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TITLE OF THESIS/TITRE DE LA THÈSE Original Strike and Latitude of Dykes and Their Bearing on the
State of Stress in the Lithosphere
UNIVERSITY/UNIVERSITÉ Carleton
DEGREE FOR WHICH THESIS WAS PRESENTED/
GRADE POUR LEQUEL CETTE THÈSE FUT PRÉSENTÉE M.Sc.
YEAR THIS DEGREE CONFERRED/ANNÉE D'OBTENTION DE CE DEGRÉ 1979
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ORIGINAL STRIKE AND LATITUDE OF DYKES AND THEIR
BEARING ON THE STATE OF STRESS IN THE LITHOSPHERE

by

© Elizabeth I. Tanczyk, B.Sc.

A thesis submitted to the Faculty of
Graduate Studies and Research in partial fulfilment
of the requirements for the degree of
Master of Science

Department of Geology
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Ottawa, Ontario
1979

The undersigned hereby recommend to the Faculty of Graduate Studies and Research acceptance of this thesis, submitted by Elizabeth I. Tanczyk, B.Sc., in partial fulfilment of the requirements for the degree of Master of Science.

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ABSTRACT

A study of original strikes and latitudes of major dyke swarms has shown non-uniform strike distributions throughout some intervals in the Earth's history. The dyke latitudes, however, show no deviation from a uniform pattern.

The original orientations and latitudes (referred to as paleoazimuths and paleolatitudes) were obtained from paleomagnetic remanent directions measured on the dyke rock. A semi-quantitative filtering scheme was applied to all available paleomagnetic data on dykes in order to weight more heavily the results from the largest and best studied swarms.

Paleoazimuths were observed to occur predominantly in the north-south direction. This pattern was clearly prominent before 1300 Ma and less markedly in the last 190 Ma. The preferred orientation of this last period is thought to reflect the latest episode of lithospheric rifting. Between 1300 and 190 Ma paleoazimuths appear to be randomly distributed.

The absence of a preferred paleolatitude indicates that dyke intrusion occurred with relative uniformity with respect to latitude. However, the presence of a global stress field characterized by overall east-west deviatoric tension is implied for the time intervals in which the dyke paleoazimuths show a predominant north-south orientation. Such a stress field could conceivably be caused by the Earth's ellipticity.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the supervision and support of Dr. G. Ranalli (Department of Geology, Carleton University) in the progress of this work, as well as his active involvement and encouragement throughout the course of the author's graduate studies. The supervision of Dr. E. Irving (Earth Physics Branch, EMR) is gratefully acknowledged; his guidance on aspects of paleomagnetism was of crucial importance. A special thanks is extended to Dr. W. A. Morris (Morris Magnetics), whose participation and advice assisted greatly in the formulation of the problem here investigated. The author also wishes to thank Dr. J. Blenkinsop (Department of Geology, Carleton University) for a thorough critical appraisal and proof-reading of the manuscript.

Financial aid by the Department of Geology and the Faculty of Graduate Studies and Research is greatly appreciated.

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Chapter 1. INTRODUCTION

The purpose of this work is to search for clues about the rheology and stress patterns of the Earth's lithosphere throughout geologic history through the analysis of paleomagnetic data on dykes. Large tectonic features owe their origin to large-scale stress systems (Turcotte and Oxburgh, 1976); the orientation of the principal stresses, σ_1 , σ_2 and σ_3 can often be deduced by analysing such features. Here σ_1 and σ_3 are the maximum and minimum normal compressive stresses, respectively. Thus σ_3 is equivalent to the direction of relative deviatoric tension. Following the convention generally used in geology, compression is considered positive.

1.1 The Use of Dykes as Stress Indicators

Dykes of all ages and from all parts of the world were selected as a source of information about the stress systems under which they were intruded. The study is limited to continental areas and can therefore be expected to yield information on the state of stress in the continental lithosphere. Dykes are planar intrusions, usually basic in composition, and are almost without exception vertical with respect to the Earth's surface (Evans, 1968). In outcrop they appear as linear features, and most commonly occur in swarms. A few cases of huge single dykes have also been recorded, such as the Foum Zguid dyke in Morocco (Hallwood and Mitchell, 1971).

The commonly observed parallelism of contemporaneous dykes within large swarms indicates that the state of stress remains relatively invariable over large areas for a given time interval. Only comparatively

few dyke swarms are distinctly radial about intrusive or volcanic centres (Larson and Strangway, 1969). Dykes tend to exhibit linear trends even when genetically linked with volcanic activity, as for instance the linear dyke swarm of Mull, which transects the Tertiary Mull volcano (Mussett et al., 1972). The persistence of linear trends implies that large-scale stress fields control the mechanism of dyke formation. An analysis of the orientations of dykes may therefore clarify tectonic stress patterns. A consistent preferred orientation through time of all world dykes would suggest that such a preferred direction of intrusion is related to a global process. A variation in orientation of intrusion of dykes through geologic history may imply that either the global stress field or the behaviour of the lithosphere changed with time. It is of course possible that dyke orientations are controlled by stress systems related to individual plates, in which case a global analysis is not sufficient. Here the working hypothesis is that dyke intrusion patterns are related to global stress fields.

