysis (Watson and Irving, 1957) was carried out on flows 1 through 7. The results are given in Table 4-2 following the format given in Chapter III. The variance ratio proved significant at the 95% level so that calculated values for k_ω and k_β are given. The number of flows would appear to be far too small for a reliable measurement of SV to be possible; nevertheless we may take $k_\beta = 239$ as being a minimum measure (maximum k) of SV during the time of extrusion.

Round Head, Kanaga Island (RDH). Round Head forms a prominent sea cliff near the easternmost extremity of Kanaga Island. It is composed of gently dipping olivine basalt flows 10 to 40 feet thick which were extruded from a vent on the northeast side of ancient Mount Kanaton. The rock is fresh and typically light in color with conspicuous large

TABLE 4-1

Flow mean statistical data for KAN series. Flows are listed in stratigraphic sequence (youngest first). Cores were all A.F. demagnetized at 380 oe. Site mean data are also given with statistics based on flow mean directions (KAN_{fld}) and on VGP's corresponding to flow mean directions (KAN_{vgp}). Flows 8A and 8B are omitted from site mean statistics (see text).

Flow No.	N	k	δ	α_{95}	$\bar{D}$	$\bar{I}$	λ	ϕ	$\bar{J}_{nrm}$
8B	5	553.6	3.1	3.3	98.2	-44.7	-25.4	283.9	855
8A	6	2.5	48.2	53.9	53.2	45.6	43.4	283.9	980
7	6	37.6	12.1	11.1	335.8	71.7	75.2	120.7	2261
6	10	41.3	12.0	7.6	345.9	65.7	80.1	74.9	1648
5	8	70.6	9.3	6.6	351.0	64.9	82.3	55.6	2828
4	7	85.7	8.1	6.6	353.9	63.5	82.1	35.6	2269
3	8	82.2	8.4	6.1	352.6	59.4	77.3	29.3	2105
2	10	51.6	10.7	6.8	11.5	61.2	77.6	319.5	1489
1	3	215.9	4.5	8.4	15.8	67.4	79.9	276.4	2337
KAN_{fld}	7	136.3	6.4	5.2	355.9	65.3	84.9	35.3	
KAN_{vgp}	7	58.0	9.9	8.0			85.0	37.8	

N = number of cores per flow or flows per site for site mean data; k, δ, and α_{95} are within-flow statistical parameters calculated according to equations (3-3), (3-5) and (3-10) respectively. $\bar{D}$ and $\bar{I}$ are mean declination and inclination directions of the north seeking magnetic vector. + or − λ and ϕ are north or south geographic latitude and east longitude of corresponding VGP except for KAN_{vgp} where mean of VGP's is given. δ, α_{95} $\bar{D}$, $\bar{I}$, λ, and ϕ are all in degrees. $\bar{J}$ is the flow mean NRM value of magnetic intensity in e.m.u. $cm^{-3} \times 10^{-6}$.

TABLE 4-2

Analysis of variance table for KAN series. Flows 8A and 8B are omitted from calculations (see text). F is ratio of mean squares; $F_{5\%,\ n,m}$ is F-ratio for 5% probability level read from standard statistical tables. See Table 3-1 and Chapter 3 for explanation.

Source	DF	SS	MS
Between flows	12	0.2886	0.02405
Within flows	90	0.7890	0.00877

$F = 2.7423 > F_{5\%,\ 12,\ 90} \simeq 1.875$; therefore k_β significant

$k_\omega = 57.01$

$k_\beta = 239.34$

phenocrysts of dark augite (Coats, 1956a; Chatterjee, unpublished, 1968). Weathered rubbly layers between the flows suggests a minimum extrusion rate of about one flow per hundred years. A K-Ar date on the next to lowest flow exposed (flow 2) yielded a date of 0.0 ± 0.6 m.y. and is therefore inconclusive. All we are able to deduce is that the RDH series post-dates the KAN series and is probably less than 500,000 years old.

Fourteen flows were sampled in June 1968 along the upper edge of the cliff southeast of Round Head summit at altitudes ranging from near sea level to about 750 feet (between military grid points DH 490963 and DH 499965 or near 51°54'N., 182°57'E.). Between 5 and 9 cores were drilled per flow. The flows are numbered from the bottom up with flow number 1 being the prominent thicker than average columnar jointed flow just northeast of the abandoned trapper's cabin on the south shore of Round Head.

As with the KAN samples, three 1 cm discs per core were cut, and stability tests indicated that cleaning in 190 oe A.F. peak field removed most of the unstable components and produced the lowest within flow scatter (Figure 4-3a, b). Accordingly, the middle disc from each core was demagnetized in this field and measured; the values thus obtained were used in the statistical analysis.

The RDH flows are all normally magnetized. All but two of the 14 flows have angular standard deviations $\delta < 10°$ and their means are fairly tightly distributed ($\delta = 3.9$, $k = 401.4$) in a roughly circular distribution about a point within 5 degrees of the axial dipole field direction (Table 4-3 and Figure 4-3c, d). However, as their α_{95} circles

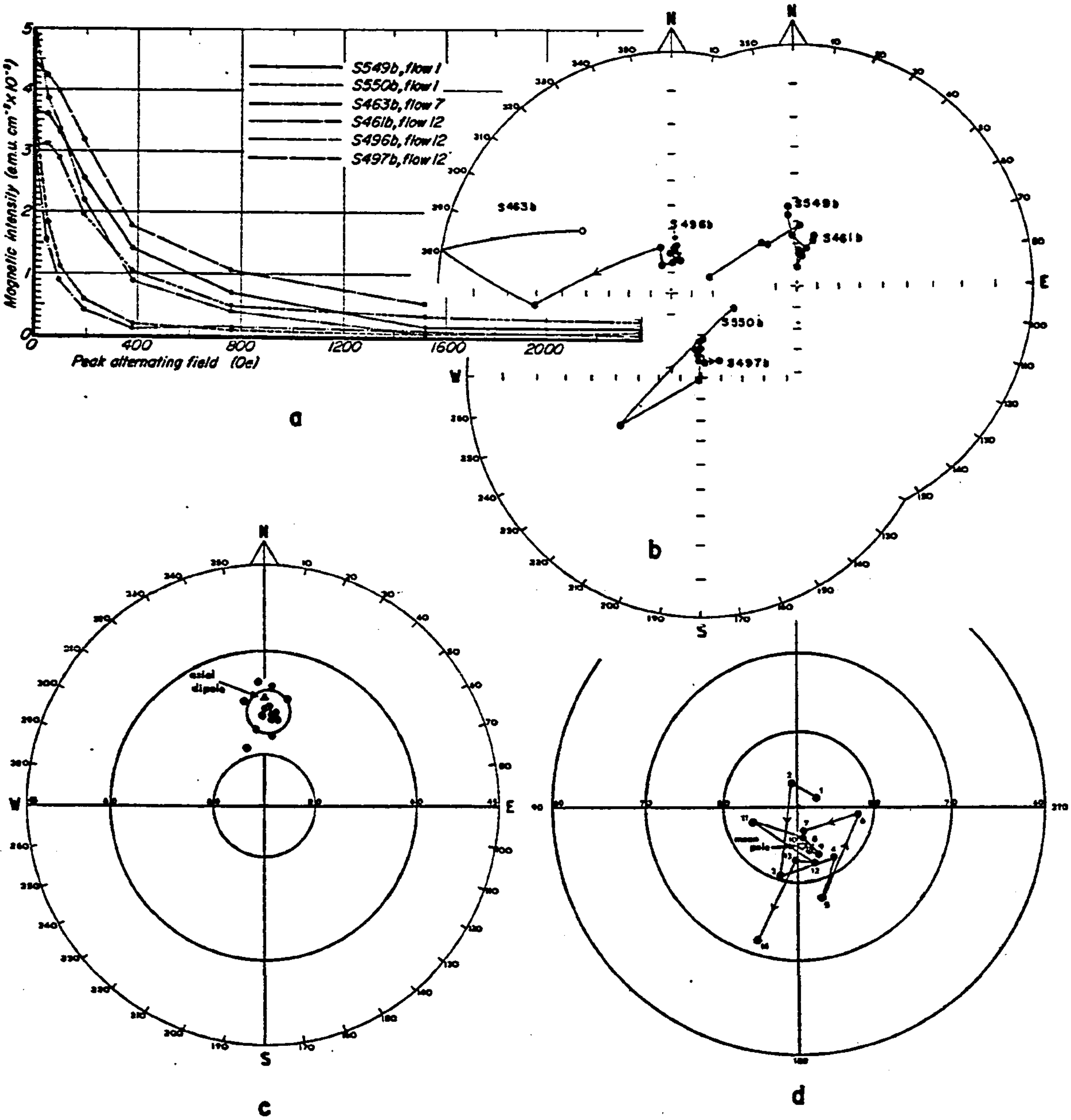


Figure 4-3. Paleomagnetic data for Round Head, Kanaga Island (RDH). (a) Magnetic intensity and (b) vector directions of pilot samples during A.F. demagnetization. (c) Flow mean magnetic vectors; circle of radius δ is drawn about site mean. (d) Corresponding flow mean VGP's. Note expanded stereonets. Mean data from Table 4-3; cf. explanation to Fig. 4-2 for further details.

TABLE 4-3

Flow mean statistical data for RDH series. Flows listed in stratigraphic sequence (youngest first). Cores A.F. demagnetized at 190 oe. Site mean data are also given (cf. Table 4-1 for explanation of symbols).

Flow No.	N	k	δ	α_{95}	$\bar{D}$	$\bar{I}$	λ	ϕ	$\bar{J}_{NRM}$
14	5	47.9	10.5	11.2	343.0	78.4	72.2	161.7	3970.6
13	5	192.8	5.2	5.5	359.0	73.1	83.1	178.7	3292.7
12	8	541.6	3.3	2.4	3.2	73.6	82.2	195.0	3421.9
11	8	94.2	7.8	5.7	349.2	69.6	83.3	109.5	3130.1
10	8	61.9	9.7	7.1	0.8	71.3	85.9	189.0	3092.2
9	6	292.8	4.3	3.9	4.7	72.7	83.2	204.5	3096.7
8	5	86.2	7.8	8.3	2.4	72.7	83.7	194.6	2795.9
7	5	218.2	4.9	5.2	1.2	70.5	87.2	196.7	3633.7
6	9	410.7	3.8	2.5	13.5	69.0	82.0	263.3	3253.5
5	5	164.0	5.7	6.0	7.0	76.5	77.0	196.6	3129.4
4	6	27.0	14.3	13.1	9.0	73.0	81.6	216.8	2758.6
3	4	156.9	5.6	7.4	353.6	74.6	80.1	164.9	3690.6
2	7	68.0	9.1	7.4	358.7	66.1	86.5	17.6	2839.6
1	7	72.4	8.8	7.1	4.3	67.6	87.0	298.1	3742.3
RDH_{fld}	14	401.4	3.9	2.0	1.1	72.2	84.6	189.0	
RDH_{vgp}	14	151.6	6.3	3.2			84.4	188.5	

TABLE 4-4

Analysis of variance table for RDH series (cf. explanation to Table 4-2).

Source	DF	SS	MS
Between flows	26	0.20381	0.0084
Within flows	148	0.804	0.00543

$F = 1.444 < F_{5\%, 26, 148} \simeq 1.55$; therefore k_β not significant.

of confidence have considerable overlap with each other, the significance of the separate flow mean directions as being representative of true field changes is doubtful. This is borne out by the analysis of variance (Table 4-4), which finds the variance ratio to be less than that which could occur randomly 5% of the time. Thus it is not possible to calculate separate k_ω and k_β and all we may conclude is that k = 401.4 represents the maximum dispersion (i.e. minimum k value) during the time of extrusion of the lavas.

The problem remains as to whether this value can be considered a measure of SV or whether we must conclude that the flows were extruded too fast for SV to be recorded. Doell (1969) argued for a very different sort of volcano in Hawaii that 54 flows took at least 9000 years to accumulate. His calculation is based on lateral extent of individual flows, circumference of the caldera and the number of summit eruptions per year (Chapter II). It is of course dangerous to extrapolate from an oceanic volcano to an island arc volcano especially when we know almost none of the necessary parameters for Kanaga Volcano let alone for ancient Mount Kanaton. Nonetheless we may make some estimates. Doell's calculation was based on one summit eruption of lava each 8 1/2 years. There has been only one known historic lava eruption of Kanaga Volcano; this was in 1906. From the activity of other Aleutian volcanoes of a similar type to Kanaga (Coats, 1950) a reasonable estimate might be between 5 and 10 eruptions per century. The three individual recent (historic?) flows of Kanaga Volcano which show on Coat's (1956a) map have the same approximate width (0.5 km) as the Mauna Loa flows in Hawaii. Nothing can be said of the geometry of the vent which gave rise to the RDH flows except that it was probably similar to other modern Aleutian volcanic vents and hence somewhat smaller than Mauna Loa. This last factor would tend to reduce the time represented at RDH, while the rate of eruption would tend to extend it. If we assume the two effects roughly cancel and extrapolate directly, we find the 14 RDH flows correspond to about 2300 years. This figure is not very different from that arrived at from the casual field observation that the weathered layer between flows probably represents a hiatus of at least 100 years. We should emphasize again the very approximate nature of the above calculation and not exclude the possibility of a somewhat shorter or even a much longer time span.

Thus on the basis of these rather tenuous extrapolations, coupled with the unusually low measured scatter, we tentatively conclude that the RDH value of K = 401.1 probably does not represent SV very well and must be taken, in fact, as an extreme lower limit (maximum k) of SV scatter for this site.

New Jersey Creek, Umnak Island (NJC). The geology of Umnak Island is outlined by Chatterjee (1971) and is detailed by Byers (1959) as well as in a preliminary report by Byers et al. (1947). The northeast end of the island is dominated by Okmok Caldera and its associated volcanics (Okmok Caldera was known during World War II as 'Zoomie Crater' (Freiday, 1945)). According to Byers, Okmok Volcano was built up during late Tertiary and early Quaternary time. The flows sampled, herein called the New Jersey Creek section (NJC), are among the earliest pre-caldera rocks exposed, and as such represent the early stages of the build-up of Okmok Volcano. The flows range from 20 to 60 feet in thickness and are described as being mafic phenocryst basalt (Byers, 1959). Their upper parts are rubbly and show evidence of considerable weathering between flow extrusions.

In August 1969 nineteen flows were sampled from prominent exposures on the cliff about 2.5 miles south of Ashishik Point, and 3.5 miles north of the rim of Okmok Caldera; the NJC site lies a few hundred yards west of New Jersey Creek itself. It is located at approximately 53°32'N., 191°55'E. The section sampled is approximately 500 feet thick (Figure 4-4). The rocks are fresh and dip very gently northwards. The flows are numbered 1 through 19 with flow 1 being the lowest one exposed. Between 4 and 7 cores were drilled from each flow.

One 2.1 cm long cylinder was cut from each core and stability tests run as previously described. A 475 oe A.F. peak field was found to produce the lowest within flow scatter and was thus assumed to have removed most of the unstable components (Figure 4-5a, b). All cores were demagnetized at this field and measured; the resulting values were used for the statistical analysis.

All flows were found to be normally magnetized and had mean directions grouped in a quasi circular distribution about a mean within 5 degrees of the axial dipole field direction (Figure 4-5c and Table 4-5). The within-flow scatter is reasonably small, only two of the flows having α_{95}'s larger than 10° and only five more with α_{95} greater than 6°. In spite of a certain amount of overlap of α_{95} circles of confidence, the analysis of variance (Table 4-6) clearly indicates the calculated value of k_β to be significant. Therefore we may take $k_\beta = 121.7$ to represent the true dispersion of the geomagnetic field during the time

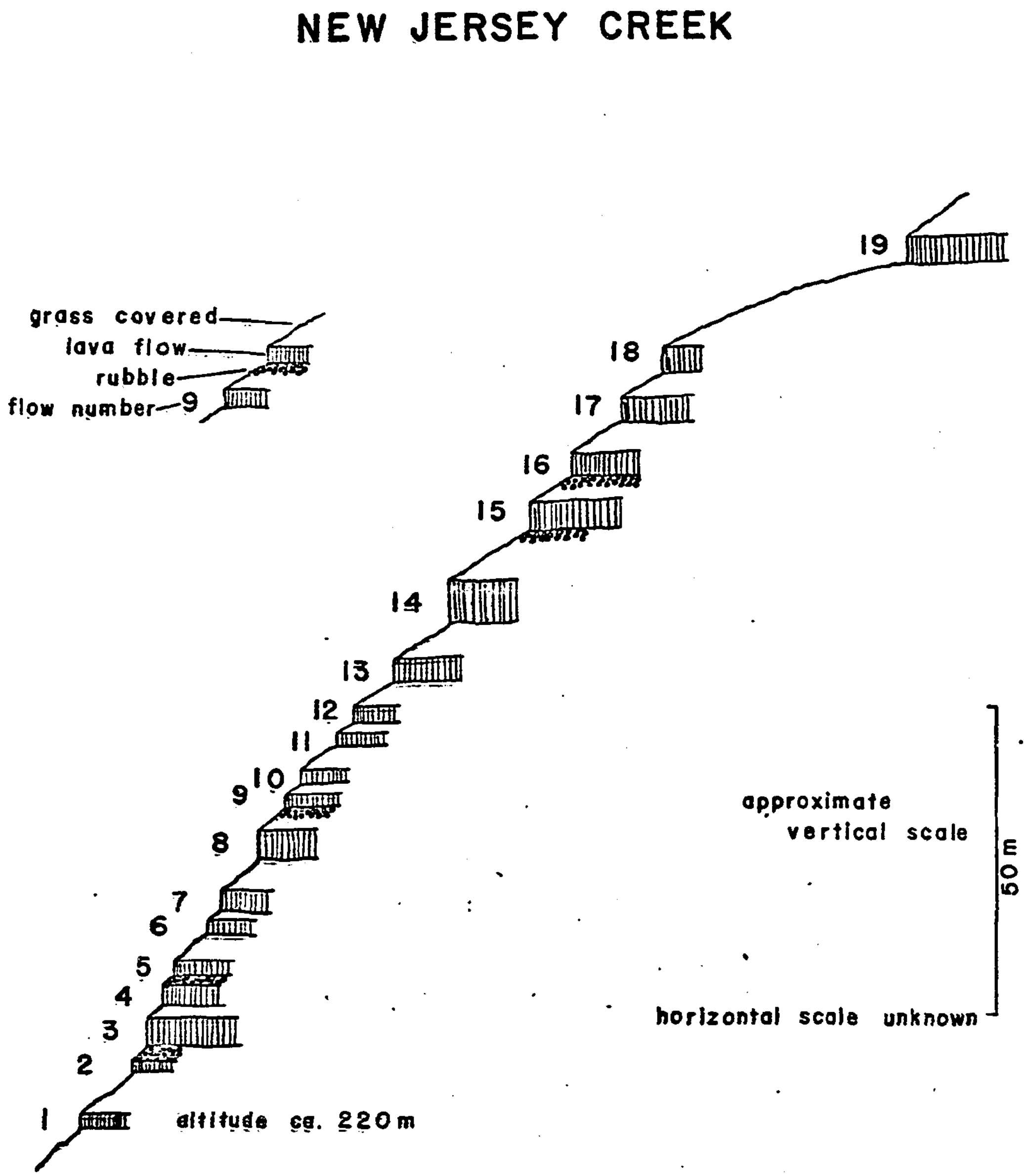


Figure 4-4. Rough geologic section for New Jersey Creek (NJC) site. Drawn from photographs, spot barometric readings and casual field observations.

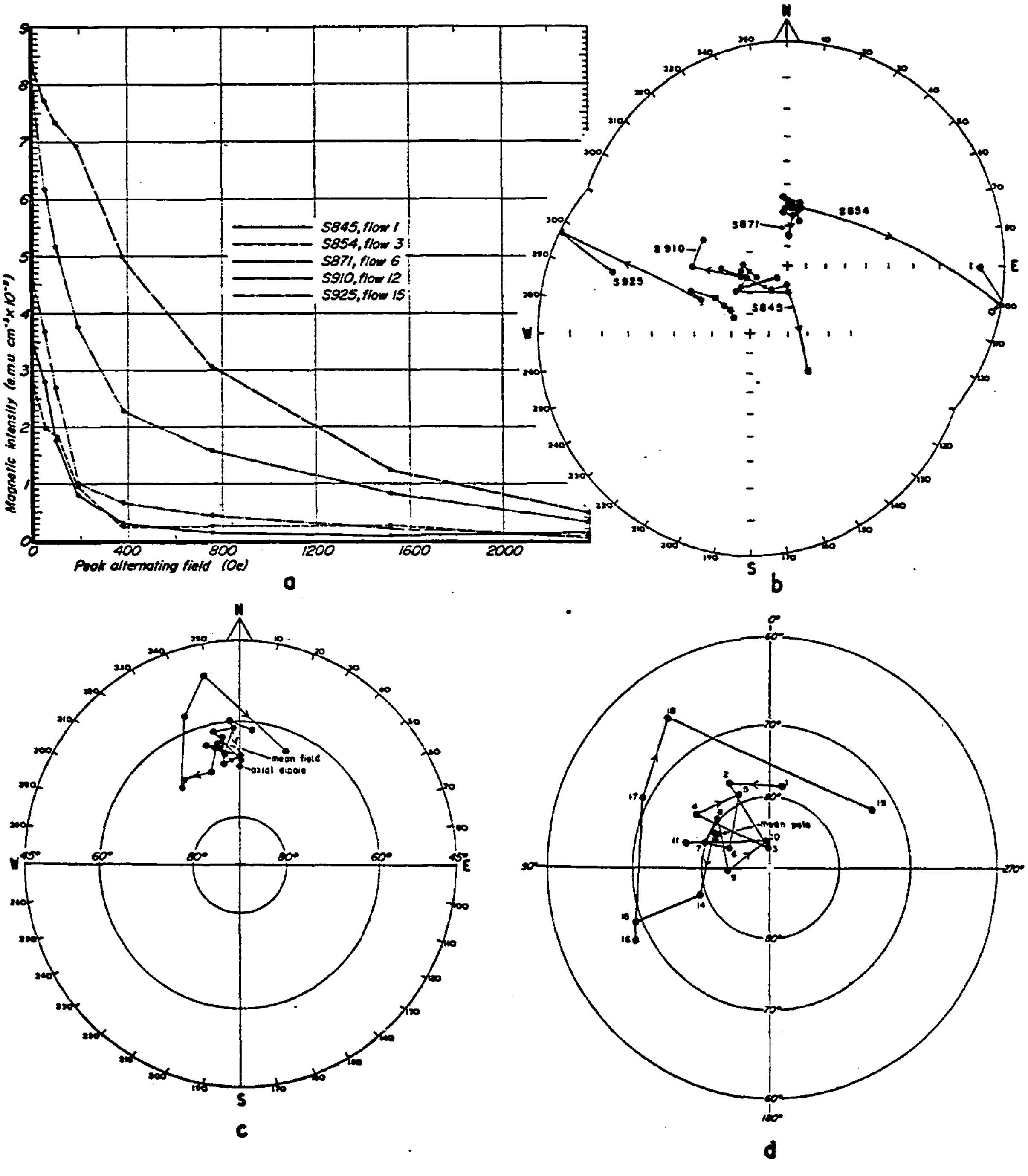


Figure 4-5. Paleomagnetic data for New Jersey Creek, Umnak Island (NJC). (a) Magnetic intensity and (b) vector directions of pilot samples during A.F. demagnetization. (c) Flow mean magnetic vector directions and (d) VGP's. Note expanded stereonets. Mean data from Table 5-4; cf. explanation to Fig. 4-2 for further details.