1.2. Mechanics of Dyke Intrusion

Dykes can be formed in various orientations with respect to the principal stress axes. A literature survey shows that in the majority of cases (about 90%) dyke intrusion is associated with tensional fractures. In the sequel, these will be referred to as tensional dykes. Tension can be produced either by the wedging effect of a magma under high pressure, which exceeds the pressure of the surrounding rock mass (Anderson, 1951), or by the lithosphere itself being in a state of tension, such as that observed at ocean ridges (Forsyth and Uyeda, 1975).

In the classical concept, the propagation of tensional fractures occurs parallel to the maximum principal stress, σ_1 , and perpendicular to the minimum principal stress, σ_3 . If σ_1 and σ_3 are in the horizontal plane, the intermediate principal stress is vertical, and lies in the plane of the tensional fractures. The dykes, therefore, form parallel to σ_1 and perpendicular to σ_3 (Figure 1.1a; see Verhoogen et al., 1970); vertical dykes are compatible with this stress system.

Tensional fractures can also occur at an angle to σ_1 . This phenomenon was observed in uniaxial tension experiments with isotropic flat metal bars and has been studied by Bijlaard (Nadai, 1950). The application of tension can produce either a fracture normal to the direction of tension or at an angle of ca. 35° to the normal (Figure 1.1b). The angular relationship between the fracture and the direction normal to the tension axis is dependent on the ratio of the width of the metal bar to its thickness. The higher this ratio is, the greater the possibility of fracture in an oblique direction. The direction of the oblique fracture is also strongly influenced by any anisotropy in the deforming material.

A further complication of the origin of dyke orientations is the existence of a small percentage of dykes, the orientation of which seems to be that of shear fractures; these will be referred to as shear dykes. The presence of apophyses and intra-dyke fabrics that have no equivalents in the country rock would indicate that shearing took place during dyke emplacement (Escher, Jack and Watterson, 1976). The orientation of such dykes is representative of the approximate direction of maximum shear (modified for internal friction) at the time of intrusion. If no shear features can be detected in the dyke fabric, the intrusion may have occurred after

Figure 1.1: Possible Orientations of Tensional Fractures

1.1a: Parallel to σ_1

1.1b: Oblique Fracture

the faulting, and the dyke may have been deflected along the fault plane. Thus, dyke orientation in some instances does not reflect the stress field at the time of emplacement. A dyke may also be intruded prior to the shearing and be deformed at a later time.

An attempt was made in this work to distinguish between dykes formed by tension and by shear, though the distinction can occasionally be very unclear; the problems just discussed can only rarely be resolved in the field. Shear dykes are a small part of the available data and do not significantly affect the results. Because of the dispersion of angles in which dykes may be intruded with respect to a given stress system, preferred orientations will not be sharply defined, but rather diffuse, thus reflecting the scatter in possible angles of tension.

1.3 Determination of Paleoazimuths

The dyke strike that is required for the analysis is the azimuth at the time of intrusion, and not the azimuth as measured at present. Most dykes of pre-Neogene age have had their original orientations significantly disturbed relative to the geographic frame by movements of lithospheric plates. Paleomagnetic results may be used to determine the original strike. Therefore, only those dykes for which paleomagnetic data were available are used. The original orientation of the dyke (referred to as the paleoazimuth A) is given by

$$A = S - D, \quad (1.1)$$

where S is the present strike and D the declination of the remanent magnetization. D gives the north (or south) direction of the field at the time of intrusion. It is the angle between present north and north at the time when the remanent magnetization was recorded (Irving, 1964).

The determination of paleoazimuths from equation 1.1 hinges on the basic assumption of paleomagnetism (Irving, 1964), that remanent magnetization is imposed by a geocentric axial dipole field. It is also assumed that the primary magnetization represents the ambient field at the time of dyke intrusion, unless there is evidence to the contrary. Chapter 2 discusses the validity of this assumption. Estimates of A are subject to error because of statistical errors in the paleomagnetic measurements and in the strike of the dykes (see Chapter 4). However, the use of equation 1.1 is adequate, as a coarse resolution into 20° intervals is used in the paleoazimuth analysis.