TABLE 4-5

Flow mean statistical data for NJC series. Flows listed in stratigraphic sequence (youngest first). Cores A.F. demagnetized at 475 oe. Site mean data are also given (cf. Table 4-1 for explanation of symbols).

Flow No.	N	k	δ	α_{95}	$\bar{D}$	$\bar{I}$	λ	ϕ	$\bar{J}_{NRM}$
19	5	586.8	3.0	3.2	23.5	64.4	73.3	298.5	5229
18	6	274.6	4.5	4.1	348.9	50.4	66.2	36.1	3006
17	6	201.0	5.2	4.7	339.2	57.5	69.0	63.2	3994
16	6	371.1	3.8	3.5	322.2	69.8	67.8	117.6	3433
15	7	134.8	6.5	5.2	325.5	68.6	69.2	111.4	4608
14	6	124.0	6.6	6.0	342.0	69.8	79.3	110.0	2807
13	6	48.6	10.6	9.7	349.0	64.8	80.6	59.8	2307
12	6	120.4	6.8	6.1	349.4	65.6	81.2	65.6	4306
11	6	251.8	4.7	4.2	343.6	64.5	77.3	74.2	8180
10	6	60.9	9.5	8.7	0.5	67.3	86.5	7.1	6314
9	6	667.6	2.9	2.6	350.2	68.8	83.9	92.5	7981
8	4	436.2	3.4	4.4	351.6	63.5	79.9	48.1	4163
7	5	174.1	5.5	5.8	347.0	65.3	79.7	70.3	6113
6	5	302.9	4.2	4.4	351.8	65.7	83.4	65.7	5405
5	5	150.8	5.9	6.3	357.0	61.4	78.8	23.4	6905
4	6	699.6	2.8	2.5	347.7	62.0	77.0	55.4	4602
3	5	52.5	10.0	10.7	0.5	68.0	87.5	4.5	2071
2	5	106.9	7.0	7.4	355.8	59.8	76.8	25.9	3293
1	6	38.1	12.0	11.0	5.5	61.5	78.5	351.1	2361
NJC_{fld}	19	122.0	7.1	3.1	350.5	64.7	80.8	57.2	
NJC_{vgp}	19	57.9	10.4	4.4			81.1	59.0	

TABLE 4-6

Analysis of variance table for NJC series (cf. explanation to Table 4-2).

Source	DF	SS	MS
Between flows	36	0.85672	0.02380
Within flows	176	0.72356	0.00411

$F = 5.79 > F_{5\%,\ 36,\ 176} \simeq 1.5$; therefore k_β significant

$k_\omega = 121.65$

$k_\beta = 142.89$

the NJC flows were extruded.

Using the same arguments as for the RDH section, following Doell (1969), we may deduce that the 19 NJC flows probably represent a minimum time of about 15,000 years. We are basing this on the same figures as before except we note that the NJC section is 10 times further from the presumed summit than the Kau series of Mauna Loa sampled by Doell (10 km vs. 1 km) so the geometric factor works in favor of a longer time interval. This of course assumes summit eruptions to be the prime contributions to the volcanic pile; there are, however, no other obvious eruptive centers nearby. There have been seven known eruptions in historic time, most of which extruded lava within the caldera (Byers et al., 1947; Chatterjee, 1971); these were in 1817, 1824, 1899, 1931, 1938 and 1945 and the other sometime since 1948 when Byers finished the geological field work for his final report (1959) - this latter is evidenced by a new flow within the caldera which does not show on Byers' map (this flow clearly originated at 'Cone A' where the 1945 eruption had taken place).

As for RDH, it seems safe to assume 5 to 10 summit eruptions per century as an eruptive rate. Again we stress that it is perhaps dangerous to extrapolate from a Hawaiian to an Aleutian volcano. Nevertheless it is unlikely that the 15,000 year figure is much too large as we have tended in our calculation to weight the figures toward shorter times. Thus we may take $k_\beta = 121.7$ as being a fairly reliable measure of SV at the NJC site during at least 10,000 years of late Tertiary times.

Ashishik Basalt, Umnak Island (ASH). Like the NJC section the sequence of lava flows here called the Ashishik Basalt (ASH) section is part of the pre-caldera rocks of Okmok Volcano. Both sections are part of what Byers (1959) calls Ashishik Basalt. The ASH section is made up of aphyric and feldspathic basalt flows 10 to 70 feet thick (Byers, 1959). Well weathered layers between flows made differentating one from another in the field easily possible.

A K-Ar age determination from the topmost flow yielded a date of 1.9 ± 0.4 m.y. The ASH flows probably post-date the NJC flows, although some interbedding does occur (Byers, 1959).

Fourteen flows were sampled in July 1968 from a northeast facing exposure 1 1/2 miles southwest of Ashishik Point and about 2 miles north-northwest of the NJC section and located at approximately 53°32'N., 191°54'E. The flows are numbered 8 through 21 with 21 being the top flow. Five cores were taken from each flow, but one core was later discarded as being erroneously oriented.

As with the KAN and RDH series, three 1 cm discs were cut from each core. Stability tests indicated that 380 oe A.F. demagnetization produced the most satisfactory results (Figure 4-6a, b); therefore the middle disc from each core was demagnetized in this field before measurement.

The bottom 13 of the 14 ASH flows were found to be reversely magnetized with fairly tight within flow scatter (all but one $\alpha_{95} < 10°$), while the topmost flow (flow 21) is weakly normally magnetized and displays very large scatter ($\alpha_{95} = 84.5°$); this flow is ignored in the site mean statistical analysis. Complete data are given in Table 4-7 and Figure 4-6 c and d. The two tier analysis (Table 4-8) indicates that

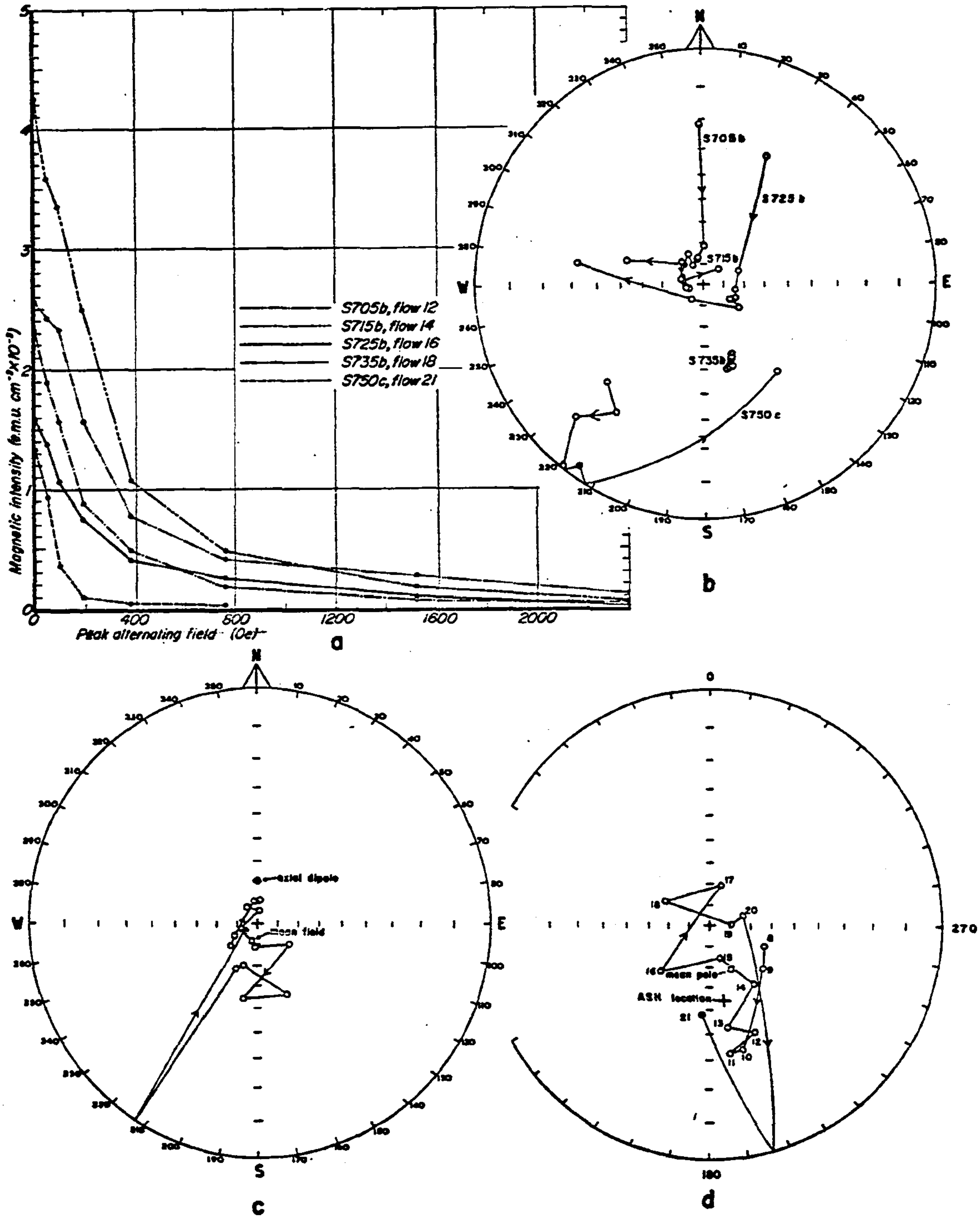


Figure 4-6. Paleomagnetic data for Ashishik Basalt, Umnak Island (ASH). (a) Magnetic intensity and (b) vector directions of pilot samples during A.F. demagnetization. (c) Flow mean magnetic vector directions and (d) VGP's. Mean data from Table 4-7; cf. explanation to Fig. 4-2 for further details.

TABLE 4-7

Flow mean statistical data for ASH series. Flows listed in stratigraphic sequence (youngest first). Cores A.F. demagnetized at 380 oe. Site mean data are also given; flow 21 not included in site mean (cf. Table 4-1 for explanation of symbols).

Flow No.	N	k	δ	α_{95}	$\bar{D}$	$\bar{I}$	λ	ϕ	$\bar{J}_{NRM}$
21	5	1.8	56.5	84.5	247.0	83.8	47.5	175.2	2341
20	5	925.4	2.4	2.5	207.0	-66.5	-72.6	106.1	8477
19	5	465.5	3.4	3.6	199.6	-69.8	-78.4	93.2	7176
18	5	251.1	4.6	4.8	156.8	-54.4	-65.2	242.4	2964
17	5	177.6	5.4	5.8	191.5	-54.4	-69.7	163.7	5898
16	5	323.6	4.0	4.3	121.4	-72.3	-57.6	312.9	2452
15	5	103.8	7.1	7.5	185.3	-79.8	-73.1	18.1	4238
14	5	456.2	3.4	3.6	255.9	-82.2	-54.5	38.1	6584
13	4	76.0	8.1	10.6	5.6	-83.8	-41.3	10.3	7246
12	5	408.8	3.6	3.8	330.7	-80.1	-36.1	23.4	3761
11	5	192.1	5.2	5.5	4.7	-78.3	-31.1	9.8	9378
10	5	263.2	4.5	4.7	351.6	-78.7	-31.9	15.6	14089
9	5	531.4	3.1	3.3	245.6	-78.0	-56.7	52.5	8286
8	5	64.7	9.0	9.6	233.3	-73.6	-60.8	68.6	3071
ASH_{fld}	13	20.8	17.1	9.3	198.1	-81.5	-68.9	26.2	
ASH_{vgp}	13	7.3	29.1	16.4			-66.2	25.7	

TABLE 4-8

Analysis of variance table for ASH series omitting flow 21 (cf. explanation to Table 4-2).

Source	DF	SS	MS
Between flows	24	2.8369	0.11832
Within flows	102	0.2670	0.00262

$F = 45.16 > F_{5\%, 24, 102} \simeq 1.63$; therefore k_β significant

$k_\omega = 190.84$

$k_\beta = 21.27$

the between flow scatter has considerable relevance and is not caused by within flow scatter. The flow mean field directions (Figure 4-6c) are fairly widely scattered in a quasi oval distribution which could hardly be described as Fisherian. The site mean lies almost 30° away from the axial dipole field direction. k and δ both indicate a large scatter about this direction (Table 4-7). The VGP's for ASH (Figure 4-6d) are even more widely distributed than the field directions and the site mean pole position is more than 20° removed from the geographic pole. Several individual flows give VGP's up to 50 or more degrees away from the geographic pole; these are located in the North Pacific. This latter observation may be related to a large geomagnetic field excursion.

The listed K-Ar date is the mean of two whole rock dates supplied by Mobil Research and Development Corporation; these are 1.7 ± 0.2 and 2.1 ± 0.2 m.y. Petrographically the rock seems to be well suited for dating (D. Turner, personal communication, 1971) but no laboratory data is available for assessing the analysis. Assuming there is no reason to doubt these dates it would appear that flow 21 was extruded during either the Gilsá (McDougall and Wensink, 1966) or the Olduvai Normal Events (Doell et al., 1966) of the Matuyama Reversed Epoch which occurred approximately 1.6 and 1.9 m.y. ago respectively (Cox and Dalrymple, 1967); however, Grommé and Hay (1971) report these may be the same event and postulate instead a double event, the Réunion Normal Event, spanning the times 2.16-2.11 and 1.98-1.95 m.y. ago. It is not possible, given the uncertainties of the ASH data, to determine which event we have in fact sampled.

Crater Creek, Umnak Island (CCR). A sequence of 15 lava flows were sampled in July 1968 on the northwest side of Crater Creek gorge where it cuts through the wall of Okmok Caldera. The sampling site is about one half mile outside the line of the Caldera rim and a few hundred yards north of Crater Creek Falls or at about 53°23'N., 191°55'E.. The Crater Creek basalt defined by Byers et al., (1947) is the youngest pre-caldera unit of Okmok Volcano and Byers (1959) lists these basalts as being Pleistocene to Recent in age. Two whole rock K-Ar age determinations on rocks from one of the upper flows (flow no. 10) yielded ages of 0.0 ± 0.15 m.y. so we can not improve on Byers' estimate.

The flows are numbered 1 through 15 from the bottom up. Byers (1959) also found 15 flows at this location and had two of them chemically analyzed. Byers' numbering scheme is the same as that used here and his numbers probably coincide with ours. Between 5 and 11 cores per flow were taken.

Chatterjee (1971) conducted rather extensive mineralogical and magnetic studies on the same samples used here in an attempt to understand the rather unusual paleomagnetic results. The flows range from tholeiites to olivine tholeiites and the opaques, which are probably solely responsible for the NRM, are fine grained and restricted to the groundmass (Chatterjee, 1971).

The usual stability tests were carried out by stepwise A.F. demagnetizing a few pilot samples and then choosing from the resulting series of measurements that peak field which seemed to remove the most soft components while at the same time preserving the original hard components (Figure 4-7a, b). A 760 oe A.F. demagnetization was finally

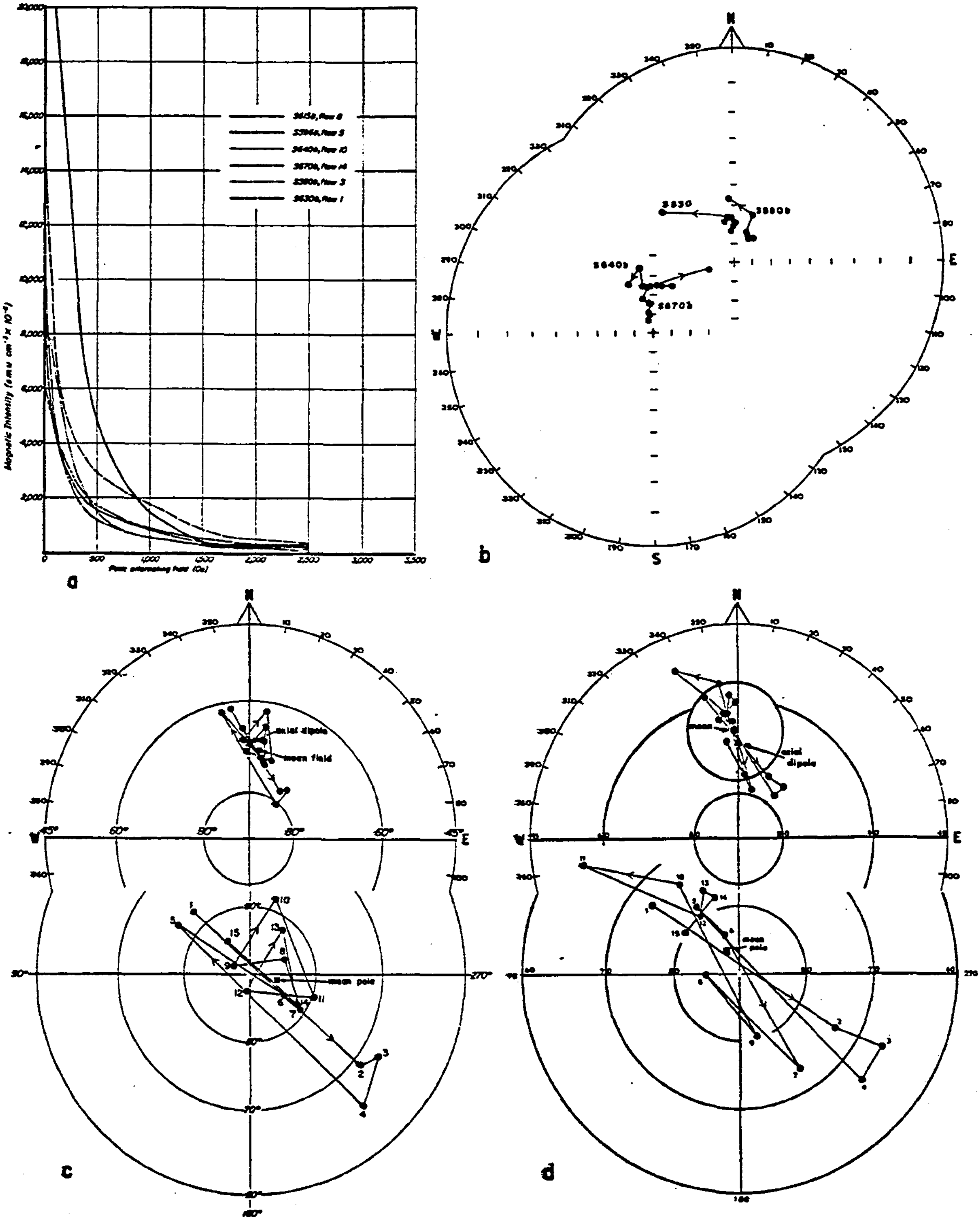


Figure 4-7. Paleomagnetic data for Crater Creek, Umnak Island (CCR). (a) Magnetic intensity (Chatterjee, 1971) and (b) vector directions of pilot samples during A.F. demagnetization. (c) Flow mean magnetic vector directions (upper) and VGP's (lower) using NRM data. (d) Flow mean magnetic vector directions (upper) and VGP's (lower) for 760 oe. A.F. demagnetization. Circle of radius δ drawn about site mean vector direction. Note expanded stereonets. Mean data from Table 4-9; cf. explanation to Fig. 4-2 for further details.

chosen as the optimum field and the middle disc from all cores was demagnetized at this field before measurement. However, on comparison of the demagnetized results with the NRM results it was found that in a number of flows the demagnetization actually increased the within flow scatter of field vectors. For this reason we have carried out full statistical calculations on both the NRM and A.F. demanetized results (Tables 4-9 and 4-10).

Chatterjee (1971) concluded on the basis of his mineralogical studies including both thermal demagnetization results (Figures 4-8 and 4-9) and x-ray diffraction analysis that most of the flows had a relatively stable but more or less random chemical remanent magnetization (CRM) component residing in very fine grains of hematite and/or maghemite in the ground mass which was not easily removed by standard A.F. demagnetization techniques. This is particularly true of flows 10 through 14 (Table 4-9). A slight correlation between small scatter and high values of the Königsberger ratio (Königsberger, 1938) is observed but this does not appear to be significant (Table 4-11).

The distribution of the flow mean directions and VGP's of the CCR section is unusual. All flows are normally magnetized and their VGP's display a clearly elongate, almost linear, distribution centered within 3° of the geographic pole and oriented roughly along the 45° and 225° E. Longitude meridians (Figure 4-7c, d). The elongate quality of the distribution is somewhat less pronounced for the NRM than it is for the A.F. demagnetized data. This distribution is difficult to explain. Chatterjee (1971), on the basis of susceptibility anisotropy measurements, concludes that susceptibility anisotropy in a preferred

TABLE 4-9

Flow mean statistical data for CCR series. Flows listed in stratigraphic order (youngest first). Subscripts $_n$ and $_a$ indicate NRM values and values calculated from 760 oe A.F. demagnetized data. Site mean data are also given (cf. Table 4-1 for explanation of symbols).

Flow No.	N_n	N_a	k_n	k_a	δ_n	δ_a	α_{95n}	α_{95a}	$\bar{D}_n$	$\bar{I}_n$	$\bar{D}_a$	$\bar{I}_a$	λ_n	ϕ_n	λ_a	ϕ_a
15	7	7	186.6	452.2	5.5	3.5	4.4	2.8	356.8	65.9	350.4	64.0	84.3	34.1	80.1	54.3
14	6	6	44.5	13.0	11.1	20.6	10.2	19.3	11.6	73.0	358.1	60.7	81.8	238.8	78.1	18.7
13	8	8	52.3	18.9	10.5	17.5	7.7	13.1	9.2	65.6	356.2	59.5	81.9	322.3	76.6	24.6
12	5	6	22.6	7.8	15.3	26.7	16.5	25.6	358.4	71.0	354.6	63.4	87.8	167.8	80.8	36.7
11	8	8	24.3	10.8	15.4	23.2	11.5	17.6	16.4	72.5	339.4	51.9	79.8	250.1	64.4	55.3
10	11	11	53.5	29.3	10.6	14.3	6.3	8.6	8.4	62.2	352.1	57.5	78.6	339.8	73.7	34.6
9	7	7	12.9	106.1	21.0	7.3	17.5	5.9	356.8	68.6	1.6	75.8	87.5	64.1	80.3	196.1
8	6	6	182.8	170.0	5.5	5.7	5.0	5.2	8.7	68.7	353.4	69.0	84.6	293.3	85.9	90.9
7	6	6	223.6	31.8	5.0	13.2	4.5	12.1	12.3	73.5	16.4	79.0	81.0	236.1	73.0	212.4
6	8	8	85.5	48.8	8.2	10.9	6.0	8.0	7.9	72.1	358.2	65.4	84.2	239.7	84.0	23.3
5	5	5	145.8	42.1	6.0	11.2	6.4	11.9	347.6	62.3	354.4	61.5	77.2	56.7	78.6	33.1
4	7	7	120.4	200.5	6.8	5.3	5.5	4.3	38.6	80.2	40.2	78.5	65.7	221.7	66.3	229.2
3	9	9	270.7	256.4	4.6	4.8	3.1	3.2	38.6	76.3	42.2	75.1	67.9	238.4	66.2	243.9
2	9	9	287.0	61.6	4.5	9.7	3.0	6.6	34.0	77.5	26.5	75.0	69.2	231.7	73.7	240.5
1	8	8	84.4	186.8	8.3	5.6	6.1	4.1	351.6	61.6	346.2	59.2	77.9	42.8	73.6	52.2
CCR_{fld}	15	15	115.7	58.2	7.3	10.3	3.6	5.1	6.9	70.6	358.0	67.1	85.8	259.9	86.2	31.7
CCR_{vgp}	15	15	45.6	26.0	11.6	15.4	5.7	7.6					85.2	254.8	87.6	33.4

TABLE 4-10

Analysis of variance table for CCR series. Subscripts $_n$ and $_a$ refer to values calculated on the basis of NRM data and on measurements made after 760 oe A.F. demagnetization (cf. explanation to Table 4-2).

Source	DF_n	DF_a	SS_n	SS_a	MS_n	MS_a
Between flows	28	28	0.9231	1.8387	0.03297	0.06567
Within flows	190	192	1.746	3.104	0.00919	0.01617

$$\left.\begin{array}{l} F_n = 3.59 > F_{5\%,\ 28,\ 190} \approx 1.70 \\ F_a = 4.06 > F_{5\%,\ 28,\ 192} \approx 1.70 \end{array}\right\} \text{therefore } k_\beta \text{ significant in both cases.}$$

$k_{\omega_n} = 54.41 \qquad k_{\beta_n} = 153.68$

$k_{\omega_a} = 30.92 \qquad k_{\beta_a} = 74.53$

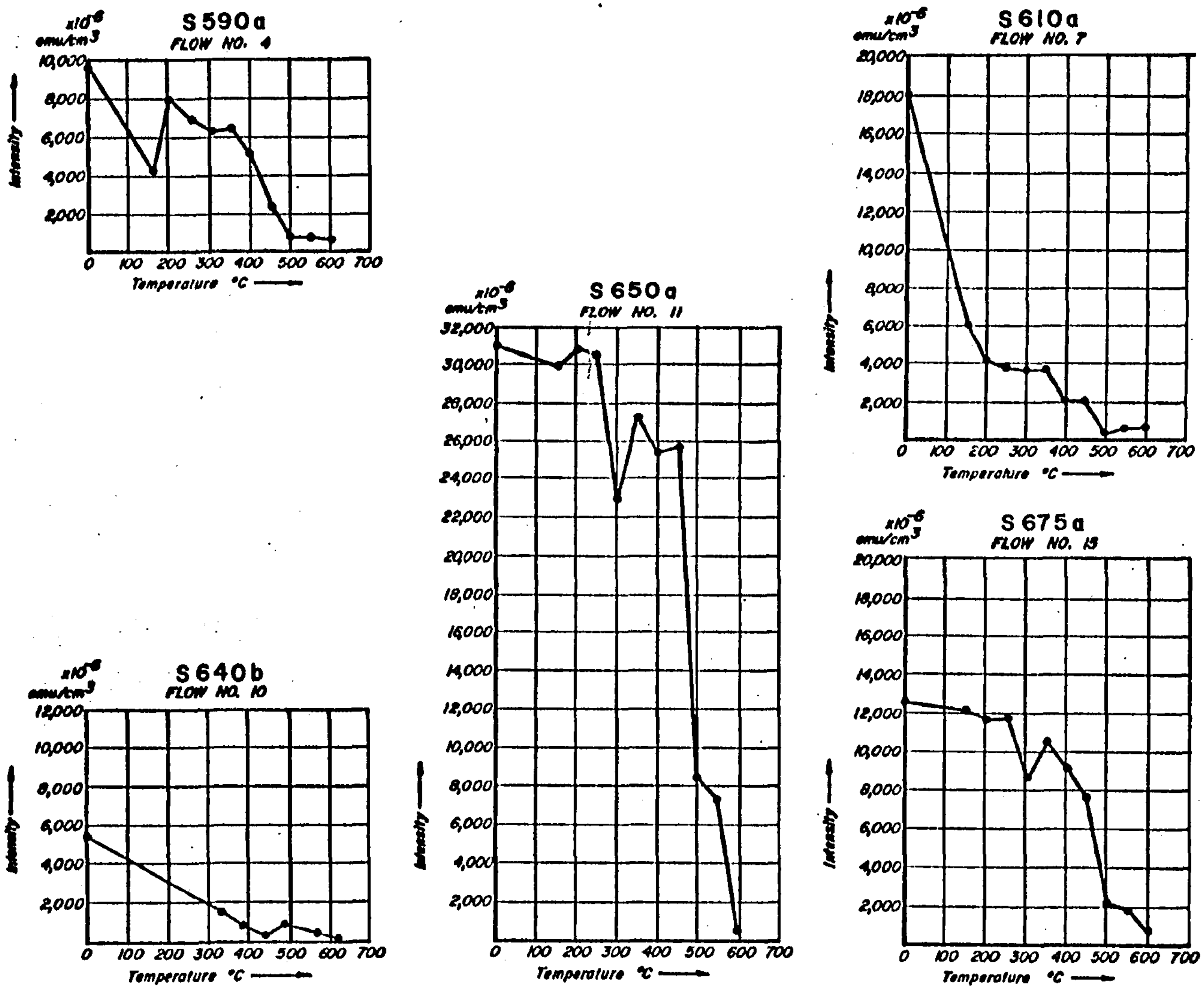


Figure 4-8. Intensity vs. temperature during thermal demagnetization of selected samples from CCR section (from Chatterjee, 1971).

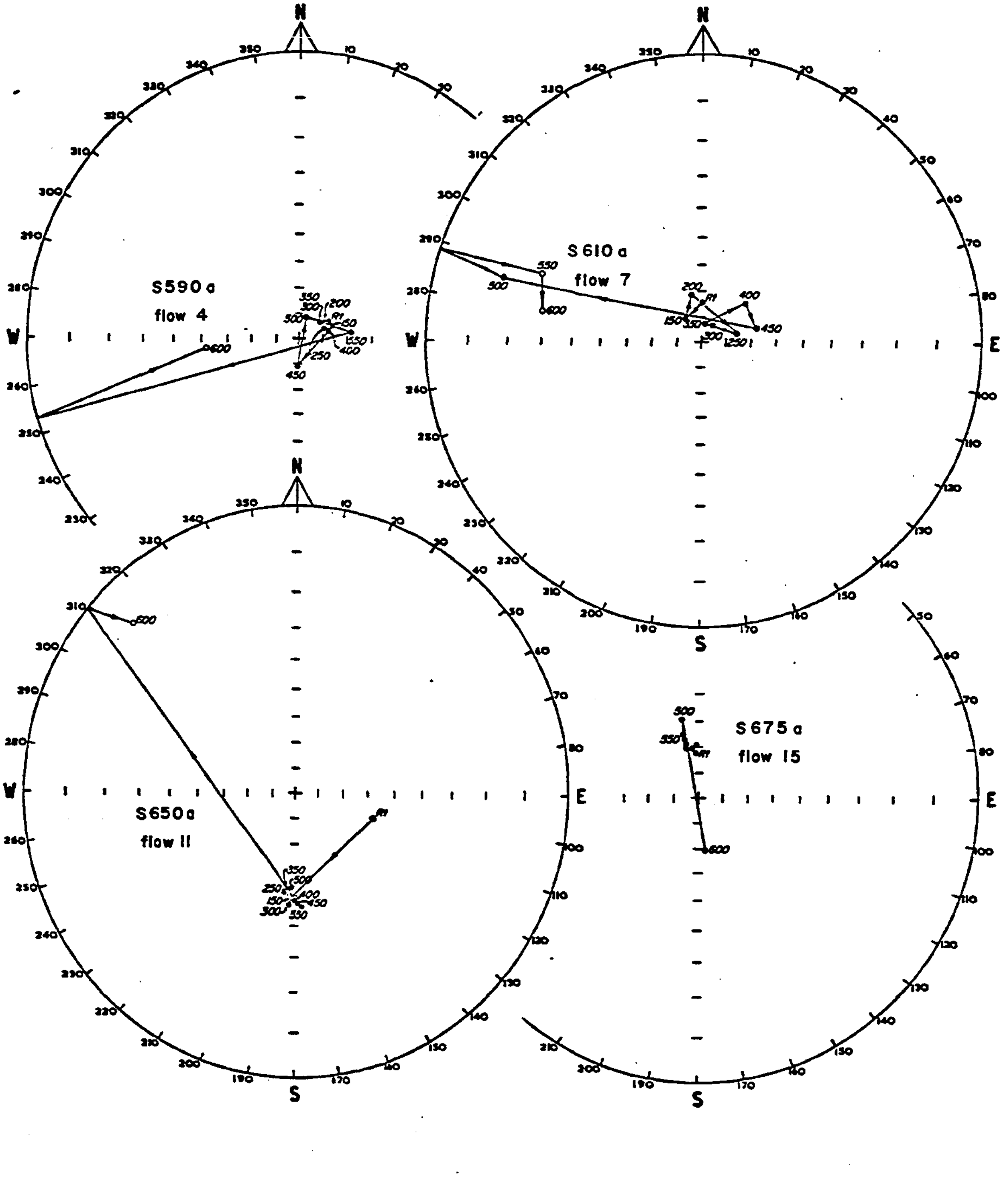


Figure 4-9. Behavior of magnetic vectors from selected CCR samples (from Chatterjee, 1971). Numerals beside data points indicate temperature in °C. Rt = room temperature. Plot for sample no. S650 a was made before correction of an orientation error. cf. explanation to Fig. 4-2 for further details.

TABLE 4-11

Susceptability χ, mean intensity $\bar{J}$, and Königsberger ratios, $Q_n = \frac{\bar{J}nrm}{\chi}$ of the 15 flows of Crater Creek Basalts (from Chatterjee, 1971).

Flow No.	N	χ(e.m.u. cm^{-3})	$\bar{J}$nrm(e.m.u. cm^{-3})	Q_n
15	7	14691×10^{-6}	13200.0×10^{-6}	0.90
14	6	17916×10^{-6}	8420.0×10^{-6}	0.47
13	8	18093×10^{-6}	10040.0×10^{-6}	0.55
12	6	21550×10^{-6}	10520.0×10^{-6}	0.49
11	8	20718×10^{-6}	12430.0×10^{-6}	0.60
10	11	18227×10^{-6}	11920.0×10^{-6}	0.65
9	7	17625×10^{-6}	12540.0×10^{-6}	0.71
8	5	9200×10^{-6}	20840.0×10^{-6}	2.27
7	6	10625×10^{-6}	15390.0×10^{-6}	1.45
6	8	10625×10^{-6}	11200.0×10^{-6}	1.05
5	5	14500×10^{-6}	13800.0×10^{-6}	0.95
4	7	17645×10^{-6}	10680.0×10^{-6}	0.61
3	9	8333×10^{-6}	11830.0×10^{-6}	1.42
2	9	13138×10^{-6}	9050.0×10^{-6}	0.68
1	8	14468×10^{-6}	8929.8×10^{-6}	0.62

direction is not a possible cause for the distribution. Tectonic mechanisms also seem unlikely. One might expect such a distribution in directions on the flank of a large volcano which was continually being inflated and deflated by the intrusion and ultimate extrusion of magma which would cause a given area to tilt back and forth about the same axis (Eaton, 1962). However, the amount of tilt required is rather excessive (the greatest such tilt observed is some two orders of magnitude less than indicated by the paleomagnetic results) and would be in the wrong direction if we assume the volcano to be inflated symmetrically. Large scale tectonic causes are also ruled out because of their necessary magnitude and lack of any other evidence for such movements. The α_{95} circles of confidence are admittedly rather large (four are > 10° for the NRM data and six are > 10° for the demagnetized data) and some of the elongate distribution may be due to chance but it seems unliekly that a large part of it is not due to true field changes during the time of extrusion of the lava flows. This conclusion is supported by the analysis of variance of both the NRM and treated data (Table 4-10). Nun and Helsey (1971) report a somewhat similar distribution of VGP's from Tertiary lava flows in Israel; in this case reversed and normal VGP's are included and they line up roughly along the 135° and 315° meridians. Hope (1957) suggests that during very recent times (last several thousand years) SV may in fact be in large part due to just such an oscillation of the north geomagnetic pole along a roughly 90-270° E. axis centered close to the geographic pole. Such a pattern may have occasionally prevailed along different meridians at earlier times.

With such an elongate distribution the usual Fisher (1953) statistics (Chapter III) are of questionable value. Nonetheless, for comparison sake, we have calculated all the statistical parameters for both cases. Because of their lower within flow scatter, the NRM values seem to hold the greatest promise of being reliable indicators of true paleo field variations and these values will be used in analysis hereafter.

Using the same extrapolation from Hawaii (Doell, 1969) as used above we find that the CCR section might represent about 4000 years as a minimum value. This is borne out by the evidence of some weathering between flows indicating not too rapid deposition.

Thus we must conclude that the NRM value of $k_\beta = 153.7$ is a relatively poor value for SV for this site.

Driftwood Bay, Unalaska Island (DFB). The geology of Unalaska Island is outlined by Drewes et al. (1961). They delineate the Makushin Volcanics as being the thick pile of little deformed volcanic rocks associated with present day Makushin Volcano on the northwest part of the island. The formation consists primarily of basalt and andesite flows 10 to 50 feet thick and probably dates from middle to late Pleistocene (Drewes et al., 1961).

In August 1969 a series of 21 lava flows was sampled from a 1000 foot high sea cliff 200 yards west of and below the Driftwood Bay White Alice and DEW Line station on the northwest shore of Unalaska Island. This section, here called the Driftwood Bay (DFB) section, is part of the Makushin Volcanics formation of Drewes et al. (1961) and appears younger than most of the formation as evidenced by youthful erosion features; it probably dates from late Pleistocene or even early Holocene. It lies approximately 12 km almost due north of Makushin Volcano and 4 km west of Driftwood Bay (the section itself runs between military grid points UK824747 and UK927745 or lies at about 53°58'N., 193°06'E.). The flows are numbered 1 through 21 from the top downwards, the bottom flow being the thick columnar jointed flow right at sea level (Figure 4-10). Six cores per flow were taken except for one from which 7 were taken.

The flows all appear to be quite recent and the rock fresh and unweathered. The flows range from 7 to 50 feet in thickness and there is considerable thickness of grass covered rubble between most of them; these layers vary from a few feet to over 100 feet in thickness. Above flow-21, the bottom flow, a considerable layer of loosely compacted, probably subaerial volcanic sediments is exposed (Figure 4-10).

One 2.1 cm long cylinder was cut from each core and a few pilot specimens were measured after A.F. demagnetization in successively higher fields. Because of the very stable directions that seemed to prevail under even fairly high A.F. demagnetization (Figure 4-11a, b) and the quite tight within flow grouping of the NRM values, it was decided to dispense with any 'blanket' A.F. demagnetizing treatment and use the NRM data for anlysis. The additional scatter generated by soft components not removed is thought to be negligible.

The DFB flows were all found to be normally magnetized. The scatter within flows is quite small; only three flows have δ's larger than 5° (Table 4-12). The two tier analysis (Table 4-13) shows that the between flow scatter is quite significant relative to the within

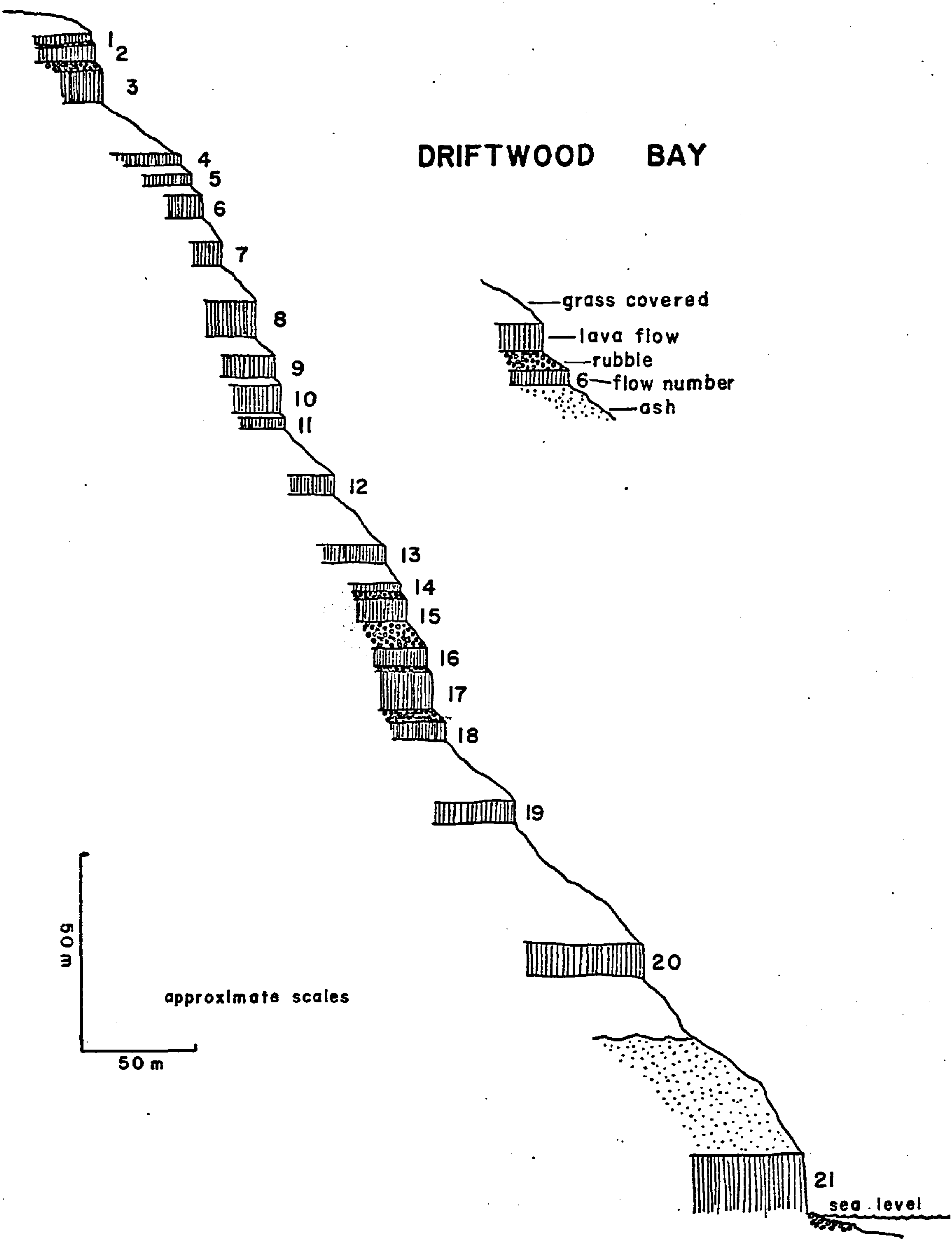


Figure 4-10. Rough geologic section for Driftwood Bay (DFB) site. Drawn approximately to scale from photographs, spot barometric altitude readings, and casual field observations.