Chapter 2. PREVIOUS WORK

2.1 Internal Demagnetizing Field of Dykes

The tendency of the remanent magnetization of dykes to fall close to the dyke plane was first commented upon by Strangway (1961 and 1964). The consistent coincidence of the direction of the ambient field with the orientation of the intrusions required an explanation. In theory, an internal demagnetizing field, H_{dem} , could be set up inside a magnetic sheet. H_{dem} would be normal to the plane of the dyke and would tend to cancel out the normal component of the external field, H_{ext} . Thus the component of H_{ext} which was closest to the dyke plane would be preferentially recorded in a stable magnetization, and would give a false impression of the dyke having been intruded close to the north-south orientation. This was the explanation proposed by Strangway.

The theory of internal demagnetization cast doubt on the reliability of paleomagnetic measurements from dykes, as it implied that they are not accurate records of the paleomagnetic field. Subsequent studies were undertaken to determine whether the demagnetizing field (H_{dem}) was significant on the geological scale. A physical argument against Strangway's mechanism is that the high susceptibility required to induce the stable component is not commonly observed (Irving, E., personal communication, June, 1979). Magnetic susceptibility for a weak field is defined by χ in the equation

$$J_1 = \chi F_1 \quad (2.1)$$

where J_1 is the magnetization induced by the field F_1 (Irving, 1964).

A further argument against Strangway's proposed mechanism is the observed abundance of positive contact tests. Many paleomagnetic studies include measurements on the contact rock, where the magnetization in the host rock heated in the vicinity of the intrusion has been reset and is now in agreement with the directions from the dyke. Though the Curie temperature of the host rock may have been exceeded, the rock has not been part of the molten sheet. Dykes accompanied by positive contact tests (that is, where the remanent magnetizations in the dyke and in the host rock agree) may safely be taken to yield directions of the true field at the time of intrusion. Examples of positive contact tests between the dyke rock and the baked contacts, such as in the Abitibi swarm (Irving and Naldrett, 1977), and the Indin swarm (McGlynn and Irving, 1975), are abundant in the literature.

In many cases a contact test is impossible to perform due to the unsuitability of the contact rock for magnetic measurements. An example is the contact between the Sudbury dykes and the Huronian sediments (Palmer, Merz and Hayatsu, 1977). If the test is attempted on magnetically weak or unstable contacts, the results are often inconclusive, such as those for the Dogrib dykes (McGlynn and Irving, 1975). The magnetic interaction between intrusives and the surrounding rocks is not yet understood in sufficient detail, and inconclusive tests are common (e.g. Park, 1974).

2.2 Probability Distribution of Angle β

Evans (1968) reasoned that the relationship between the dyke plane and the direction of magnetization can be a consequence of the Earth's

geometry. He showed that, given a random areal distribution and orientation of dykes over the Earth's surface, there will be a strong probability for the dyke plane and the magnetization direction to be spatially related. The reason for this lies in the variation of β , the angle between the remanence vector and the plane of the dyke. The orientation of the remanence vector is defined by declination D and the inclination I , as shown in Figure 2.1a (Irving, 1964). Evans assumed that the majority of dykes are vertical, and the literature search carried out for the present work supports this assumption fully. It is obvious from Figure 2.1b that β is a function of I and A , the latter being the paleoazimuth defined by equation 1.1. The angle β will remain small if i) A is small, ii) I is large. The only way a large β can be produced is by the combination of a large A and a small I , i.e. by intruding a dyke near the magnetic equator and in an east-west orientation; thus large β 's are comparatively rare. Trigonometrically β can be expressed as

$$\beta = \sin^{-1} (\cos I \sin A) \quad (\text{Evans, 1968}) \quad (2.2)$$

I can be converted to paleolatitude by the relationship

$$I = \tan^{-1} (2 \tan \lambda) \quad (\text{Irving, 1964}) \quad (2.3)$$

Substituting for I in 2.2 gives

$$\beta = \sin^{-1} [\cos [\tan^{-1} (2 \tan \lambda)] \sin A] \quad (2.4)$$

Varying A and λ together produces a probability distribution for the values of β . Figure 2.2 shows the total sample space for β as plotted by Evans. (The paleoazimuth A is denoted by δ in his diagram). Evans compared observations to his model and concluded that the abundance of

Figure 2.1: Geometric Relationships

2.1a: Remanence Vector R (After Irving, 1964) 2.1b: Angle δ (After Evans, 1968)

- N = Present north pole
- P = Paleomagnetic pole
- C = Centre of the Earth
- S = Sampling locality
- D = Declination
- I = Inclination
- δ = Dyke paleoazimuth

Figure 2.2: Total Sample Space for β for Vertical Dykes;
Curves of Constant β are shown. (After Evans, 1968).

Figure 2.3: Paleozoic Paleozoic Paleozoic Paleozoic Paleozoic
(After Morris and Tanczyk, 1978)

cases in which the remanence vector is close to the dyke plane can be explained by the probability distribution of β .