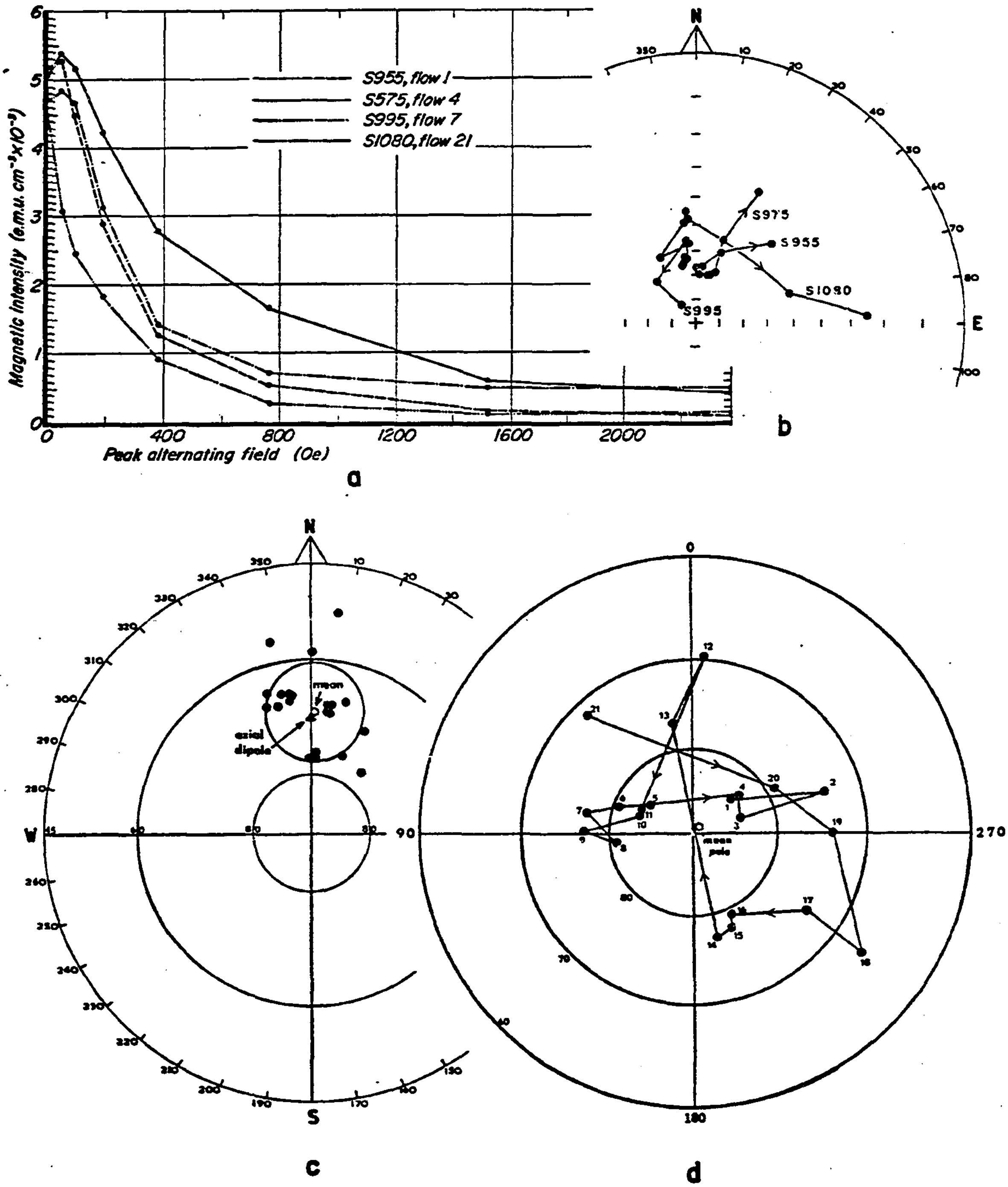


Figure 4-11. Paleomagnetic data for Driftwood Bay, Unalaska Island (DFB). (a) Magnetic intensity and (b) vector directions of pilot samples during A.F. demagnetization. (c) Flow mean magnetic vectors. Circle of radius δ is drawn about site mean. (d) Corresponding flow mean VGP's. Note expanded stereonets. Mean data from Table 4-12; cf. explanation to Fig. 4-2 for further details.

TABLE 4-12

Flow mean statistical data for DFB series. Flows listed in stratigraphic sequence (youngest first). Statistics based on NRM data. Site mean data are also given (cf. Table 4-1 for explanation of symbols).

Flow No.	N	k	δ	α_{95}	$\bar{D}$	$\bar{I}$	λ	ϕ	$\bar{J}_{nrm}$
1	6	176.3	5.6	5.1	7.5	67.9	84.5	314.4	5447
2	6	89.1	7.8	7.1	8.4	69.6	85.0	286.8	3705
3	6	223.3	5.0	4.5	9.6	69.3	84.2	290.2	4245
4	6	1192.6	2.1	1.9	9.0	68.0	83.8	307.0	2741
5	6	417.7	3.6	3.3	353.3	66.8	83.9	58.3	3959
6	6	235.9	4.8	4.4	348.5	66.1	81.0	70.6	4740
7	6	322.8	4.1	3.7	342.9	65.4	77.4	78.9	10182
8	6	617.0	3.0	2.7	345.0	68.6	80.8	96.0	7601
9	6	432.9	3.6	3.2	340.9	67.1	77.5	91.2	4430
10	6	284.2	4.4	4.0	351.3	67.4	83.5	71.7	2427
11	6	845.5	2.5	2.3	351.0	67.0	82.9	68.6	4423
12	6	224.9	4.9	4.5	6.9	53.9	69.8	356.3	4520
13	6	895.9	2.5	2.2	0.9	60.0	76.9	10.2	5969
14	6	290.3	4.3	3.9	359.6	77.8	77.4	192.3	11060
15	6	863.9	2.5	2.3	4.8	77.4	77.8	202.4	6312
16	7	286.6	4.4	3.6	4.9	76.8	78.8	203.9	3345
17	6	234.7	4.8	4.4	23.8	76.5	74.1	232.7	3424
18	6	55.1	10.0	9.1	41.3	77.9	66.5	233.9	15054
19	6	441.1	3.5	3.2	28.1	70.4	73.7	269.8	11492
20	6	462.3	3.4	3.1	15.8	67.1	79.5	299.6	5673
21	6	373.6	3.8	3.5	347.2	57.2	71.6	46.9	2213
DFB_{fld}	21	94.8	8.1	3.3	0.9	69.1	88.5	351.1	
DFB_{vgp}	21	40.7	12.4	5.0			89.0	322.5	

TABLE 4-13

Analysis of variance table for DFB series (cf. explanation to Table 4-2).

Source	DF	SS	MS
Between flows	40	1.2732	0.03183
Within flows	212	0.4210	0.00199

$F = 15.995 > F_{5\%,40,212} = 1.44$; therefore k_β significant

$k_\omega = 251.26$

$k_\beta = 101.33$

flow scatter thus giving the calculated values of k_ω and k_β good validity. The flow mean field directions have a slightly elongate distribution centered within a degree of the axial dipole field direction (Figure 4-11c). The VGP distribution is slightly less elongate and centered almost on the geographic pole (Figure 4-11d). The flow mean distribution of field directions is fairly tight with k = 94.8. There is a certain degree of serial correlation between flow mean directions possibly indicating short time intervals between successive flows. This hypothesis is strengthened by comparing the plot of successive VGP's (Figure 4-11d) with the geologic section (Figure 4-10) and noting that flows which are closely spaced in altitude tend to have closely spaced VGP's while wide physical separation tends to produce widely spaced VGP's (see especially flows 14 through 18 vs. flows 11 through 13 and 19 through 21).

Taking all the same geometric and eruptive rate data as for NJC we once again extrapolate from Doell's (1969) Hawaiian calculations and deduce that the DFB section may represent about 16,000 years. We note at the same time that there have been no lava eruptions of Makushin Volcano observed in historic time in spite of the fact that there has been a Russian or American settlement near Unalaska Village in plain view of the summit of the volcano since the late 18th century (Drews et al., 1961); this fact could lower the effective eruptive rate. Also the DFB section is slightly further from the presumed center of eruption than the NJC Section. Both these factors serve to make our time span estimate too low. Balancing these considerations is the observed serial correlation tending to make our calculated value too high.

Recognizing the inherent dangers of such an extrapolation from Doell's calculation, it nonetheless seems to be reasonable to assume that the DFB section represents at least 10,000 years and take $k_\beta = 101.33$ as being probably a fairly reliable indicator of SV at this location during the late Pleistocene.

Aleutian mean secular variation. Of the six Aleutian Island sites discussed above only two sites appear to be such as to give reliable readings for secular variation; these are the New Jersey Creek (NJC) and Driftwood Bay (DFB) sites. All the other SV determinations are of dubious value because of grossly non-Fisherian distribution or short time spans being represented. In order to obtain a more representative indication of late Tertiary-Quaternary SV we have combined the data from all the flows in the six Aleutian Island sites.

If we are to use primarily field direction statistics for the combined data as previously, rather than VGP statistics, it becomes necessary to make the assumption that the differences in field directions at different sites corresponding to the same VGP's are small compared with SV effects on field directions. This seems to be a reasonable assumption if the sites are situated at a not too high paleo latitude and are spread out along the same paleo latitude. This is effectively the situation with the KAN, RDH, NJC, ASH, CCR, and DFB sites where the spread in latitude is only 2.1° and the longitudinal spread is 10.2°. Besides those flows already omitted from the analysis, all the flows except for a few at the ASH site have VGP's near enough to the present geographic pole so that their corresponding paleo latitudes differ by approximately the same amounts as their present latitudes. The few

ASH flows having low latitude VGP's are fully compatable with the above assumption since this happens at only <u>one</u> site; effectively we can consider all the other data 'transferred' to the ASH site.

One additional site has been included in the Aleutian Island statistics. In June 1968 one lava flow was sampled on Atka Island. There are no published geological reports on Atka and the only topographic map besides coastal charts published by the U.S. Coast and Geodetic Survey is a rough sketch map published by Bergsland (1959). The unit sampled lies on the lower slopes of Mount Korovin, a currently active (Coats, 1950) Quaternary volcano. The basaltic flow appeared to be very fresh but definitely not historic. Two K-Ar whole rock dates run on a hand sample from the flow yielded inconclusive dates of 0.19 ± 0.38 and 0.24 ± 0.31 m.y. The flow is approximately 100 feet thick and is situated about 300 feet above the beach, 1/2 mile southeast of the wartime pier in Atka Harbor (approximate coordinates 52°13'N., 174°10'W.). 12 cores were taken and cut into three 1 cm discs. As the NRM results appeared stable the samples were not demagnetized. The results are given in Table 4-14.

The results of treating the six Aleutian SV sites along with Atka are shown in Table 4-15. With 90 flows and certainly more than 10^4 years represented we may take these values ($k = 56$, $\delta = 10.8$) as fairly good estimates of SV during the late Tertiary and Quaternary period in the Aleutian Islands region. For completeness and to avoid the problem of geographical spread of the sites mentioned above, we have calculated full statistics on VGP's as well.

TABLE 4-14

Site mean statistical data for Atka (one flow only). NRM values used (cf. Table 4-1 for explanation of symbols).

	N	k	α	α_{95}	$\bar{D}$	$\bar{I}$	λ	φ
Atka_{fld}	12	17.1	18.4	10.8	342.8	64.5	77.4	75.1
Atka_{vgp}	12	22.5	16.4	9.4			79.4	84.1

TABLE 4-15

Statistical data for late Tertiary-Quarternary paleomagnetic sites in the Aleutian Islands. Data from KAN (7 flows), RDH (14 flows), NJC (19 flows), ASH (13 flows), CCR (15 flows), DFB (21 flows) and from Atka (1 flow) treated as if at one site (see text) (cf. Table 4-1 for explanation of symbols).

	N	k	α	α_{95}	$\bar{D}$	$\bar{I}$	λ	φ
$\text{Aleutian Islands}_{fld}$	90	56.0	10.8	2.0	179.4	70.5	87.3	175.7
$\text{Aleutian Islands}_{vgp}$	90	19.5	18.3	3.5			88.0	197.8

Wait Creek, Nabesna (WCR). In June 1968 and June 1969 a 21 flow sequence of Tertiary lavas was sampled near Wait Creek, a tributary of Jacksina Creek, about 5 miles south-southwest of the Nabesna Mine in the northeastern Wrangell Mountains of south central Alaska (the flow sequence is located in NW 1/2, Sec. 12, T.6 N., R. 12 E., Copper River Meridian or near 62°18.7'N., 143°6'W.).

The flows are numbered 1 through 21 from the bottom up. Four to seven cores per flow were taken except for flow 1 in which 25 cores were taken in an attempt to get a better paleomagnetic VGP reading. Each core was cut into three or more 1 cm discs. The paleomagnetism of flows 6 through 14 collected in 1968 is discussed by Stone (1970). The entire sequence of flows has a fairly uniform dip of 10° toward the west. This dip has been compensated for in all the calculations below.

These lavas are part of what is mapped as the Wrangell Lavas of Tertiary age by Moffit et al. (1910) and Moffit (1943); the earliest of these lavas are said to be Eocene in age. The flows are largely andesites though the top flow collected appears dacitic, apparently coinciding with the bottom of a section of dacite flows found a mile to the east (Deininger, 1971). They are interbedded with thick layers of volcanic conglomerate and sandstone, notably between flow numbers 1 and 2 and between numbers 5 and 6, which may represent considerable time intervals (Figure 4-12). Two K-Ar dates for the WCR sequence were obtained: a date of 13.5 ± 0.8 m.y. for flow number 1 and 6.5 ± 0.8 m.y. for flow number 13. The former date appears to be probably reliable; the latter is perhaps too young as evidenced by the large amount of glass in the sample dated.

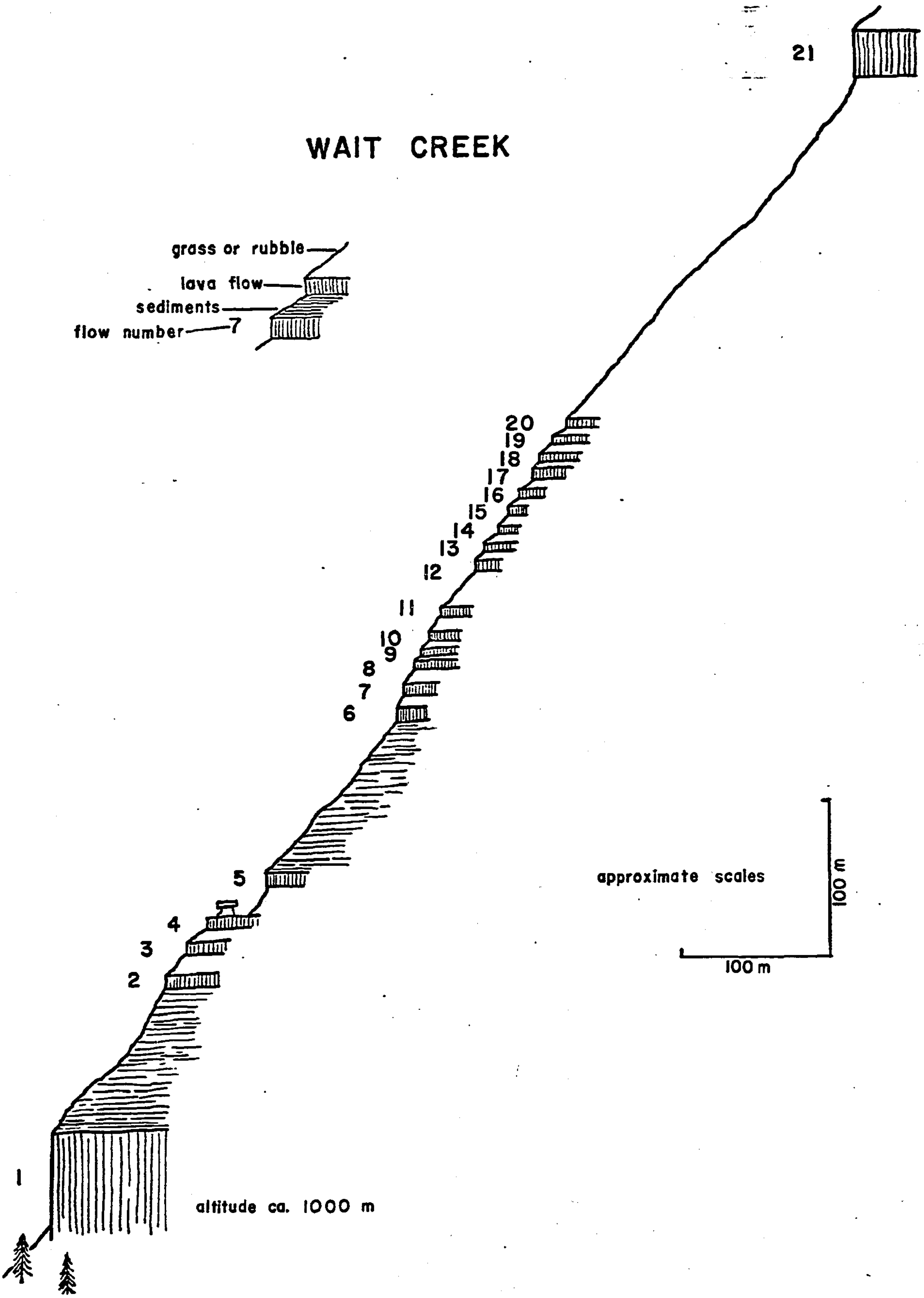


Figure 4-12. Rough geologic section for Wait Creek (WCR) site. Drawn approximately to scale from photographs, spot barometric altitude readings and casual field observations and from Cameron (unpublished, 1967).

The NRM measurements of the bottom five flows showed very wide scatter, both within flow and between flows, and appeared to be different in direction from the 15 flows up section. Due to this fact as well as the knowledge of a hiatus of perhaps a few million years represented by the sedimentary layers, only NRM measurements were made for flows 1 through 5. The data is only reproduced here (Table 4-16) for the record and is not further utilized.

Successive stepwise A. F. demagnetization and measurements were carried out on pilot samples to determine a suitable field for use in magnetic cleaning of the remaining samples (Figure 4-13a, b). A field of 380 oe was found to remove most of the softer components, while still leaving enough of the primary magnetism for good measurements. The middle discs from each core in flows 6 through 21 were cleaned in this field and measured with all statistical analysis done on the resulting data.

The within flow scatter is quite small for all of flows 6 through 21, with δ being less than 10° for all but three flows and less than 5° for seven flows. This indicates that each flow fairly well recorded a spot reading of the geomagnetic field at the time of extrusion. Flows 6 through 16 all have mean directions which are considerably removed from the mean axial dipole field direction, giving VGP's located in eastern Siberia. They are grouped about a mean of $D = 306°$, $I = 47°$ (Figure 4-13c) so tightly ($k = 614$) that an F-ratio test shows their separate directions to be not significantly different from each other; we are forced to conclude either that they do not represent true variations in the geomagnetic field because they were all extruded during

TABLE 4-16

Flow mean statistical data for WCR Series. Flows listed in stratigraphic sequence (youngest first). Samples A.F. demagnetized at 380 oe. except those from flows 1 through 5 for which NRM data is given. Site mean statistics based on (a) sixteen flows, nos. 6-21, treated separately, (b) flows 6 through 16 treated separately, and (c) flows 6 through 16 treated as one 'flow' using mean values obtained in (b) along with flows 17 through 21 treated as individual flows (see text) (cf. Table 4-1 for explanation of symbols).

Flow No.	N	k	δ	α_{95}	$\bar{D}$	$\bar{I}$	λ	ϕ	$\bar{J}_{NRM}$
21	5	417.8	3.6	3.7	302.9	78.8	66.4	166.2	1780.7
20	6	71.0	8.8	8.0	295.7	79.2	64.1	169.6	88.0
19	6	28.2	14.0	12.8	291.5	74.6	59.0	155.9	217.5
18	6	12.5	21.0	19.7	304.0	77.5	66.1	160.4	564.5
17	6	41.4	11.5	10.5	302.5	58.2	48.6	120.1	1075.3
16	7	108.0	7.2	5.8	306.2	53.0	46.0	112.0	979.4
15	6	311.2	4.2	3.8	307.0	48.9	43.0	108.5	897.4
14	6	62.1	9.4	8.6	304.5	49.7	42.5	111.5	1352.4
13	4	225.1	4.7	6.1	306.3	45.8	40.5	107.3	1207.9
12	5	240.4	4.7	4.9	303.3	43.5	37.6	109.2	1179.6
11	6	122.5	6.7	6.1	308.3	43.5	39.8	104.1	1153.3
10	6	214.4	5.1	4.6	307.9	44.5	40.3	105.1	1224.3
9	5	587.7	3.0	3.2	304.1	48.1	41.2	110.9	1390.3
8	6	804.6	2.6	2.4	303.9	47.0	40.3	110.4	1611.6
7	6	69.3	8.9	8.1	306.3	50.5	43.9	110.1	417.8
6	6	333.6	4.1	3.7	306.6	46.9	42.3	105.6	390.2
5	5	12.9	20.3	22.2	158.0	49.8	-52.0	35.4	560.7
4	6	5.1	33.1	32.7	39.4	-16.8	49.6	108.4	1178.5
3	5	23.2	15.1	16.2	86.9	-22.8	2.9	105.7	1989.2
2	5	188.1	5.3	5.6	35.3	-87.6	2.9	181.0	1935.5
1	25	5.6	34.1	13.5	9.6	4.4	29.5	25.9	2496.6
WCR (a)fld	16	35.1	13.3	6.3	305.1	55.5	47.5	115.1	
(a)vgp	16	22.9	16.5	7.9			49.3	117.5	
WCR (b)fld	11	613.9	3.1	1.8	306.0	47.4	41.5	108.5	
(b)vgp	11	703.2	2.9	1.7			41.6	108.6	
WCR (c)fld	6	36.6	12.3	11.2	301.8	69.4	58.8	137.1	
(c)vgp	6	21.6	16.0	14.7			60.1	141.2	

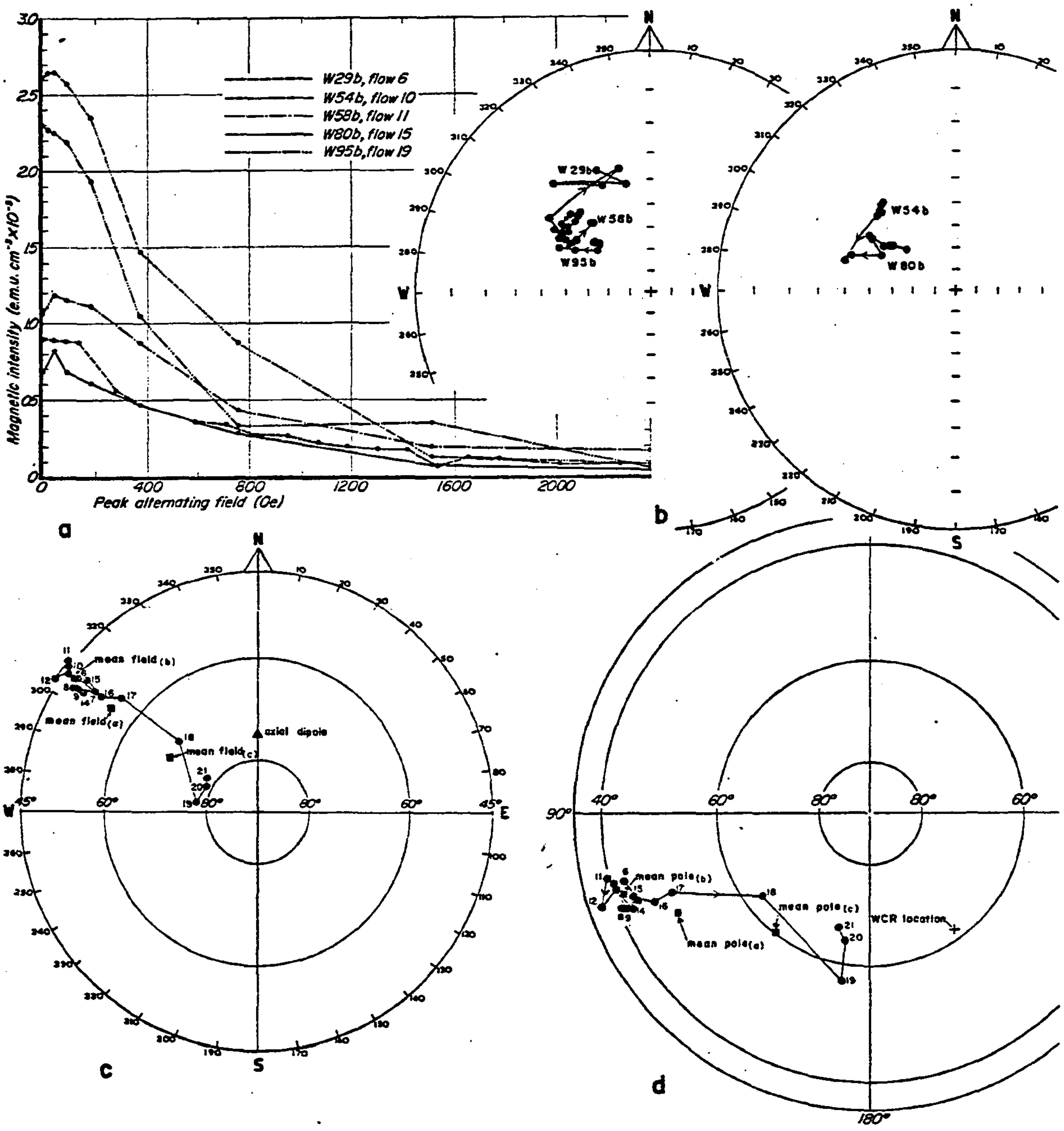


Figure 4-13. Paleomagnetic data for Wait Creek, Nabesna. (a) Magnetic intensity and (b) vector directions of pilot samples during A.F. demagnetization. (c) Flow mean magnetic vector directions and (d) VGP's. Mean data from Table 4-16; cf. explanation to Fig. 4-2 for further details.

a time short compared with common rates of field change, or that they were extruded during an exceptionally stable period of the geomagnetic field when at the same time the field displayed an inordinately wide field excursion. The latter case was assumed by Stone (1970) who only used data from flows 6 through 14 sampled in 1968. We have made the necessary statistical calculations for both assumptions (Table 4-16), but the resulting dispersions differ only slightly. The flows themselves do not appear to have been extruded all at once for they seem to be well separated by weathered layers and rubble. However, for the purposes of further calculations and comparison with the work of other investigators, we have assumed that the former case gives a more reliable value for SV on the basis that, since a large field excursion has evidently taken place, any secular variation which occurred during that excursion probably represents 'abnormal' field behavior. We have therefore lumped all eleven flows together as one data point to calculate the secular variation based on six 'flows'. Flows 17 through 20 show a return toward the normal dipole field direction (Figure 4-13c). The two tier analysis (Watson and Irving, 1957) giving $k_\beta = 33.2$ for the six 'flows' is shown in Table 4-17.

Unfortunately,it is not possible to carry out the Doell (1969) time span analysis on the Wait Creek site as we have done for the Aleutian sites because we know almost nothing about either the eruptive rate or about the geometry of the situation at the time of extrusion due to the very heavy erosional down cutting. Stone (1970) has discussed this problem and all we can do is to suggest on the basis of rubble and soil layers between flows that at least a few thousand years but perhaps not as much as 10,000 years are represented.

TABLE 4-17

Analysis of variance Table for WCR series using (c) mean data from Table 4-16 (cf. explanation to Table 4-2).

Source	DF	SS	MS
Between flows	10	1.1029	0.110289
Within flows	68	0.7933	0.011666

$F = 9.454 > F_{5\%,\ 10,\ 68} \simeq 1.98$; therefore k_β significant

$k_\omega=42.859$

$k_\beta=33.207$

Other Nabesna sites. Ten flows from two outcrops half a mile apart (Castle I and Castle II) and nine flows from a site a few miles away (Air II) were collected by D. B. Stone in 1965. The Castles are about half a mile north of Skookum Creek and about six miles north-northeast of the Wait Creek site. The Air II site is about two miles west of the Castles and appears to be stratigraphically just above the Castles (Stone, unpublished, 1965). Both sequences are part of the Wrangell lavas and are approximately contemporaneous with the WCR flows (Stone 1970).

The paleomagnetism of these sites and its bearing on secular variation has been published by Stone (1970). Some small errors in Stone's data have been corrected and additional statistics calculated. Full data are presented in Tables 4-18 and 4-19 where it should be noted that flow mean statistics have been calculated treating all discs separately (except for two Castle flows calculated using cores). Thus the true number of cores per flow is approximately 1/3 of N (because there were usually three discs cut from each core). Since dispersion between discs in the same core is generally much less than between core dispersion (Doell and Cox, 1963), this method of calculation gives unrealistically small within flow dispersion.

Stone (1970), on the basis of the simplified two tier analysis (eq. (3-11)), concluded that the within-flow scatter was too large and that much too short a time interval was represented by both these series for any reliable value of SV to be obtained. This suggestion is strengthened by the low dispersion values observed at the two sites. ($\delta = 5.8°$ and 6.0° for Castles and Air II respectively). The Air II site mean is

TABLE 4-18

Flow mean statistical data for Castles section. Flows listed in stratigraphic sequence (youngest first). Data in part from Stone (1970). Statistics based on NRM data. Site mean statistics are also given (see Table 4-1 for explanation of symbols). N refers to number of discs per flow except for flows 3 and 10 where it refers to number of cores (D. B. Stone, private communication, 1971).

Flow No.	N	k	δ	α_{95}	$\bar{D}$	$\bar{I}$	λ	ϕ
11	3	---	2.8	5.2	43.8	76.7		
10	5	118.4	6.7	7.1	171.5	83.2		
9	15	34.5	13.3	6.6	102.4	72.8		
8	7	533.8	3.3	2.6	121.2	79.5		
6	12	146.6	6.4	3.6	104.9	79.6		
5	11	121.4	7.0	4.2	68.4	83.1		
4	15	135.9	6.7	3.3	99.0	80.6		
3	6	149.5	6.0	5.5	91.8	81.6		
2	12	76.4	8.9	5.0	109.7	78.8		
1	3	---	1.5	2.9	93.1	71.7		
Cas.$_{fld}$	10	174.3	5.8	3.7	108.8	79.7	51.4	248.1

TABLE 4-19

Flow mean statistical data for Air II series. Flows listed in stratigraphic sequence (youngest first). Data in part from Stone (1970). Statistics based on NRM data. Site mean statistics are also given (cf. Table 4-1 for explanation of symbols). N refers to number of discs per flow (see text).

Flow No.	N	k	δ	α_{95}	$\bar{D}$	$\bar{I}$	λ	ϕ
9	16	246.6	5.0	2.4	335.1	77.5		
8	11	454.4	3.6	2.1	350.3	78.2		
7	9	615.3	3.1	2.1	346.2	81.5		
6	15	835.7	2.7	1.3	340.6	79.3		
5	13	276.7	4.7	2.5	348.5	75.4		
4	9	82.1	8.4	5.7	8.0	62.9		
3	12	446.6	3.7	2.1	1.9	71.1		
2	12	150.7	6.3	3.5	7.4	79.6		
1	11	1012.1	7.7	1.4	353.8	78.2		
A.II$_{fld}$	9	161.1	6.0	4.1	354.7	76.2	87.2	161.0

quite close to the axial dipole field while the Castles site mean is about 20° removed from the axial dipole field (Fig. 4-14) and gives a VGP in southeastern Alberta; the latter presumably represents a field excursion.

Wrangell Mountains area mean secular variation. None of the three Nabesna area sampling sites apparently represents sufficient time for a reliable determination of paleosecular variation. Since all three sites have significantly different mean pole positions and since evidently tectonic differences are minimal (Stone, 1970) it is clear that the flows are not exactly contemporaneous and probably span at least the 10^4 years necessary for SV analysis. On the other hand the formation can be roughly traced between the sites so that all three sites seem to be approximately contemporaneous and represent at most a period of a few million years.

In order to obtain a value of SV for the Nabesna area which is perhaps more meaningful than those determined for the individual sites we have treated the flow mean data from the three sites WCR, Castles, and Air II as if they were all at the same site. The possible problems arising due to geographic spread of sampling sites in such combining of data, alluded to in calculating the Aleutian mean SV, don't arise here because the sites are all within less than half a degree of each other. For WCR we have treated flows 6 through 16 as one 'flow'. This gives a total of 25 flows. The statistics are presented in Table 4-20.

The Tertiary value for SV determined in this manner for the Wrangell Mountain area is large ($\delta = 15.3$) and it may be argued unrealistic because of the apparent field excursions observed at both the WCR and

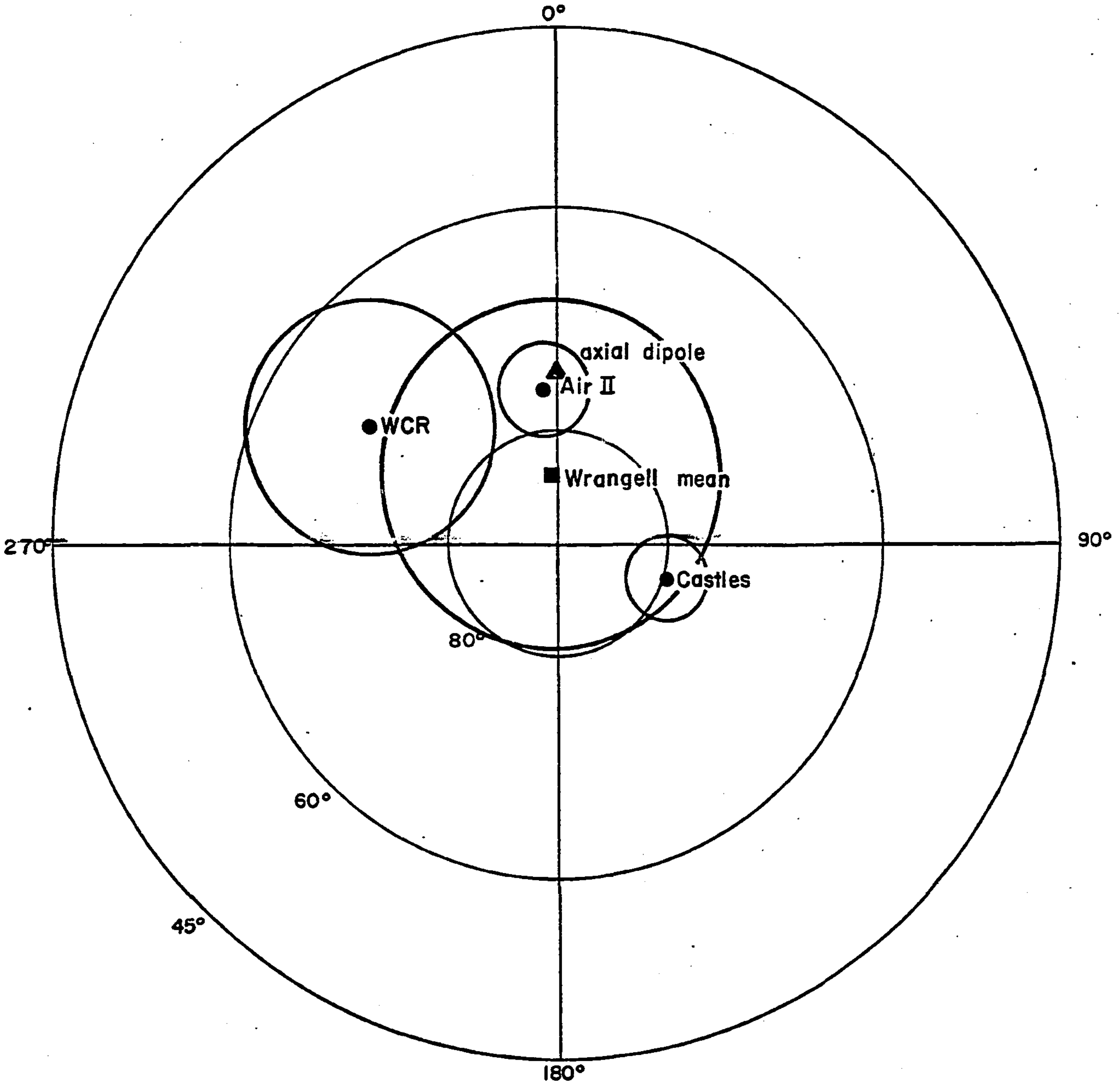


Figure 4-14. Nabesna area mean field directions. Circles of radius δ. WCR mean is 6 'flow' mean (cf. Table 4-16). Other data from Tables 4-18, 4-19 and 4-20.

TABLE 4-20

Statistical data for Tertiary sites in the vicinity of Nabesna, Alaska. Flow mean data from WCR (6 'flows'), Castles I and II (10 flows), and Air II (9 flows) treated as if they were at one site (cf. Table 4-1 for explanation of symbols).

	N	k	δ	α_{95}	$\bar{D}$	$\bar{I}$	λ	ϕ
$\text{Nabesna}_{\text{fld}}$	25	27.1	15.3	5.7	354.4	83.7	74.7	212.2

Castles sites. In the analysis of the Aleutian sites we tended to ignore data representing large scale field excursions because they indicated 'abnormal' geomagnetic field behavior or were associated with field reversals. In fact, only 3 out of the total of 90 flows were ignored in the Aleutian analysis; these were at the KAN and ASH sites; in both cases they were associated with reversals. However, in considering the Nabesna area sites we note that we have recorded two distinct field excursions among the three sites sampled; in terms of flows, 21 out of the 35 flows represent field excursions. This is surely a high percentage to have occurred by chance sampling alone. It seems in the case of the Tertiary that these field excursions may not be such an 'abnormal' feature of the geomagnetic field; in fact, they may be a comparatively common occurrence. Therefore we have not ignored them in calculating the apparent paleosecular variation for the Wrangell Mountain area. It should be noted that since there is a possibility that a time span of up to a few million years is represented by the Wrangell Mountain area data there may be factors other than SV included in the measurement.

Other Alaskan sites. Stone (1970) reported on paleosecular variation measurements at two additional Alaskan sites: Mount Griggs in Katmai National Monument and Mount Edgecumbe on Krusof Island near Sitka in southeast Alaska. Both are Quaternary to Recent volcanoes. At both sites only 5 flows were sampled; this is considered too small a number for reliable SV measurement. Nonetheless Stone's (1970) data have been recalculated after correcting some small errors to give $\delta = 6.7$ for Mount Griggs and $\delta = 7.2$ for Mount Edgecumbe. Both site mean field directions lie within a few degrees of the axial dipole (cf. Table 5-1 in the next chapter for more complete data). These data might be combined with the Aleutain mean data given above to obtain a better Quaternary value for SV but it was thought that the problems of geographical spread of the sites would render such a value relatively meaningless. Flow mean VGP data were not readily available for these two sites precluding combining VGP statistics to avoid the geographical spread problem.

Cox and Doell (1964) in a discussion of the latitude variation of secular variation (cf. next chapter) present diagrams containing SV data for Quaternary basalts on Nunivak Island just off Alaska's western coast. Exact numberical data are not available and only the approximate values of $N \doteq 43$ and $\Delta_{vgp} \doteq 24°$ may be read from the published diagrams (Figures 7 and 8 of Cox and Doell, 1964). We have calculated the corresponding dispersion for field directions instead of for VGP's using the relations (Cox, 1962),

$$\Delta_{fld} = C\Delta_{vgp}, \qquad (4\text{-}1)$$

where

$$C = 1/4\ (1 + 3\cos^2 I_m + \sqrt{1 + 3\cos I_m}); \qquad (4\text{-}2)$$

I_m is the mean inclination of magnetic field directions. Lacking exact data, I_m was taken as the axial dipole field; this is not thought to introduce a significant error. This gives $\Delta_{fld} \doteq 14.0°$ from which $k = 33.5$ may be found using equation (3-6).

Due to the relatively high value of N the Nunivak Island data is probably a fairly good value of SV during the past million years. However, as little detailed information has been published it is difficult to assess this value.

Cameron and Stone (1970) reported on the paleomagnetism of seven mid-late Miocene instrusives on Shemya Island in the Aleutian Islands. Two of these were K-Ar dated at 12.3 ± 1.5 and 15 ± 3 m.y. All the sites are thought to be approximately contemporaneous but as three of the seven are magnetically reversed it is clear that they were not intruded simultaneously. The relatively small measured dispersion of the seven site mean values ($\delta = 6.2$, $k = 146.8$) may indicate a small SV value for Shemya, for surely more than 10^4 years is represented in the time span. However, $N = 7$ is generally considered too small to place much confidence in an SV measurement. Due to the geographical spread involved, we have demurred from combining the Shemya data with the Wrangell Mountains area data which represent approximately the same age. We only note that if the Shemya values are reliable, SV appears to have been considerably less during the late Miocene at the end of the Aleutian Island chain than on Mainland Alaska nearly 3000 km to the northeast.

V. SECULAR VARIATION DISTRIBUTION IN SPACE AND TIME

In seeking a greater understanding of the earth's interior through study of the secular variation of the geomagnetic field it is of obvious importance to learn about its distribution over the surface of the globe throughout geologic time. It is only through the study of paleomagnetism that we may obtain direct un-extrapolated data on the internal constitution of the earth during the geologic past (Petrova and Khramov, 1970).

Latitudinal variations

Since one of the most dominant features of present secular variation is its westward drift, Creer (1962a, b) has suggested that one can learn about the distribution of long term SV as a function of latitude, by considering the longitudinal variance of the geomagnetic field at a given instant around a circle of latitude as being equivalent to the time variance at any fixed point on the same latitude over a significant number of years. Taking values of the 1945.0 field at 10° intervals around lines of latitude 10° apart he calculates their dispersion k and δ as a function of latitude. The variation of δ is shown in Figure 5-1 (curve 1). In an attempt to sort out the effects of non-dipole sources from the main dipolar field, he carried out similar analyses on the best fit inclined dipole (curve 2) and on the total field, but around lines of geomagnetic instead of geographic latitude (curve 3). These data show that in each case δ is a maximum near the equator and has minimum values near the poles. Also, it is clear (curves 1 and 3) that there is an asymmetrical distribution of field

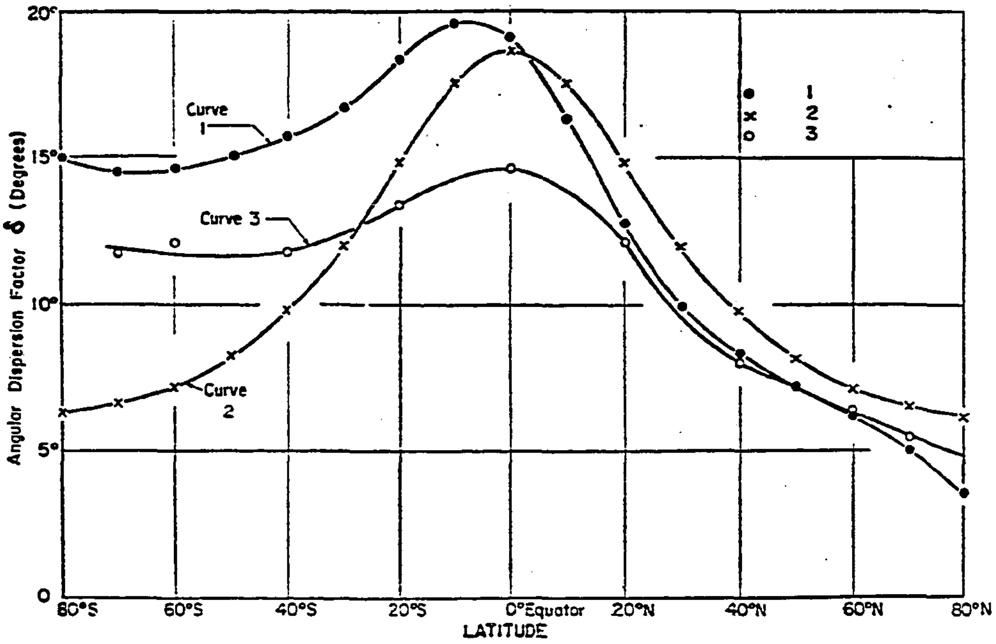


Figure 5-1. Angular standard deviation, δ, of field directions around different lines of latitude, as a function of latitude. Abscissa is geographic latitude for curves 1 and 2 but geomagnetic latitude for curve 3. Ordinate is dispersion of whole field for curve 1, dispersion of the best-fit dipole for curve 2, and dispersion of the non-dipole field for curve 3. For epoch 1945.0 (after Creer, 1962a).

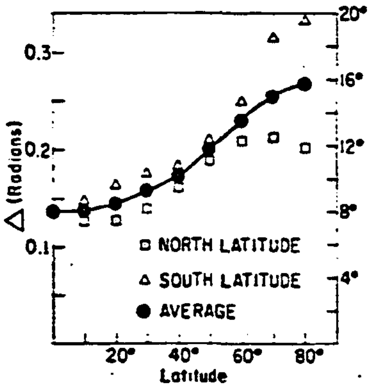


Figure 5-2. Angular standard deviation, Δ, calculated by equation (3-6) for VGP displacement angles corresponding to total field direction in 1945.0 along circles of latitude (from Cox and Doell, 1964).

direction scatter between the northern and southern hemispheres, the latter having the greater scatter.

Cox (1962), and Cox and Doell (1964) made a similar assumption, but applied it to virtual geomagnetic poles (VGP's) calculated from 1945.0 field data. They used a slightly different statistical methodology based on a known true mean pole position, λ_o, ϕ_o(= present geomagnetic pole found by spherical harmonic analysis (Chapman and Bartels, 1940; Vestine *et al.*, 1947)), taking

$$k = \frac{N}{N - R\cos\delta_o}$$

and

$$\delta = \cos^{-1}\left(\frac{R}{N}\cos\delta_o\right) \quad ,$$

where δ_o is the angle between the true mean $(\lambda_o, \phi_o)$and the mean of N vectors drawn from an infinite population of vectors. Since, however, for his analysis $\delta_o \approx 0.5°$ the difference between these values and those calculated using equations (3-3) and(3-5) is negligible.

The result of carrying out this sort of analysis on VGP's instead of on magnetic vector directions gives a relation which is apparently opposite to Creer's (1962a, b) result (Fig. 5-2). Maximum scatter appears toward the poles with a minimum at the equator. The same conclusion as Creer's may, however, be drawn with regard to North-South asymmetry: dispersion is greater in the southern hemisphere.