2.3 Preferred Dyke Paleoazimuths

Both Strangway and Evans have dealt with the relationship between the remanence vector R and the dyke plane. As β is a function of both λ and A , it cannot be directly used to account for preferred orientations in dyke paleoazimuths. A study by Morris and Tanczyk (1978) has revealed a strong north-south preferred orientation in the paleoazimuths of Precambrian dykes (Figure 2.3). Thus, a preferred orientation of dykes may be real, and requires further investigation. In the work by Morris and Tanczyk, all data were assigned equal weight, regardless of whether the paleomagnetic measurements were done on a small dyke or on a large swarm. About 50% of the $0^\circ - 10^\circ$ peak in Figure 2.3 is due to single dyke determinations. The present work deals separately with the two variables A and λ , and is based on a more extensive data search and a more refined data set. Dykes of all ages are included, subdivided into three time intervals, and their latitudes of intrusion as well as strikes are examined. Also, an attempt is made to put data into their proper perspective by emphasizing large-scale structures, i.e. the average paleoazimuths and paleolatitudes of extensive dyke swarms.

Chapter 3. PROCEDURE

3.1 Data Collecting

A search for all available paleomagnetic results on dyke swarms has been carried out. The essential information drawn from the references included the results of the paleomagnetic study, and all relevant geological information such as strike, size of swarm and apparent mechanism of intrusion (tensional or shear). In an attempt to assess the problem in a consistent and semi-quantitative way a weighting scheme was used.

When the data included several studies by the same author on the same dyke swarm, the latest results were normally used (e.g. Larochelle, 1966). Where different workers studied the same area and where the paleomagnetic results were in close agreement, the most extensive study was accepted (e.g. Palmer, Merz and Hayatsu, 1977). Where two results on the same area were in disagreement, both were accepted, because the disagreement may mean that there was more than one episode of dyke intrusion present (e.g. Poorter, 1972, Storetvedt and Gidskehaug, 1968).

If the strike direction of a swarm was not known, the datum could be used only for the calculation of paleolatitude. An approximate strike mentioned in the original reference was accepted if a map was unavailable (e.g. Hargraves, 1968). Where possible, the present orientation of the dykes was measured from maps in the original. If sampling localities were shown on the map, an attempt was made to average the strike over the paleomagnetically studied area. Swarms may consist of dykes of different ages and thus have different remanent directions.

Thus it is more accurate to average the strikes of only those dykes which were sampled. Where this was impossible because of incomplete reporting of results in the original, the strikes were averaged over the entire swarm. All strike directions were recorded in cases where more than one distinct direction could be singled out. If it was not clear which strikes corresponded to which paleomagnetic data (e.g. Verma and Prasad, 1974), the study could not be used for calculating paleoazimuths.

3.2 Site Average D, I

The mean paleomagnetic direction (D, I) for a dyke swarm is the average of the individual directions from the sampling sites. In most cases there was no need to refine the given (D, I) average, but in some instances it had to be computed from the site directions listed in originals. This was done if;

- . . . an average was not given in the original;
- . . . the study included many coeval formations; an average (D, I) for dykes only has been calculated;
- . . . there were several strike directions; a mean direction has been obtained for each set;
- . . . the author's average contained intermediate directions, which recorded the transitional field during a reversal.

An example of intermediate directions can be found in the study of the Mull swarm by Ade-Hall et al, (1972). Such directions are irrelevant to this work, as they do not satisfy the assumption of D relating to the true paleomagnetic north and I relating to the true paleolatitude in reference to the geocentric axial dipole.

The average (D, I) is an estimated mean direction for the dyke swarm. A measure of the reliability of this estimate is required. By Fisher statistics (Irving, 1964) the true mean of a set of averaged directions will lie within a circular cone whose axis is the estimated mean (D, I) . The semivertical angle of the cone is the measure of the confidence limit of the estimated mean, and is defined as:

$$\alpha_{(1-p)} = \cos^{-1} \left[1 - \frac{N - R}{R} \left[\left(\frac{1}{p} \right)^{\frac{1}{N-1}} - 1 \right] \right] \quad (3.1)$$

where α = semivertical angle

$(1-p)$ = confidence level

N = number of individual directions,

and R is defined as:

$$R = \sum_{n=1}^N l_i^2 + \sum_{n=1}^N m_i^2 + \sum_{n=1}^N n_i^2 \quad (3.2)$$

where l_i , m_i and n_i are the direction cosines of the individual directions.

The confidence level is usually taken as 95% and $\alpha_{(1-p)}$ is known throughout the literature as α_{95} .

3.3 Weighting Scheme

The notes abstracted from the original were coded on specially designed data sheets. An example is given in Table 3.1. It is headed with the name of the dyke swarm or the dyke locality, and bibliographic references. The basic data are grouped in the "Data" block, containing D , I , α_{95} , S the present strike, ϕ the present latitude, t the age of the dyke intrusion, A the paleoazimuth calculated from equation 1.1, λ the paleolatitude calculated from equation 2.3 and δ calculated from equation 2.4.