The question as to which is the preferable method of analyzing SV, that is between using geomagnetic field directions or VGP's, is a perplexing one. Since the VGP is effectively only a mathematical construct with no real physical meaning (Chap. III), it would seem that using magnetic field vector directions would be the more fundamental method. On the other hand the VGP analytical method allows an easier separation of the effects of dipole wobble and non-dipole sources, since the angular dispersion of VGP's due to dipole wobble is invariant with respect to latitude (Cox, 1962; Cox and Doell, 1964). Cox (1970) in a careful analysis of the VGP - field direction problem concludes that the VGP method is preferable, but that there is not enough world-wide data to use his techniques for separation of non-dipole from dipole components.

Because the paleosecular variation measurement process involves statistical parameters which assume a Fisher, or at least a circular distribution, there is further question as to the suitability of vector directions or VGP's for analysis. A circular distribution of field directions transforms into an oval distribution of VGP's, while a circular distribution of VGP's transforms into an oval distribution of field directions. The various sources of scatter are likely to produce either circular or oval distributions depending on how they are calculated. Any experimental errors of the type referred to in Chapter III will tend to produce a circular scatter of magnetic field directions with consequent oval VGP distribution. This statement is only strictly true of random errors and will not necessarily hold for other errors such as those produced by VRM and susceptibility anisotropy which will tend to produce elongate distributions; only by chance will these be such as to produce circular VGP distribution. Secular variation itself may produce scatter consisting of both circular and oval components. Dipole wobble will produce a circular VGP distribution and an oval magnetic field distribution, if, as is commonly done, we assume it takes place in a more or less random fashion about the geographic pole (e.g. Green, 1958; Irving and Ward, 1964). The part of SV due to non-centric dipole or to non-dipole sources (depending on the model one assumes) may be expected to produce a circular scatter of vector directions at the sampling site but an oval VGP distribution.

In addition to the above circular-oval transformation problems, there is a magnitude effect, even if one ignores the circularity of the scatter. Cox and Doell (1960, 1964) show that the ratio of the angular standard deviations calculated using equation (3-5) varies from

$$\frac{\delta_{fld}}{\delta_{vgp}} = \frac{1}{2}$$

at the poles to

$$\frac{\delta_{fld}}{\delta_{vgp}} = \frac{3}{2}$$

at the equator. These relations are in part responsible for the apparently opposite results of Creer (1962a) and Cox and Doell (1964).

Thus it would seem that for the study of secular variation of the geomagnetic field it would be advantageous to separate the circular and oval components of scatter from each other. Unfortunately, at the present time no statistical formulation exists for conveniently resolving these components. Even if such a method were available, paleomagnetic data are only rarely scattered in a sufficiently Fisherian manner to enable one to use such statistical refinements.

Since it is probable that random errors and non-dipole components generally predominate in paleosecular variation measurements, and to conform to the majority of other published results, we have chosen to do comparative statistical calculations almost exclusively on vector directions instead of VGP's. For the benefit of future workers, however, we have carried out full VGP statistics on our own Alaskan data (Chap. IV).

Creer (1962a, 1967), Cox (1962), Cox and Doell (1964), and Creer and Sanver (1970) compare latitudinal variations of the scatter of the 1945.0 field with paleomagnetic data with varying success. In the next section a more comprehensive comparision will be attempted.

Longitudinal variations

If one looks at recent SV on a global scale by examining almost any type of geomagnetic analysis maps, be they isoporic maps (Fig. 1-1) or maps showing deviations of VGP's derived from the geomagnetic field away from the best-fit dipole field, such as that of Cox and Doell (1964) (Fig. 5-3) one feature is immediately evident: secular variation of the present day geomagnetic field is less in the hemisphere containing the Pacific Ocean than it is in the remaining part of the world (Fisk, 1931; Fleming, 1939; Chapman and Bartels, 1940; Vestine et al., 1947; Runcorn, 1956; Depietri, 1961; Vestine and Kahle, 1966; Doell and Cox, 1971; and others). It is difficult to know where to draw the boundary between areas of high and low SV but there is no doubt of the difference. Cox (1962) singled out an area comprised of less than half the Pacific Ocean for separate analysis, though it might seem that a larger area could have been chosen. Not only is the secular variation small in the Pacific area, but Cox's data shows that the non-dipole

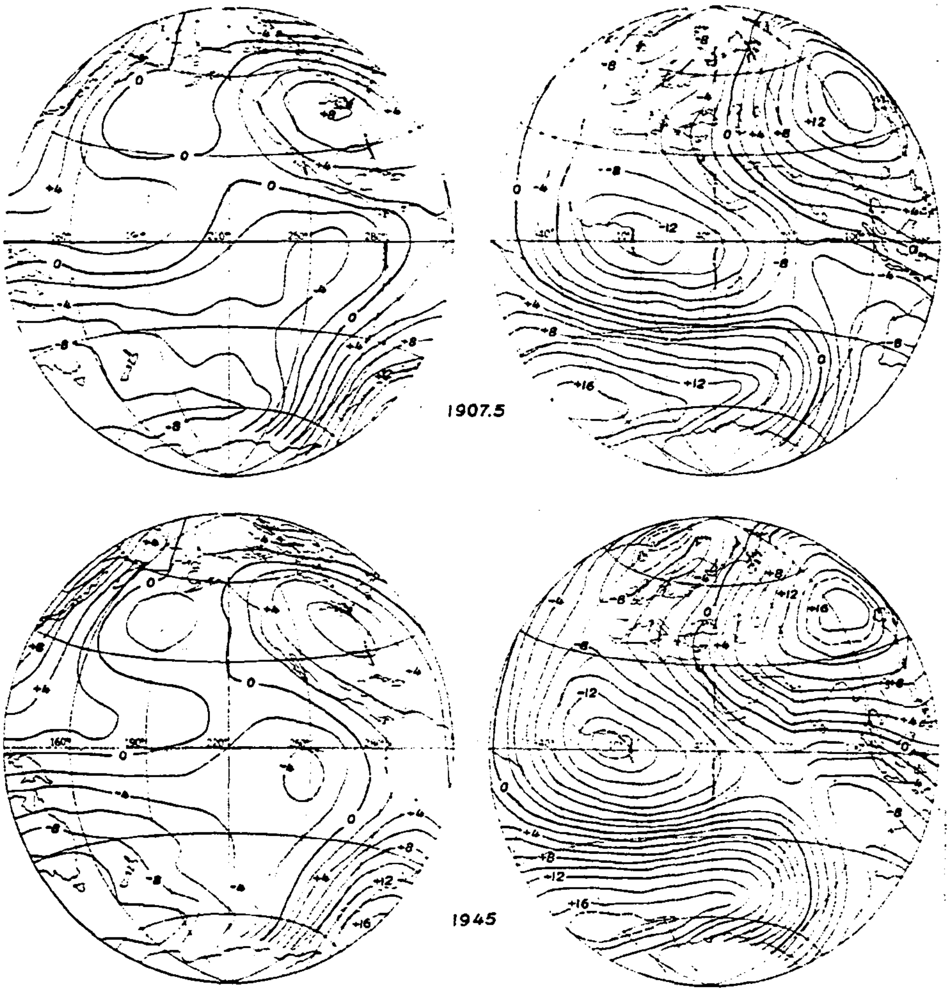


Figure 5-3. Vertical component of the non-dipole field. Original data (Bullard et al., 1950) for epochs 1907.5 and 1945 have been contoured on equal area projections. Interval of closed contours is 2000 gammas, that of dashed contours 1000 gammas (from Cox and Doell, 1964).

field is small, thus making the Pacific area a 'window' through which we may 'view' the main inclined dipole undistorted (Cox, 1962).

An immediate question is whether or not the Pacific low is a permanent feature of the secular variation field in time as well as space. Cox and Doell (1964) and Doell and Cox (1961, 1965) tentatively conclude, after an analysis of Pacific paleomagnetic data from the Galapagos Islands to Alaska, that the non-dipole component of SV has been subdued in the Pacific during the last 10^6 years. However, Tarling's (1967) studies in Hawaii, Samoa, and the Cook Islands indicate that SV has not been anomalously low during the last 5 m.y. when time averages of 10^5 to 10^6 years are considered.

One can devise various models to explain the low SV values in the Pacific, which may treat the problem as either a transient or a permanent phenomenon. It is clear that this difference in distribution of SV can not be caused by the broad differences in crustal structure which exist between the 'oceanic' Pacific hemisphere and the essentially 'continental' non-Pacific hemisphere, but rather must have its origin in deep seated variations in the structure or physical processes occuring within the mantle and/or the core; if the SV differences in fact do persist over geologic time, this may require a basic reformulation of the physics of the earth's interior which formerly has relied on a spherically symmetric earth (Runcorn, 1956). Assuming that the non-dipole components of SV are due to eddies within the upper levels of the earth's core (Chapter I), Cox (1962) delineates three possible models to explain the Pacific SV low:

(1) Non-dipole sources of SV don't form under the Pacific region.

(2) Non-dipole sources of SV are present under the Pacific but their effects are screened from observation at the earth's surface by highly conducting, possibly fluid, layers in the mantle.

(3) Non-dipole sources may be present or absent beneath the Pacific but at the present time there are none in this region.

These configurations consider only the non-dipole part of SV, since presumably that part due to movement of the main dipole itself (wobble, etc.) will be detected equally world wide. Also, direct (historic) SV measurements record almost exclusively non-dipole components (Chap. I).

The last of these possibilities, (3), is perhaps the easiest explanation for the Pacific SV low. Given the present uncertainties surrounding paleomagnetic methods of SV measurement and the conflicting results of various researchers, there is a finite probability that the present SV distribution is due to a temporary chance arrangement of non-dipole sources within the earth. Until more definitive paleomagnetic results become available, however, this explanation appears to be begging the question and it is fruitful to look for models which provide for a long term low SV in the Pacific region.

A number of workers have attempted to explain model (2). Creer (1963) hypothesizes magnetic shielding of the SV field by an asymmetric mantle. Starting from Elsasser's (1963) cold accretion hypothesis of global origin, Creer imagines a layer of molten iron forming in the upper mantle during early stages of the earth's formation. This layer would form into a roughly spherical drop which would grow to be quite large in size. It would eventually sink slowly to the geo-center, pushing iron-rich 'proto-core' material out ahead of it while leaving iron-poor material in its wake. Due to rotational forces these masses of material would tend to move into a position more or less on the earth's rotational axis; if the geographic axis then moved with respect to the earth's mantle and crust, 'fossil' poles of high and low SV would be created. These would be due respectively to low and high iron content in the mantle. As supporting evidence Creer cites the area of present day high SV off South Africa roughly antipodal to the center of the Pacific SV low; these two points would, according to the theory, define an ancient axis of rotation. In addition, the high SV at the present North Pole is presumably due to the most recent sweeping out of iron-rich material from the mantle by the sinking of a 'drop' of iron along the present axis. He also notes that Paleozoic paleopoles for North America, as determined paleomagnetically, fall near the center of the Pacific SV low (This would imply, however, that the Pacific has not moved relative to North America since Paleozoic times which would contradict some aspects of modern theories of plate tectonics and ocean floor spreading (Vine and Matthews, 1963; Heirtzler et al., 1968; Dietz and Holden, 1970a and 1970b; and others)).

A central problem in the magnetic shielding hypothesis is to account for the amount of shielding which is apparently necessary. Unreasonably high conductivities or great thickness of the shielding layer are required. McDonald (1957), Hide and Roberts (1961), and Currie (1967) find from theoretical calculations that, taking a world average, the mantle has a time constant of about four years and that it acts as a low-pass filter which effectively blocks out magnetic variations with shorter time scales. Ball et al. (1968) find a time lag of 5 to 8 years for transmission of SV disturbances from the core to the surface (Chap. I). Cox and Doell (1964) point out that conductivities large enough to attenuate SV in the 10^2 to 10^3 year range would reduce short period 10 year variations below noise level; but short period variations have indeed been observed in Hawaii. It seems possible, however, that such short period variations are due to external sources rather than internal ones (Chap. I).

Any well defined shielding layer thick enough to produce the requisite SV attenuation beneath the Pacific should be thick enough to be detectable seismically. In a study of attenuation of different frequency components of P waves diffracted along the core-mantle boundary, Alexander and Phinney (1966; Phinney and Alexander, 1966) find systematic differences between the central Pacific and the other areas they studied. On the basis of lengthy calculations from their data, they postulate that in the lower mantle beneath the Pacific there is a region between 30 and 160 km thick with a reduced shear velocity and an increased density. What this means in terms of shielding of SV is a matter for speculation, but it could be indicative of residual iron such as that hypothesized by Creer (1963).

Cox's (1962) model (I) advanced to explain the Pacific SV low, namely that non-dipole SV sources don't form under the Pacific, is perhaps easier to justify physically than the shielding hypothesis, though it is equally difficult to prove. By this hypothesis there are lateral variations in the sources that produce SV rather than variations in the transmission parameters of the medium through which SV disturbances must travel. Cox and Doell (1964) propose that temperature differences in the lower mantle may be sufficient to affect the convection currents in the core which produce the non-dipole field. Citing MacDonald's (1963) calculations showing 50° to 150° C. higher temperatures 1000 km beneath the oceans than beneath continents, they propose that under the essentially 'oceanic' Pacific hemisphere the lower mantle may be hot enough to suppress near surface core convection by causing reduced lateral as well as radial temperature gradients. Thus non-dipole features of the field would decay upon moving into the Pacific area.

Vestine and Kahle (1966) propose the existence of non-uniform core surface velocities with a general downflow of core material beneath the Pacific Ocean. By carrying magnetic disturbances caused by local eddies deeper into the core, lower values of SV would be produced than in areas where core motions were predominantly horizontal or upwards, and where there is less shielding core material above them.

Doell and Cox (1971), following Hide (1966, 1967) suggest a different way to cause core eddy currents sufficiently asymmetric to produce the Pacific SV low. In comparing motions of the core with those of the atmosphere, they note that while both are essentially axially symmetric when averaged over sufficient time spans, both have more or less permanent perturbations of this symmetry due to the topographic relief of the solid-fluid interface, as well as due to the possible temperature variations over the interface referred to above. As with the production of standing waves in the atmosphere due to mountains, it is conceiveable that there may be a broad topographic high or low in the core-mantle interface associated with the Pacific hemisphere which is sufficient to produce an anomalous lack of eddy currents in this region.

Bisque and Rouse (1968), in an anlysis of the core-mantle interface, based on their global tectonic scheme involving planes tangent to the core which intersect the earth's surface along geologic features (Rouse and Bisque, 1968), derive a core topography which is notably smoother beneath the Pacific than elsewhere. Perhaps the anomalous relief necessary to subdue SV sources is a flatter than average core topography.

In an attempt to learn more about the world-wide distribution of paleosecular variation, a survey was made of paleomagnetic literature to select existing data which could be considered to be a measure of SV (Tables 5-1 and 5-2). As a starting point, we have relied heavily on the compilations of paleomagnetic data of Irving (1964) and McElhinny (1968a, 1968b, 1969, and 1970). Where available, most of the suitable original source literature referred to in these compilations has been checked in order to ascertain the reliability of the data. An attempt has been made to review every paper since the last of these compilations but no claim at completeness is made.

The following criteria have been used in selecting data:

(1) Only data from rocks of the Cenozoic Era have been considered.

(2) A minimum of N = 10 flows or sites sampled within a volcanic sequence was required. A few exceptions were made in order to include data from isolated regions of the earth, and to include some Alaskan data.

(3) Studies with α_{95} confidence limits greater than 15° about the mean vector direction were rejected on the basis that either the errors from various sources were large, or that the sequence included values

TABLE 5-1

Paleomagnetic statistical data from the Pacific region selected according to criteria described in the text.

λ and ϕ are latitude and east longitude of sampling site in degrees. $+\lambda$ and $-\lambda$ indicates North and South latitude respectively. Where values are calculated for widely spaced units an approximate mean location is given. Pole No. refers to paleopole reference numbers in the data compilation of Irving (1964) (decimal format; e.g. 12.42) or in the compilations of McElhinny (1968a, b, 1969, 1970) (slash format; e.g. 10/24) where available. Age is given in million years before present when known or using standard letter symbols for geologic periods as used in the published compilations referred to above and elsewhere in the literature. N is the number of lava flows or units which were used to calculate the statistics. k_T refers to the Fisher (1953) parameter, equation (3-3), giving unit treatment to N flows or units. k_ω and k_β are the within-flow and between-flow Fisher parameters calculated according to the method of Watson and Irving (1957) (see text). δ and Δ_T are angular standard deviations in degrees calculated using equations (3-5) and (3-6) respectively. $+\varepsilon$ and $-\varepsilon$ are 95% confidence limits on Δ_T in degrees calculated according to Cox (1969). α_{95} is the radius in degrees of the 95% circle of confidence about the mean paleofield direction. $\bar{D}$ and $\bar{I}$ are the mean declination in degrees east of true north and degrees of dip below or above horizontal (indicated positive or negative respectively) of the paleofield direction after correction for local tectonic movement. In a few cases we have calculated some of the parameters from published data where complete data were not given.

Notes to Table 5-1

[1] N read from published diagrams; may be low by ca. 5. Δ_T calculated from values of Δ for VGP's given in reference paper using eqs. (4-1) and (4-2). k_T calculated from Δ_T by eq. (3-6). No mean directions available.

[2] k_ω and k_β calculated from δ_ω and δ_β using eq. (3-6) where δ_ω and δ_β are related according to eq. (3-11).

[3] Mean vector directions not available.

[4] Dated at 4000 B.C. to 1600 A.D.

[5] Dated at 325 to 1779 A.D.

[6] Δ_T calculated from k_β since k_T not available.

TABLE 5-1

Paleomagnetic data from the Pacific region (cf. explanation on previous page)

Site Description	λ	φ	Reference	Pole No.	Age	N	Fisher Parameter			Angular St'd Dev.				α_{95}	$\bar{D}$	$\bar{I}$
							k_1,	k_ω	k_β	δ	Δ_T,	$+\epsilon$,	$-\epsilon$			
Alaska: Castles	62.4	216.8	Stone, 1970		6?	10	171.3			5.9	6.2,	+2.6,	-1.4	3.7	108.6	79.7
Air II	62.4	216.8	" "		6?	9	161.1			6.0	6.4,	+2.8,	-1.5	4.1	354.7	76.2
WCR	62.3	216.5	this paper		6	6	36.6	42.9	33.2	12.2	13.4,	+7.7,	-3.6	11.2	301.8	69.4
Wrangell mean	62.4	216.7	" "		6?	25	26.4			15.5	15.8,	+3.8,	-2.5	5.7	355.3	83.9
Nunivak Is.	60.1	193.5	Cox & Doell, 1964		<1	43	33.5[1]				14.0[1],	+2.4,	-1.8			
Mt. Griggs	58.3	204.7	Stone, 1970		T-Q	5	118.8			6.7	7.4,	+4.8,	-2.1	7.0	334.8	76.2
DFB	54.0	193.1	this paper		<1	21	94.8	251.3	101.3	8.1	8.3,	+2.6,	-1.4	3.3	0.9	69.1
CCR	53.5	191.9	" "		<.16	15	115.7	54.4	153.7	7.3	7.5,	+2.5,	-1.5	3.6	6.9	70.6
NJC	53.5	191.9	" "		T-Q	19	70.3	22.9	282.6	9.4	9.7,	+2.7,	-1.7	4.0	349.8	63.4
ASH	53.5	191.9	" "		>1.9±.2	13	20.8	190.8	21.3	17.1	17.7,	+6.2,	-3.6	9.3	198.1	-81.5
KAN	51.9	182.9	" "		>.18±.09	7	136.3	57.0	239.3	6.4	6.9,	+3.6,	-1.8	5.2	355.9	65.3
RDH	51.9	182.9	" "		<0.6	14	401.4			3.9	4.0,	+1.3,	-0.8	2.0	1.1	72.2
Aleutian mean	53	188	" "		T-Q	90	56.0			10.8	10.8,	+1.2,	-1.0	2.0	359.4	70.4
Mt. Edgecumbe	57	224.3	Stone, 1970		Q	5	102.5			7.2	7.9	+5.1,	-2.2	13.8	334.6	77.5
Shemya intrusive & extr rx	52.7	174.1	Cameron & Stone, 1970		10.8-18	7	146.8			6.2	6.7,	+3.5,	-1.7	5.0	11.3	78.8
British Columbia: Caribou Reg.	51.7	233	Symons, 1969	11/17	Tmu	48	44.3				12.2,	+2.0,	-1.5	3.0	356.4	72.3
Columbia River basalts	46.5	239.5	Campbell & Runcorn, 1956	11.106	Tm	11	29				15.0,	+5.9,	-3.3	9	7	65
Columbia Plateau basalts	44.5	240.4	Watkins, 1965a	8/28	14.5-21.3	433	12.8				22.6,	+1.2,	-1.0	6.4	2.9	62.7
Oregon: Marys Peak Sill	44.5	236.4	Clark, 1969	11/24	29.6	26	13.6			21.6	21.9,	+5.1,	-3.5	8.0	21.1	39.8
Suttle Lake	44.4	238.3	Stone, unpublished		T-Q	20	907			2.6	2.7,	+0.7,	-0.5	6.3	178.1	-60.9
Abert Rim	42.6	239.8	Watkins, 1969b	8/26	~15	16	48				11.7,	+3.7,	-2.2	5	180	-52
Steens Mt.	42.6	241.3	Watkins, 1969		15	62	8.3			28.2	28.1,	+4.0,	-3.1	6.7	331.3	77.1
"Western U.S."	40	-----	Cox & Doell, 1964		<1	26[1]	37.2[1]				13.3 ,	+3.1,	-2.1			
Japan: Quat ig rx	36	138	Kumagai *et al.*, 1950	12.39	Q[4]	11	18				19.1,	+7.5,	-4.2	11	359	47
baked clays	35.7	139.8	Watanabe, 1958, 1959	12.41	historic[5]	174	17				19.6,	+1.6,	-1.4	3	356	53
historic flows	35.7	139.8	Kato & Nagata, 1953	12.40	historic	12	100				8.1	+3.0,	-1.7	4	357	46
N. Izu & Hakone rx	35	139	Nagata et al., 1957a,b	12.38	Qp-r	42	10			17.2	25.6,	+4.5,	-3.3	7	343	51
Volcanics	35	134	Sasajima *et al.*, 1968	10/40	Te-o	10	40				12.8,	+5.3,	-3.4	7.1	33	53
Usami Volc	35	139	Kono, 1968	10/12	Qp	11	33				14.0	+5.5,	-3.1	8	338	52
Yamaguchi basalt	34.5	131.5	Domen, 1960	12.37	Qp	85	18				19.1,	+2.3,	-1.8	4	0	57
Kyushu bslts, normal	33	130	Creer & Ispir, 1970		Tp	12	31.2	45.6[2]	33.5[2]		14.5,	+5.4,	-3.1		[3]	[3]
Kyushu bslts, reversed	33	130	Nomura, 1967		Tp	14	17.3	12.4[2]	19.2[2]		19.5,	+6.6	-3.9		[3]	[3]
Hawaii: five diff't is.	21.4	202	Tarling, 1965	8/5	~1.2-5.7	38	18		25		19.1,	+3.6,	-2.6	5	357	30
five series on Hawaii	20	204	Doell & Cox, 1965	8/4	0.8	112	27	198	29		15.6,	+1.6,	-1.4	2.6	5.7	31.1
Kau series	19.5	204.5	Doell, 1969	11/1	<0.01	54	479	304	610		3.7,	+0.6,	-0.4	0.9	354.8	24.1
Galapagos Islands	- 2	268	Cox & Doell, 1964		<1	21[1]	24.2[1]				16.5[1],	+5.2,	-2.9			
Samoa	-14.7	188.8	Tarling, 1966b	8/12	2	16	20		25		18.1,	+5.7,	-3.5	8	5	-32
Australia: Q'land lvas & dks	-27.0	152.2	Robertson, 1966	8/29	Tu	12	25				16.2,	+6.0,	-3.4	9	13	-49
Nandewar volc's	-30.3	152.2	Wellman *et al.*, 1969	11/20	17.5±.3	34	43.1			12.1	12.3,	+2.4,	-1.7	3.7	192.4	53.0
Liverpool volc's	-31.7	150.2	" " " "	11/22	33.4±.7	36	45.5			11.8	12.0,	+2.3,	-1.7	3.5	200.4	59.2
Barrington volc's	-32.0	151.4	" " " "	11/27	51.6±.7	33	48.5			11.4	11.6,	+2.3,	-1.7	3.6	193.0	65.5
Victoria, old volc's	-38.0	145.5	Irving & Green, 1957a,b	11.093	Te-0	15			35	13.7	13.7[6],	+4.5,	-2.7	6.8	17.0	-72.9
Victoria, new volc's	-38.0	143.5	Green & Irving, 1958	12.45	Tp-Qr	32			37	13.2	13.3[6],	+2.7,	-1.9	4.8	3.4	-59.8
Victoria	-38	143.5	McDougall *et al.*, 1966	8/9	0.5-4.5	11	56				10.8,	+4.2,	-2.4	6	350	-56
New Zealand: N. Island	-38.5	176	Cox, 1969	11.9	<0.68	22	49	322	49.9[2]		11.6,	+3.0,	-2.0	4.5	2.0	-63.1
Akaroa Volcano	-43.9	173.0	Evans, 1970		8.4-9.1	70	13.8	10.4[2]	19.4[2]	21.8	21.8	+2.9,	-2.3	4.7	177.3	54.9

TABLE 5-2

World-wide paleomagnetic statistical data from outside the Pacific region selected according to criteria described in the text.

See caption to Table 5-1 for explanation of symbols.

Notes to Table 5-2

[1] Dated by carbon-14 to the period 0-1000 A.D.

[2] Dated by carbon-14 to the period 1100 B.C. to 750 A.D.

[3] Δ_T meaned from 5 values for different series read from diagram. $\overline{D}$ and $\overline{I}$ not available.

[4] Statistics calculated from site mean statistics given in paper; several sites omitted because of large α_{95}.

[5] Historically dated from 394 B.C. to 1911 A.D.

[6] These data include some lavas from the above three entries.

TABLE 5-2

World-wide paleomagnetid data from outside the Pacific region

(cf. explanation on previous page)

Site Description	λ	ϕ	Reference	Pole No.	Age	N	Fisher Parameter			Angular St'd Dev.				α_{95}	$\bar{D}$	$\bar{I}$
							k_T,	k_ω	k_β	δ	Δ_T,	+ ε,	−ε			
Norway: Jan Mayen Lavas	71.1	351.8	Fitch *et al.*, 1965	8/3	Qr	10	52				11.2,	+4.6,	-2.5	7	340	83
Iceland: volcanics	66	336.5	Kristjansson, 1968	10/39	Te-m	60	12.9			22.5	22.6,	+3.3,	-2.5	5.3	0.5	73.0
Jökuldalur	65.3	344.8	Wensink, 1964		Tp-Qp	16	94.0			8.1	8.3,	+2.6,	-1.6	3.8	10.8	79.0
Miocene lavas	65.2	340	Hospers, 1953-54, 1955	11.108	Tm	102	7			10.7	30.6,	+3.3,	-2.7	5.5	1.5	77.8
Sweden: post-glac vrvs I	63.1	17.7	Bancroft, 1951	12.12	historic$_2^1$	46	42				12.5,	+2.1,	-1.6	3.3	357.4	73.4
post-glac vrvs II	63.1	17.7	Griffiths, 1953, 1955	12.13	historic	29	34				13.9,	+3.0,	-2.1	4	2	75
Faeroe Islands: lavas	61.8	353.0	Tarling, 1968, 1970		53-59	253	30[3]				15.8,	+1.0,	-0.9			
Scotland: Skye lvas & intr	57.4	353.7	Khan, 1960	11.012	Te-o	53	60				10.4,	+1.6,	-1.2	3	186	-60
N. Ireland: Antrim rx	55.1	353.6	Wilson, 1959	11.024	Te-o	89	18				19.1,	+2.2,	-1.8	4	188	-63
Ireland: Carren Pt.	55.1	353.9	Wilson, 1970		T	25	26.4				13.8,	+3.3,	-2.2	5.1	184.7	-54.3
British Iles: Tert ig rx	56	355	Irving, 1964	11.026	Te-o	11	123				7.3,	+2.9,	-1.6	4	6	63
Tert dykes	53.6	357.1	Dagley, 1969	11/28	Te	11	25.9			15.2	15.9,	+6.2,	-3.5	9.1	169.5	-61.4
Poland: Low Silesia[4]	51.1	15.5	Birkenmajer & Nairn, 1969	11/16	To-Qp	56	18.0			19.0	19.1,	+2.9,	-2.2	4.6	184.3	-65.6
Wżar andesite dks	49.2	20.2	Birkenmajer & Nairn, 1968	11/21	Tm	15	17.5				19.4,	+6.1,	-3.8	9.4	191.5	-73.2
Czechoslovakia: T & Q ig rx	48.5	19	Nairn, 1966	10/24	Tm-p	94	10				25.6,	+2.9,	-2.3	5	11	63
volcanics	48	21	Nairn, 1967	9/24	Tm	33	14				21.7,	+4.4,	-3.1	7	359	64
Hungary	47.5	19.3	Dagley & Ade-Hall, 1970		T	33	28			15	15.3,	+3.1,	-2.2	4.8	2.2	61.0
Germany: Gottingen volc's	51.4	9.8	Schult, 1963; Irving, 1964	11.115	Tm-p	15	14				21.6,	+7.0,	-4.3	11	184	-64
Lausitz	51	14.7	Nairn & Vollstadt, 1967	10/35	To-m	27	16				20.3,	+4.6,	-3.2	7	200	-63
Reinl. Pf. ig rx	50.6	7.5	Nairn, 1962	11.113	To-Q	22	38			9.5	13.1,	+3.4,	-2.2	5	28	62
Suevites, N. Ries	49.9	10.5	Peterson *et al.*, 1965	8/30	14.8±7.0	12	997				2.6,	+1.0,	-0.6	2	191	-60
France: Ch. des Puys, Louch	45	3	Bonhommet & Zähringer, 1969	11/4	Qr	10	193				5.8,	+2.4,	-1.3		114	57
Ch. des Puys, Bruhnes	45	3	Doell, 1970		<0.7	31	47.0	199.3	47.8		11.9,	+2.5,	-2.4	3.8	357.8	60.3
Ch. des Puys, Matuyama	45	3	Doell, 1970		>0.7	10	16.9	144.6	17.3		19.9,	+8.3,	-4.5	12.1	357.9	49.4
Plateau du Velay	45	3.8	Bobier, 1969	11/12	<2.5	28	130		49		7.1,	+1.6,	-1.1	4	9.5	58
Coiron lavas	44.6	4.6	Wensink, 1970		Tm-Qp	36	17.6				19.2,	+3.7,	-2.7	5.8	9.5	54.9
Sardinia: Logudoro lavas	40.5	8.5	Bobier & Coulon, 1970		Tm	21	40				12.8,	+4.0,	-2.2	10	328.5	43
Italy: Mt. Etna Lavas	37.7	15.0	Chevallier, 1925	12.09	historic[5]	11	50				11.5,	+4.5,	-2.5	7	356	69
Portugal: Lisbon volc's	38.8	350.8	Watkins & Richardson, 1968	10/42	Te	12	15.9	63.3	17.1		20.3,	+7.5,	-4.3	11.2	346.7	37.2
Madiera volc's	32.5	347	Watkins *et al.*, 1966b	8/19	≤Tm	29	20.9				17.7,	+3.8,	-2.7	6.0	3.5	47.5

TABLE 5-2 (Continued)

Site Description	λ	φ	Reference	Pole No.	Age	N	Fisher Parameter			δ	Angular St'd Dev.			α_{95}	$\bar{D}$	$\bar{I}$
							k_T	k_ω	k_β		Δ_T,	+ε,	−ε			
USSR:																
Georgia, volc & seds	42	43	Vekua, 1961	11.117	Te	11	10				25.6,	+10.0,	-5.6	15	356	45
Azerbardzhan	41	49	Khramov & Andreyeva, 1964	8/13	Tp	13	11.4				24.0,	+ 8.4,	-4.9	13	12	49
Turkmenian seds	39.5	55	Khramov, 1958	11.044	Tpa-o	26	10				25.6,	+ 6.0,	-4.0	9	34	44
Baku Beds	39.5	53.2	" "	12.29	Q	47	26				15.9,	+ 2.6,	-2.0	4	11	54
Apsh. & Akch. stages	39	53	" "	12.30	Tp-Qp	47	9				27.0,	+ 4.5,	-3.3	8	359	42
Algeria:																
Massif de Cavallo	32	5	Bobier & Robin, 1969	11/19	Tm	13	1381				2.2,	+ 0.8,	-0.5	2	1	54
Aden:																
volcanics	12.8	45.0	Irving & Tarling, 1961	12.42	T-Q	12	2740	52	340		1.5,	+ 0.6,	-0.3	2.7	353.1	24.0
Ethiopia:																
flood basalts	9.5	38.7	Brock et al., 1970		Te-m	20	34.9	25.8	86.4		13.7,	+ 3.8,	-2.4	5.6	7.2	7.2
Canary Islands:																
Lanzarote	29	346.5	Watkins et al., 1966a	8/18	Tm-Qr?	38	22.7				17.0,	+ 3.2,	-2.3	5.0	10.9	34.6
Gran Canaria	28	344	" " " "	8/17	Tm-Qr?	39	7.1				30.4,	+ 5.6,	-4.1	9.3	10.1	37.6
Teneriffee	28	343	" " " "	8/16	Tm-Qr?	46	14.9				21.0,	+ 3.5,	-2.6	5.6	3.4	39.8
Gomera	28	342.5	" " " "	8/15	Tm-Qr?	18	8.1				28.5,	+ 8.3,	-5.2	13.0	7.9	33.1
Hierro	28	342	" " " "	8/14	Tm-Qr?	33	17.3				19.5,	+ 3.9,	-2.8	6.2	6.9	45.6
Cape Verde Islands	16.5	336	Watkins et al., 1968	10/32	Tm	138	12.6				22.8,	+ 2.1,	-1.7	3.5	1.6	22.2
Fernando Noronha	- 3.9	327.6	Richardson & Watkins, 1967		Tm	24	9.1				26.9,	+ 6.5,	-4.4	10.4	0.8	-11.9
Réunion Is.:																
Gp. I lvas	-21	55.5	Chaumalaun, 1968	10/6	0.6-1.0	49	16.7				19.8,	+ 3.2,	-2.4	5.1	6.3	-39.2
Gp. III lvas	-21	55.5	" "	10/8	1.9-2.0	38	15.4				20.6,	+ 3.8,	-2.8	6.1	181.1	35.4
Mauritius:																
late lvas	-20.3	57.5	McDougall & Chaumalaun, 1969	11/10	0.17-0.70	13	58.4			10.1	10.6,	+ 3.7,	-2.2	5.4	359.3	-45.7
early lvas	-20.3	57.5	" " "	11/11	1.96-3.44	10	11.8			22.5	23.6,	+ 9.8,	-5.4	14.7	4.9	-45.2
older volc series	-20.3	57.5	" " "	11/13	5.26-7.88	26	11.9			23.1	23.5,	+ 5.5,	-3.7	8.5	358.3	-42.2
Tristan de Cuna & Inaccess.	-37	347	Creer, 1964	8/2	Qr	10	58				10.6,	+ 4.4,	-2.4	7.2	0	-50
Heard Is.	-53	73.5	Irving et al., 1965	8/10	T-Qr	9	42	113	53	11.2	12.5,	+ 5.6,	-2.9	8	35.3	-62
Nevada:																
Lousetown Fm	39.4	240	Heinrichs, 1967	9/11	1.1-1.9	23	14.1				21.6,	+ 5.4,	-3.6	8.4	22.7	45.3
New Mexico:																
Rio Grand	36.5	254.3	Ozima et al., 1967		3.7-4.4	14	16.6			19.2	19.9,	+ 6.7,	-4.0	10.0	351.2	47.4
Valles Caldera	35.9	253.4	Doell et al., 1969	11/8	0.43-1.37	16	26.8			15.2	15.6,	+ 4.9,	-3.0	7.3	2.9	53.3
N.Mex. & Arizona:																
lvas & seds	35.2	248.4	Kono et al., 1967	9/13	3.7-4.5	24	9				27.0,	+ 6.6,	-4.4	10	177	-51
Argentina:																
Neuq.-Mend. balt	-37.5	290	Valencio & Creer, 1968	10/21	0.45-27.6	24	16				20.3,	+ 4.9,	-3.3	8	352	-60
Neuquen lavas	-38	290	Creer, 1958	12.48	Q	58	15.4				20.6,	+ 3.0	-2.3	5.0	1	-61
Neuquen	-39	294.0	Valencio, 1965a, b		Tm-p	16	91.1			8.2	8.5,	+ 2.7,	-1.6	3.9	337.0	-59.6
basalts[6]	-37.5	290	Creer & Valencio, 1970	11/15	To-Q	18	38.8	16.4	54.2		13.0,	+ 3.8,	-2.4	6	359	-59

resulting from unusually large field excursions. This criterion tended to eliminate many papers with too small N but still large enough to be allowable by (2) above.

(4) If the mean VGP of a set of data differed from the present geographic pole by more than 40° the data were rejected on the grounds that they probably represent a large scale field excursion (with one exception from our own results which is included). Since such excursions seem to be rare, their inclusion in paleosecular variation studies could lead to abnormally high values for SV (Doell, 1970b).

(5) Only data which appeared by suitable tests to represent stable paleomagnetic results were selected. In all the more recent papers, tests such as A.F. or thermal demagnetization or storage were carried out. In many of the earlier papers, stability was indicated by such tests as divergence of the mean from the present field, the presence of reversed and normal magnetization directions approximately 180° apart, and the tightness of distribution (Irving, 1964).

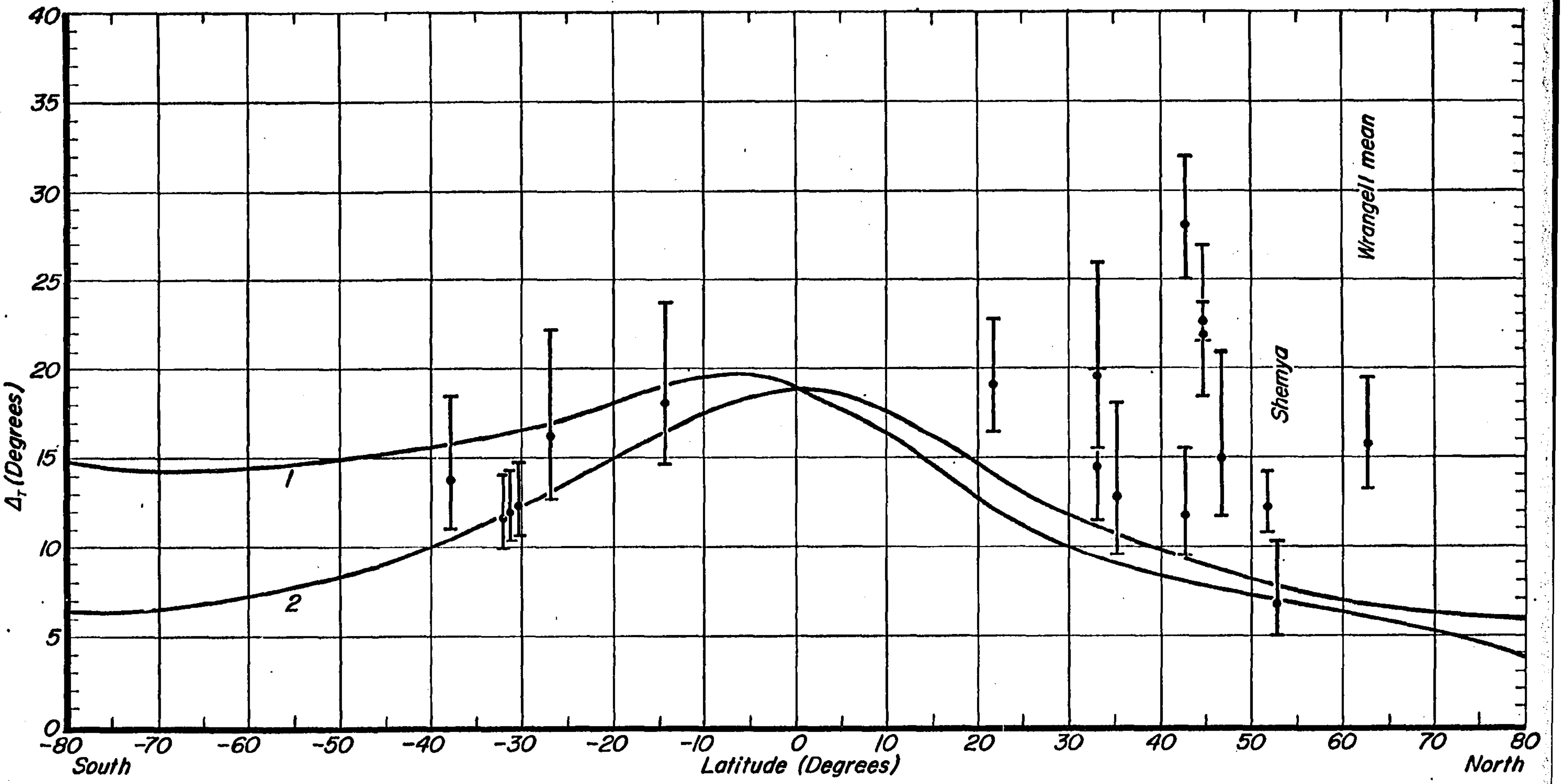
(6) For inclusion in the compilation, enough data had to be given to allow values for at least N, k_T or δ, Δ_T, α_{95}, $\overline{D}$, $\overline{I}$ to be calculated. A few exceptions were made for data of reasonable interest or reliability.

We have somewhat arbitrarily divided the results geographically into two groups: data from the Pacific region (Table 5-1) and data from outside this region (Table 5-2); the data are listed roughly according to present day geographic latitude. The Pacific region includes all Alaskan sites, Japan, the west coast of continental United States, eastern Australia, New Zealand and all the Pacific islands.

This division is admittedly artificial, as it is difficult to sharply delineate areas of 'high' and 'low' secular variation. Later we shall find that the Pacific region in which SV is low should perhaps be further restricted.

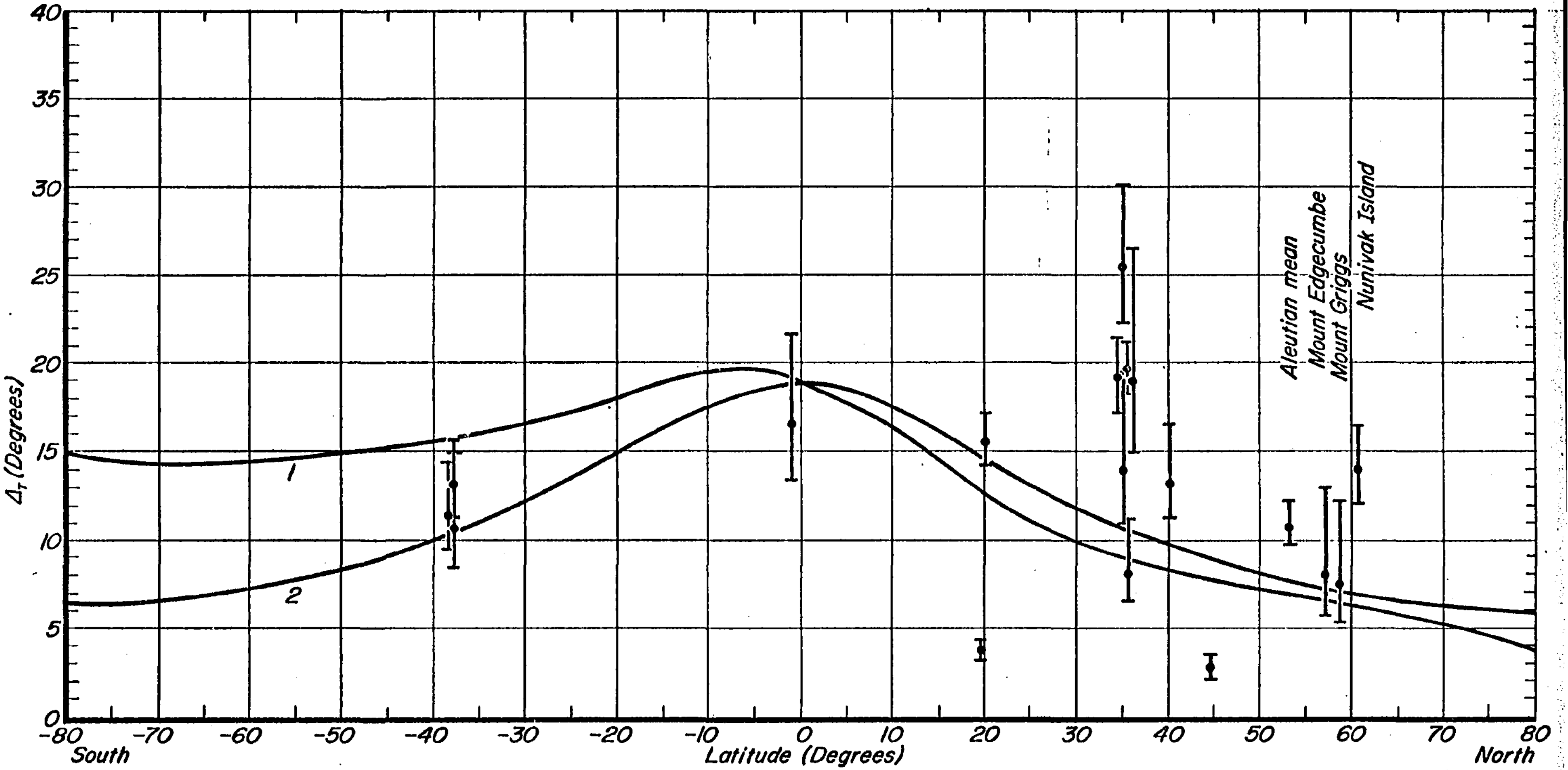
Making an additional subdivision of the data in Tables 5-1 and 5-2 according to geologic age represented, we have plotted Δ_T against present day latitude of the sampling sites (Figs. 5-4 through 5-7). (We have not plotted the Aleutian Islands sites or the Wrangell Mountains sites individually in Figures 5-4 and 5-5 but only the mean values calculated in Chapter IV and also included in Table 5-1). Due to our restriction (4) above, it was not thought worthwhile to use paleolatitudes in these diagrams; for only a very few of the points is the paleolatitude significantly different from the present day latitude and the overall picture would be changed little. Like the division into geographic regions described above, the separation of data from such widely varying sources into Tertiary and Quaternary groupings is somewhat arbitrary. Many of the dates are but poorly known as indicated by such ages as 'T-Q' in the tables. Generally we have chosen such designated ages to be Quaternary unless there seemed to be some reason to include the data with the Tertiary sites.