Table 3.1 Sample Data Sheet

Name:					Reference:			
DATA								
D°	I°	α_{95}	S°	ϕ°	t (Ma)	A°	λ°	β°
GENERAL WEIGHTING								
GEOLOGICAL				PALEOMAGNETIC				
SWARM EXTENT	ΔS			SAMPLING EXTENT	ΔD		ΔP	
3, 2 or 1	2, 1 or 0			3, 2 or 1	2 1 or 0		2, 1 or 0	
SPECIAL WEIGHTING								
GEOLOGICAL					PALEOMAGNETIC			
MECHANICS: 2, 1 or 0					REMAGNETIZATION: 2 or 0			
$\Delta\phi$: 1 or 0								
Δt : 1 or 0								
COMPOSITION: 1 or 0					CONTACT TEST: 1 or 0			
DYKE%: 2, 1 or 0								
FILTERS								
F_1 :		F_2 :		F_3 :		F_4 :		

The weighting factors are divided into "General Weighting" and "Special Weighting". The former is a set of parameters applicable to all dyke swarms. The latter consists of factors that did not apply to the majority of dyke swarms, but could not be ignored in particular cases. Four filters were calculated in different ways from this weighting scheme, and were used in an attempt to separate the reliable data from the less reliable. Filters F_1 and F_2 are derived from "General Weighting" factors, F_3 and F_4 from "Special Weighting" factors. Filters F_1 and F_3 evaluate the errors in A , and were used for plotting the paleoazimuths. Filters F_2 and F_4 evaluate the errors in λ , and were used for plotting the paleolatitudes. The following three chapters discuss the general and special weighting schemes and the four filters in more detail.

Chapter 4. GENERAL WEIGHTING FACTORS

4.1 Swarm Extent

As the interest of this work is in large-scale stress fields, large dyke swarms are weighted more than small ones, since they are less likely to be related to local perturbations of the stress field. A swarm covering 50 km^2 or more was considered large and assigned a weight of 3, the maximum value for this weighting factor. A swarm that covered an area of 20 to 50 km^2 was considered intermediate and assigned a weight of 2. A small swarm of less than 20 km^2 was given unit weight. Ideally it would have been more correct to calculate the total area of each swarm. It was not always possible to determine the exact areal extent of the swarm, and an educated guess often had to be made. A further problem arises because of the variable density of dykes. For example, a few dykes scattered over 40 km^2 could be considered small, whereas a single dyke with a length of several hundred kilometers could be considered large. Despite these and other possible uncertainties, the classification of "Swarm Extent" into three categories, as a first order approximation, can be reasonably considered as representing the scale of the tectonic events.

4.2 Strike Error ΔS Associated with Measuring S

The error ΔS involved in estimating S is probably one of the largest errors in this work. The problem lies in the fact that very rarely are most dykes in the same swarm exactly parallel. ΔS was given the maximum weight of 2 if the variation in large-scale strike according to published maps was $\pm 5^\circ$. It was given unit weight if the variation was $\pm 10^\circ$. If

the $\pm 10^\circ$ limit was exceeded, zero weight was assigned, the strikes were considered to be too scattered, and the datum was not therefore used for calculating a paleoazimuth. If the strike is not shown on a map but only given in the text, ΔS was assigned a value of 1: it is presumed that the strike was well enough defined for the author to have measured to an accuracy better than $\pm 10^\circ$.

Intruding dykes tend to follow zones of weakness, and their strikes may be scattered on a local scale, even though the trend of the whole system may be distinct. Such local deviations were intentionally overlooked, as they were not considered representative of the overall trend of the swarm that was sampled.

4.3 Sampling Extent

The number of sampling sites for paleomagnetic measurements is critical in the calculation of the remanent directions. According to equation 3.1 the dependability of the results decreases with a decreasing number of sites. A paleomagnetic average based on 10 or more sites was considered fairly reliable (Irving, Tanczyk and Hastie, 1976). When this was the case, the sampling extent was weighted at 3. When the number of sites was between 5 and 9, a weight of 2 was given, and when there were fewer than 5 sites, unit weight was assigned.

The sampling extent is not necessarily a simple function of the swarm extent - a large swarm could have been poorly sampled, or a small swarm intensively sampled. "Extent" factors comprise 6 out of the 10 points composing filters F_1 and F_2 . They are heavily weighted, because the first (swarm extent) represents the area affected by dyke injection, and

the second (sampling extent) represents the significance of the paleomagnetic result, on the basis of which A and λ are calculated.

The sampling extent is equated to the swarm extent in the special case where a large swarm was covered by sampling sites belonging to separate studies. An example is the Coast Parallel dykes in Greenland (Ketelaar, 1963, Piper, 1975 and Fahrig and Freda, 1975). If the swarm extent was repeatedly classified as "large" for each study, over-weighting could result. For this reason if the entire swarm was studied, each sampling area is treated as if it were a separate swarm.

4.4 Declination Error ΔD and Inclination Error ΔP

The Fisher statistic α_{95} is a measure of the uncertainty in the mean remanence vector R . As in this work D and I were used separately to calculate A and λ , it is appropriate to use separate errors for D and I , which can be derived from α_{95} . These are the standard errors in declination and inclination, ΔD and ΔP , respectively, which at the 63% confidence level are defined as (Irving, 1964)

$$\Delta D = \frac{\alpha_{95} \sec I}{2}, \text{ and} \quad (4.1)$$

$$\Delta P = \frac{\alpha_{95} [1 - 3 \cos^2 (90 - |\lambda|)]}{4} \quad (4.2)$$

The distinction between the two errors is necessary because the error in declination is related to the inclination. The spherical geometry of the Earth causes the declination to become less well defined towards the paleomagnetic pole. The steeper is the inclination, the greater is the error in declination.

With a low number of sites, α_{95} tends to be high despite the fact

that the individual paleomagnetic measurements obtained from the sites could be in very close agreement. To take this into account, ΔD and ΔP are weighted in the following way, allowing some flexibility for the number of sites which composed the average:

Table 4.1: WEIGHTING OF ΔD AND ΔP

<u>No. of Sites N</u>	<u>Range of ΔD or ΔP Acceptable for 2 Weighting Points</u>	<u>Range of ΔD or ΔP Acceptable for 1 Weighting Point</u>
$N < 5$	0 - 10.0	10.1 - 15.0
$N \geq 5$	0 - 7.0	7.1 - 12.0

The limits were decided on empirically after surveying the data and comparing the values of ΔD and ΔP to α_{95} .

Chapter 5. SPECIAL WEIGHTING FACTORS

5.1 Mechanics

The distinction between ~~tensional~~ and shear dykes was coded in this category. Unless otherwise stated, a linear dyke swarm was assumed to be tensional and a weight of 2 was assigned. If three strike directions were found, the central one was used to represent tensional dykes, and the other two were considered to be conjugate shear dyke directions (De Boer, 1967). Because of this assumption, a datum containing three strike directions was reduced to unit weight. Zero weight was assigned if all dykes were suspected of representing shear directions. This was the case if:

- . . . two directions of dykes were present, suggesting conjugate shears;
- . . . the dykes were parallel to contemporaneous regional shear features;
- . . . the original work stated that the dykes were intruded syn-tectonically in the direction of shear.

5.2 Error in Present Latitude $\Delta\phi$

In a few cases sampling sites were so far apart that it was difficult to estimate the present latitude of the swarm, and the midpoint had to be taken (e.g. Fahrig and Jones, 1969). Averaging D and I over such a large area could be of questionable value to this work, as it could affect the paleolatitude. When such difficulties arose, the $\Delta\phi$ category was given zero weight. Otherwise it was assigned unit weight.

5.3 Error in Age Δt

For the age resolution required in this work the errors in radiometric

and/or geological age of intrusion are insignificant, and do not need to be considered. The time subdivisions used were pre-1300 Ma, 1300 - 190 Ma, and post-190 Ma, and the reasons for choosing them are discussed in Section 8.1. In a few cases where age control was sufficiently questionable, such as, for example, where only a minimum or a maximum age was available (e.g. Neuvonen and Grundstrom, 1969), the Δt category was given zero weight. Where the problem did not exist, unit weight was assigned.

5.4 Composition

The majority of dyke rocks studied paleomagnetically are basic in composition. This includes basalt, diabase, lamprophyre and gabbro. Unit weight was therefore assigned to basic dyke swarms. There are rare examples such as the Spanish Peaks swarm in Colorado (Larson and Strangway, 1969), where the composition is acidic. Such dyke swarms are of small extent and they tend to be associated with volcanic centers, so their origin may not be directly related to large-scale tectonic processes, and may only add noise to the results. Thus, zero weight was assigned to dykes of such unusual composition.

5.5 Dyke Percent

In many instances the original reference listed data obtained not only on dykes, but also on sills, flows and intercalated sediments that were believed to be coeval (e.g. Roche and Cattala, 1959). A weight of 2 was assigned if all or nearly all of the measurements were made on dykes. If about 50% of all measurements represented dykes, unit weight was given, and where the percentage was significantly less than 50%, the weight was reduced to zero.

5.6 Remagnetization

It is particularly important in this work to filter out all paleomagnetic data that may be reflecting a later remagnetization, and thus be unrelated to the magnetic field at the time of dyke intrusion. If the measured remanence was believed by the original authors to be primary, a weight of 2 was assigned. The weight was reduced to zero if there were geological or paleomagnetic reasons to suspect a later remagnetization (e.g. Halvorsen, 1972). (A weight of 1 was intentionally omitted - see Chapter 6.)