In an attempt to match measured paleosecular variation with different models we have also included in Figure 5-5 through 5-7 two curves from Figure 5-1 (Creer, 1962a). Curve 1 is the dispersion of the 1945.0 field and curve 2 is the dispersion of the 1945.0 best-fit dipole field.



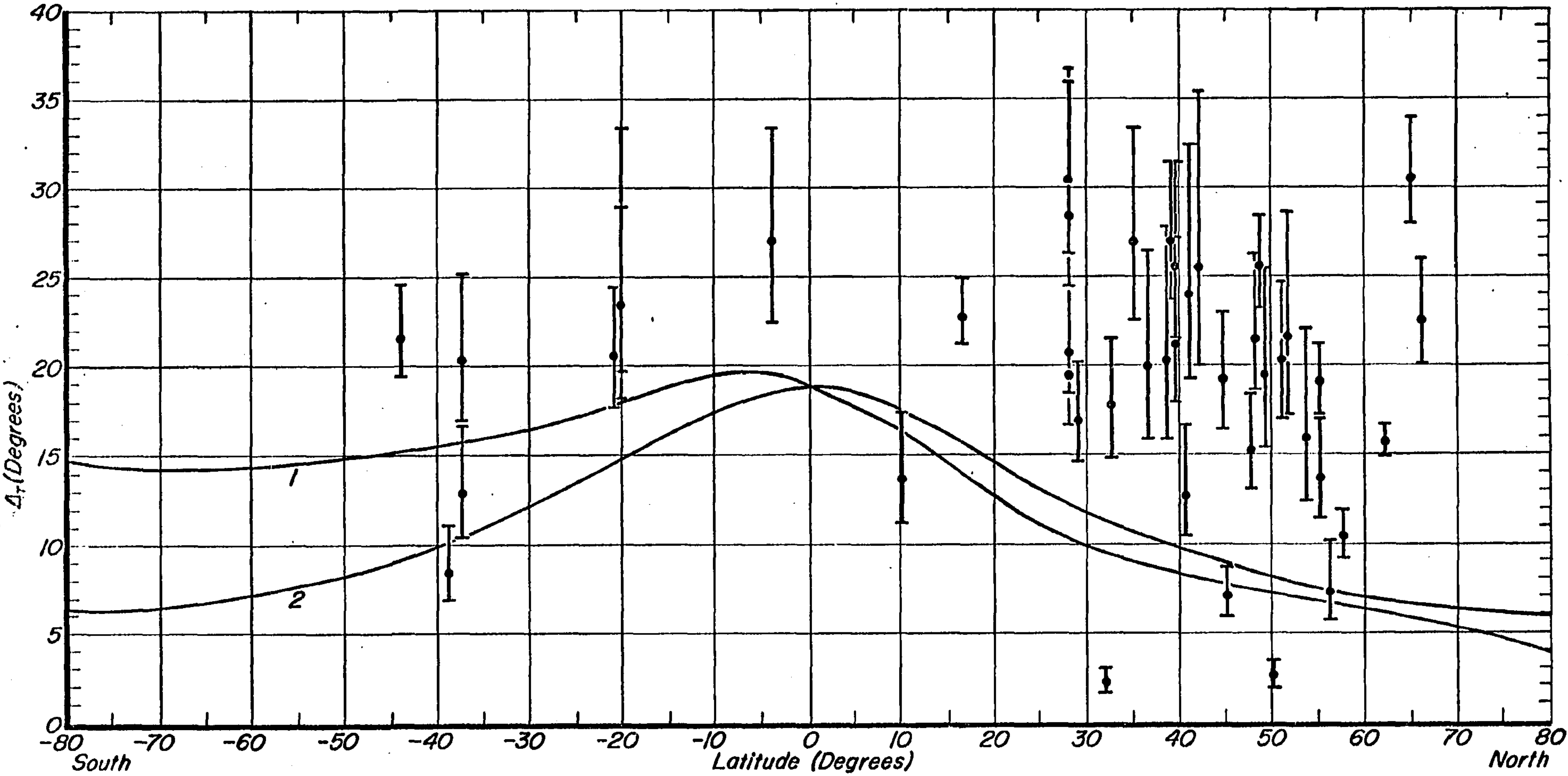
PACIFIC: TERTIARY

Figure 5-4, Tertiary paleosecular variation data for the Pacific region. Δ_T in degrees plotted against latitude. Error bars on Δ_T calculated according to Cox(1969a). Data from Table 5-1, Curves 1 and 2 from Figure 5-1. Alaskan data is indicated.



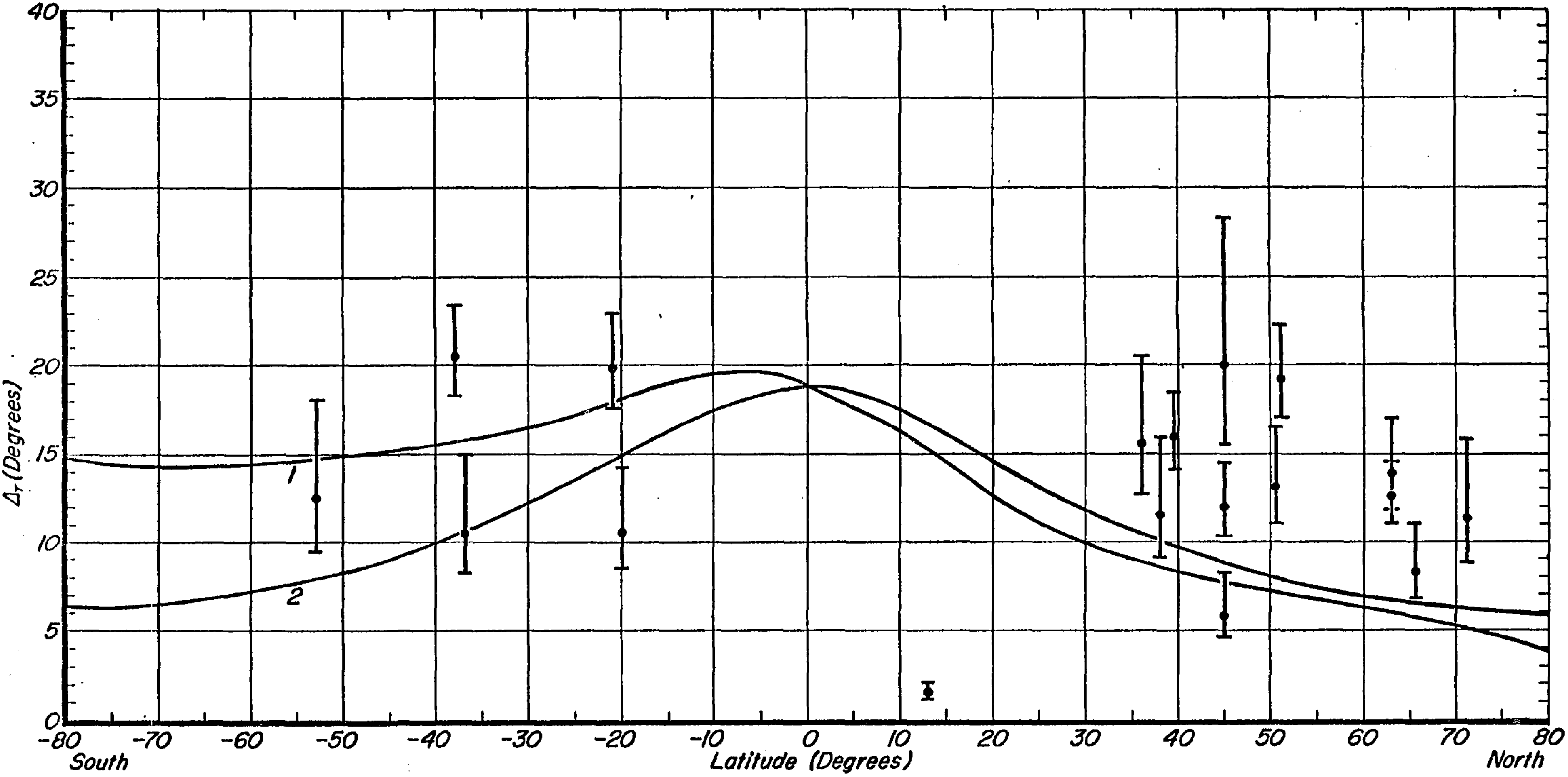
PACIFIC: QUATERNARY

Figure 5-5, Quaternary paleosecular variation data for the Pacific region. Δ_T in degrees plotted against latitude. Error bars on Δ_T calculated according to Cox(1969a). Data from Table 5-1, Curves 1 and 2 from Figure 5-1. Alaskan data is indicated.



NON-PACIFIC: TERTIARY

Figure 5-6, Tertiary paleosecular variation data from outside the Pacific region. Δ_T in degrees plotted against latitude. Error bars on Δ_T calculated according to Cox(1969a). Data from Table 5-2, Curves 1 and 2 from Figure 5-1.



NON-PACIFIC: QUATERNARY

Figure 5-7, Quaternary paleosecular variation data from outside the Pacific region. Δ_T in degrees plotted against latitude. Error bars on Δ_T calculated according to Cox(1969a). Data from Table 5-2, Curves 1 and 2 from Figure 5-1.

Discussion

Creer and Sanver (1970) have made plots of Δ_β vs. latitude for Cenozoic data similar to our Figures 5-4 through 5-7; however, they have grouped them according to normally magnetized, reversely magnetized or mixed polarity data with no geographical or temporal grouping (Fig. 5-8). They used slightly more rigid selection criteria in chosing their data and thus narrowed the literature down to 26 papers while the data in our Tables 5-1 and 5-2 represent more than three times that number of papers. The principal difference in selection criteria is that Creer and Sanver required sufficient data to be available to complete a 2 tier analysis of variance of either the Watson and Irving (1957) type (Table 3-1) or the simpler type described by equation (3-11). Thus their diagrams (Fig. 5-8) show Δ_β corresponding to our k_β using the relation (3-6) instead of Δ_T as used in Figures 5-4 through 5-7. For the purposes of this study it was felt that such a condition might be overly restrictive, and that the increase in uncertainty would not outweigh the advantage to be gained by having more data points (where available the results of 2 tier analyses have been included in Tables 5-1 and 5-2 to facilitate future studies).

Creer and Sanver (1970) conclude from their study that on a world average throughout the Cenozoic Era, SV has had about the same latitude dependence as is obtained by rotating the present (1945.0) field about the geographic axis (Creer, 1962a, b), except that the north-south asymmetry is averaged out. They find no significant difference between the reversed, normal or mixed polarity sets of data.

Figures 5-4 to 5-7 show considerable scatter of points making their interpretation difficult. Without, for the moment, making

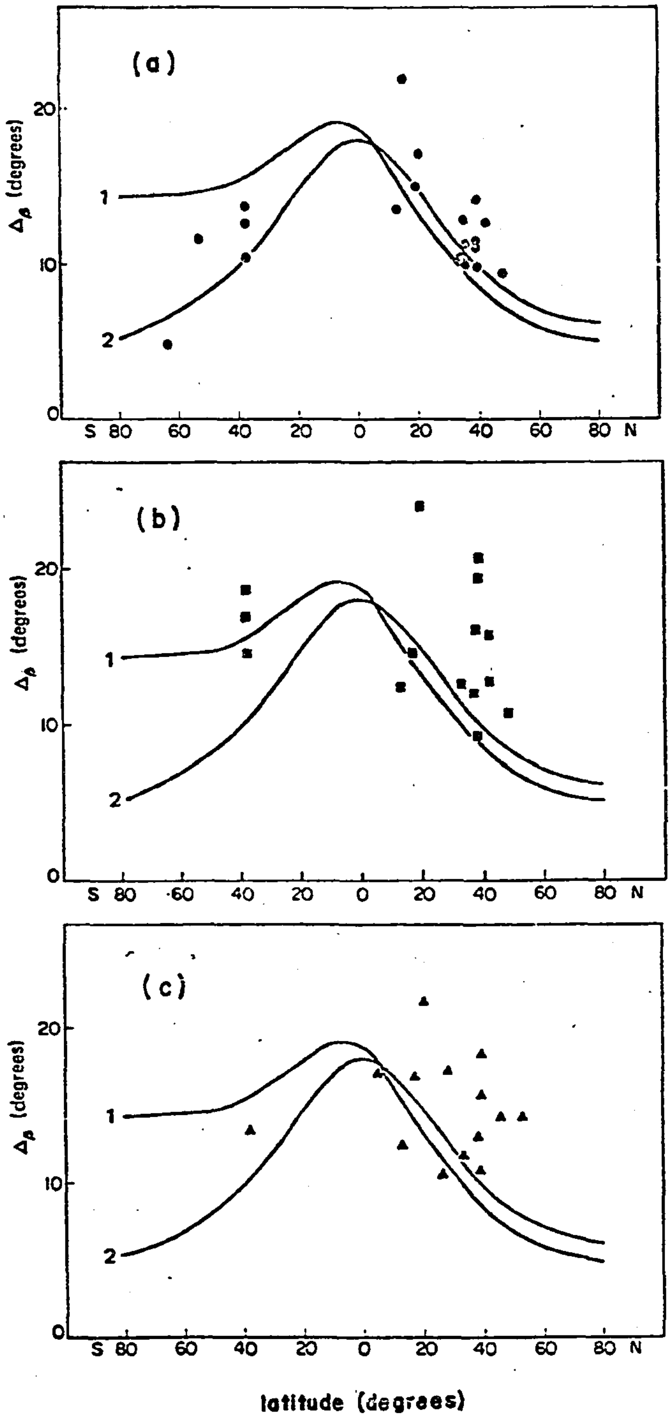


Figure 5-8. Cenozoic paleosecular variation data. Δ_β plotted against latitude for (a) normal polarity sets of data, (b) reversed polarity sets of data, and (c) mixed polarity sets of data (from Creer and Sanver, 1970). Curves 1 and 2 are from Figure 5-1.

allowances for the statistical as well as other uncertainties in the data, we shall discuss the implications of the trends displayed in these figures.

On comparing the Pacific region data with the non-Pacific region data (i.e., Fig. 5-4 with 5-6 and Fig. 5-5 with 5-7), it would appear that there has been only a very slight tendency for SV to be lower in the Pacific region than elsewhere during the Cenozoic Era. This contrast between Pacific and non-Pacific SV is clearer in the southern hemisphere where there are fewer points on all four diagrams displaying less scatter amongst themselves than in the northern hemisphere. This hemispherical difference in SV contrast may be due to having set too broad boundaries on the Pacific region in the northern hemisphere (cf. below).

It is also possible to discern, using a little imagination, a somewhat greater tendency for smaller Pacific area SV during the Tertiary than during the Quaternary, though given the probable errors involved, this difference is not thought to be significant.

If one mentally combines the Pacific and non-Pacific data for the Tertiary (Figs. 5-4 and 5-6) and for the Quaternary (Figs. 5-5 and 5-7), it appears that, taking a global average, secular variation has had a nearly constant distribution during the Cenozoic Era. However, the Wrangell Mountains area data indicates a greater number of field excursions during Tertiary times than is observed elsewhere during Tertiary or Quaternary time (Chap. IV). It is, however, unwise to draw conclusions about world wide SV from findings at a single site.

It is possible that for the purposes of this analysis we should redefine the boundaries of the Pacific region so as to exclude some of the surrounding continental margins. From Table 5-1 and Figures 5-4 and

5-5 it is clear that the highest SV values for the Quaternary in the Pacific region are for sites in Japan and for the Tertiary period for sites in western North America as well as Japan (Fig. 5-4). SV data for the Alaskan mainland for both periods does not appear to be significantly lower than for the non-Pacific hemisphere with the exception of Quaternary sites, Mounts Griggs and Edgecumbe; however, for both of these sites the data are based on statistically rather small numbers of 'spot readings' of the paleo-field (Chaps. II - IV).

For the Aleutian SV data, both the Quaternary mean (Fig. 5-5) and especially the Tertiary value for Shemya (Fig. 5-4), appear significantly less than non-Pacific area data at corresponding latitudes. If one looks at the original site mean data for the Aleutians (Table 5-I and Chap. IV) one finds that most of the data fall considerably below the Aleutian mean figure. If one ignores the possibilities of too rapid lava flow accumulations at some of these sites, as referred to in Chapter IV, and assumes that the data from these sites better represents true SV than was previously accepted, the case is strengthened for the Aleutian Islands representing part of the region of low paleosecular variation centered on the Pacific Ocean during Quaternary times. Likewise the Shemya data, though based on only seven intrusions, may be more reliable than previously suggested, because reversed data are also included and it clearly represents at least several thousand years. Thus perhaps during Tertiary times as well we should consider the Aleutians to have been part of the SV low in the Pacific region.

If the above changes are made in Figures 5-4 through 5-7 the low SV in the Pacific region becomes much more pronounced than previously; the north south difference in Pacific - non-Pacific SV contrast is also reduced. However, so few data points are left in the Pacific region after doing this that the significance of the conclusion becomes doubtful.

It is also interesting to note that, contrary to present day secular variation which is generally greater in the southern hemisphere (Creer, 1962a, b; Cox 1962; Cox and Doell, 1964; and others; cf. also curve 1 in Figs. 5-1, 5-4 through 5-8), all of Figures 5-4 through 5-7 and especially those showing SV in the Pacific region (Figs. 5-4 and 5-5), indicate that the reverse asymmetry has existed in the past - i.e. that secular variation has been stronger in the northern hemisphere than in the southern hemisphere. This relation is also just detectable in Creer and Sanver's (1970) diagrams (Fig. 5-8).

Curve 2 shown on Figures 5-4 through 5-8 as well as in Figure 5-1 is the dispersion obtained by rotating the 1945.0 best fit dipole about the geographic axis (Creer, 1962) and therefore represents approximately the contribution to SV from dipole wobble alone. If we accept Creer's (1962a, b) field rotation model and assume that the present inclination of the dipole away from the geographic axis is indicative of past dipole wobble then deviation upwards from curve 2 represent the effects of non-dipole components of SV (apart from the not insignificant part of these deviations due to errors and sampling uncertainties). However, the points are too scattered on all the diagrams to be able to progress very far in calculating the relative amounts of SV due to dipole wobble and to non-dipole components, let alone to determine their variation with time or location on the earth.

We have not attempted in our analysis of the time variation of SV to carry the study further back than the Tertiary period. As older and older rocks are sampled the problems of magnetic stability, local, regional or global tectonics, thermal events and other problems multiply to such an extent that it was believed the additional uncertainties introduced in the data would render analyses of this type almost completely meaningless. The only attempts at studying the distribution of paleosecular variation for periods earlier than Cenozoic known to the author are Gough _et al_., (1964) and McElhinny _et al_. (1968). Both these papers present African data from Precambrian to Tertiary times; the latitude dependence (in this case paleo latitude) of SV seems to be similar to today and there appears to be no significant change in SV over geologic time. If these deductions are valid, then we must conclude that there have been no gross changes in the processes which produce SV occurring in the core, and therefore probably no changes in core-lower mantle structure since the Precambrian; such a conclusion has obvious implications in theories of the history of the internal structure of the earth. However, a more complete survey of world wide early SV data is needed before much confidence can be placed in such statements.

Conclusions

Considering the limitations caused by the uncertainties of the paleomagnetic method of determining paleosecular variation at any given site (Chap. II), and the great variation in reliability of data due to both different techniques employed by different workers and to the necessary variations in the local geology of the sampling sites, it is exceedingly difficult to arrive at any firm conclusions, or even to ascertain confidence limits on tentative deductions based on these data.

There is no statistical scheme which allows one to determine the degree of confidence to place in conclusions drawn from such a variety of data; thus we can not, for instance, run a 1, 5 or even a 50% F-ratio test on our conclusions to determine if they could be arrived at by chance.

With the above comments in mind we may draw the following tentative general conclusions:

(1) Excluding the west coast of North America, mainland Alaska and Japan from the Pacific region, Cenozoic secular variation has been somewhat less in this region than elsewhere on the globe.

(2) The Aleutian Island chain should be included in the region of low secular variation which is centered on the Pacific Ocean.

(3) The contrast in SV between the Pacific and non-Pacific regions of the earth was slightly greater during Tertiary than Quaternary time.

(4) The present north-south asymmetry with respect to SV was reversed during most of Cenozoic time.

(5) World-wide secular variation has been approximately constant during the Cenozoic Era.

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