5.7 Contact Test

If an inconclusive or a negative test was reported in the original, this category was weighted at zero. Failed contact tests imply the possibility that Strangway's internal demagnetizing field may operate in isolated instances. If this is the case, the measured remanence does not represent the true magnetic field at the time of intrusion. If the contact test was positive, unit weight was given. As only a small number of contact tests are other than positive, unit weight was also assigned to those data where no contact test has been reported.

Chapter 6. FILTERS

The four filters are sums of different assigned weights in the weighting scheme (Table 3.1). The maximum value for each filter is 10, which represents the best data. Filters F_1 and F_2 were calculated from the five general weighting factors. Filter F_1 is the sum of the assigned weights:

$$F_1 = \frac{\text{swarm}}{\text{extent}} + \Delta S + \frac{\text{sampling}}{\text{extent}} + \Delta D \quad (6.1)$$

F_1 is used for filtering out unreliable paleoazimuths. The analogous filter for paleolatitudes is F_2 , which is the same as F_1 , except that ΔP is substituted for ΔD :

$$F_2 = \frac{\text{swarm}}{\text{extent}} + \Delta S + \frac{\text{sampling}}{\text{extent}} + \Delta P \quad (6.2)$$

In both cases data with values of F from 7 to 10 inclusive were accepted for further analysis, and data with $F < 7$ were discarded.

The second pair of filters was developed so as to weed out data points where special problems existed. Filters F_3 and F_4 are the sums of the seven special weighting factors:

$$F_3 \text{ or } F_4 = \text{Mechanics} + \Delta\phi + \Delta t + \text{Composition} + \text{Dyke \%} + \text{Remagnetization} \\ + \text{Contact Test} \quad (6.3)$$

F_3 pertains to paleoazimuths and F_4 to paleolatitudes. They are equivalent except in the following two cases:

- . . . If the error in present latitude is great, $\Delta\phi$ is 0 in the F_4 sum, but is considered 1 in the F_3 sum, as $\Delta\phi$ has no bearing on paleoazimuth and should not be counted against F_3 .
- . . . If three strike directions are present, the mechanics factor is 1 in the F_3 sum, but is considered 2 in the F_4 sum, as the

presence of three strike directions does not affect the paleo-latitude. In the case of shear the mechanics factor was 0 in both F_3 and F_4 .

The values for F_3 and F_4 had to be 9 or 10 for the data to be acceptable. The reason for this was to automatically eliminate any datum that had at least one of the following problems, resulting in a loss of two points:

- . . . possibility of shear*,
- . . . possibility of remagnetization,
- . . . datum essentially not on dykes.

In other cases, there had to be at least two problems leading to a loss of two points before the datum was discarded.

The combined use of the four filters forms a general acceptance rule: to be accepted, a paleoazimuth must have $F_1 \geq 7$ and $F_3 \geq 9$.

Analogously, a paleolatitude must have $F_2 \geq 7$ and $F_4 \geq 9$.

*Shear dykes, however, were retrieved in some special cases (see Chapter 8).

Chapter 7. DISTRIBUTION OF DATA

7.1 Geographical Distribution

A total of 149 data points were selected after filtering the original material. The geographical distribution of the data is shown in Figures 7.1 to 7.7 and summarized in Table 7.1. The percentages per continent show that the distribution is biased towards North America and Europe. In other parts of the world, dyke swarms have been studied less extensively.

Table 7.1: PERCENTAGES OF DYKE DATA PER CONTINENT

<u>Figure No.</u>	<u>Continent</u>	<u>Data %</u>
7.1	North America	49
7.2	Europe	18
7.3	Asia	11
7.4	Africa	10
7.5	Australia	8
7.6	South America and Caribbean	3
7.7	Antarctica	1

The data shown in Figures 7.1 to 7.7 can be subdivided into the following types:

- (1) Those for which a strike direction was unavailable and which are used only for analysis of paleolatitude;
- (2) Those which have a measurable strike direction and which were used both for paleoazimuth and paleolatitude analysis.

Type (2) data can be further subdivided into:

- ... those which have one tensional direction of strike and give rise to one paleoazimuth;

- ... those which have one (or two conjugate) shear direction(s) of strike and give rise to one (or two) paleoazimuth(s);
- ... those which have three strike directions (one tensional and two shear), and give rise to three paleoazimuths.

The different types of data points are coded in the figures by the four following symbols:

- - scattered or unknown strike;
- - tensional direction of strike;
- x - shear direction of strike (two such symbols are used to denote conjugate shears);
- ▽ - one tensional and two shear strikes.

All data points are assigned a map number, and a legend for these numbers follows each figure. The map numbers start from 1 on each figure. Figures 7.5, 7.6 and 7.7 have been grouped on one page due to scarcity of data, and one legend covers these three areas. The numbering of the dyke localities generally progresses from west to east. Exceptions are large dyke swarms such as the Mackenzie, grouped under one number, 6, but represented by many widely separated areas of study, 6A, 6B, etc. No. 6D is the only data point that was plotted twice, the reason being that dykes from two localities distant from each other, Northeast Manitoba and Melville Peninsula (Fahrig and Jones, 1969), were included in one paleomagnetic average.

In many cases one number may refer to several closely spaced data. These are normally separate studies on the same dyke system, however in some cases swarms from the same area known by the same name can vary in age, strike or magnetization. Examples are:

Legend to Figure 7.1 (North America)

<u>Map No.</u>	<u>Symbol</u>	<u>Locality</u>	<u>Reference No. In List A</u>
1	○	Coast Range	88
2	x	Western Channel	37
3	x	Indin - Northeast	55
	x	Northwest	55
4	x	Dogrib	55
5	●	"X"	55
6a	●	Mackenzie - Muskox	76
6b	●	Northwest Territories	20
6c	●	Great Slave Lake	21, 36
6d	●	Manitoba & Melville	21
6e	○	Miscellaneous	67
7	●	Sparrow	54
8	○	Wind River - Older	84
	●	Younger	84
9	○	Bighorn	50
10	○	Spanish Peaks	49
11	x	Molson - North - South	18
	x	Northeast, 1	18
	●	Northeast, 2	20
12	○	Kaminak - Lamprophyre	11
	○	Diabase	11
13	●	Christopher Island	66
14a	●	Franklin - Coronation	22
14b	●	Boothia	22
14c	○	Miscellaneous	67
14d	●	Baffin	22, 24
15	○	Iron Mountain	16
16	●	Logan	77
17	●	Baraga	31
18	○	Marathon	20
19	●	Matachewan - Reversed, 1	38
	●	Reversed, 2	20
	●	Normal	20
20	●	Sudbury - Normal	64
	●	Reversed, 1	48
	●	Reversed, 2	81
21	○	Otto Stock	75

<u>Map No.</u>	<u>Symbol</u>	<u>Locality</u>	<u>Reference No. In List A</u>
22	○	Nipissing	79
	○	Post-Nipissing	89
23	●	Abitibi - Normal, 1	46
	●	Normal, 2	38
24a	●	Appalachian - South	15
24b	▽	Central	15
24c	▽	North	15
25a	●	Grenville - Younger	57
25b	●	Older	87
26	●	Maryland	83
27	●	Frontenac	65
28	●	Connecticut - Buttress	83
	●	Cross Rock	83
29	○	Otish	25
30	●	Nova Scotia	47
31	●	Harp	39
32	○	Aillik	23
33	x	Indian Harbour	58
34	x	Kangamuit - Deformed	7
	x	Undeformed	27
35	●	Coast Parallel - Normal	41
	●	Reversed	26
	●	Iviglut	26
	●	Arsuk	69
	●	Tugtutoq	69
36a	○	Gardar West - Lamprophyre	71
	●	Diabase	71
36b	●	Gardar East	71
37	●	Giant Dykes - Gabbro	70
	●	Hviddal	70

Figure 7.2: Reference Map of Europe

Legend to Figure 7.2 (Europe)

<u>Map No.</u>	<u>Symbol</u>	<u>Locality</u>	<u>Reference No. In List A</u>
1	○	Jan Mayen	35
2	●	Scotland - Mainland	82
	●	Mull	2, 59
	●	Skye	95
3	○	Antrim	94
4	●	Lundy	8, 60
5	●	Britain	12
6	○	Egersund - Older 1	86
	●	Older 2	85
	●	Younger	72
7	●	Hunnedalen	72
8	○	Ny - Hellesund	85
9	●	Corsica	61
10	○	Camparno Staro	35
11	○	Schio	14
12	○	Capo Passero	6, 80
13	●	Skane - Older	10
	●	Younger	74
14	x	Sweden - Older	74
	x	Younger	1, 68, 73
15	○	Aland - Foglo	63
	○	Market	63
16	○	Wzar	35
17	●	Hame	62
18	●	Batsfjord	45
19	●	Crimea	42

Figure 7.3: Reference Map of Asia

Legend to Figure 7.3 (Asia)

<u>Map No.</u>	<u>Symbol</u>	<u>Locality</u>	<u>Reference No.</u> <u>In List A</u>
1	○	Mysore	34
2	●	Damodar	4
3	○	Alandi	5
4	○	Singhbhum	91
5	▽	Nizhnaya Tunguska	3, 43
6		Maimecha - Kotuy	
	xx	Bolshaya Romanikha	3, 43
	○	Maimecha	43
	▽	Kotuy	3, 43
7	●	Viliui	3, 42
8	○	Kuantan & Massai	53
9	○	Singapore	53
10	○	Primorye	44

Figure 7.4: Reference Map of Africa

Legend to Figure 7.4 (Africa)

<u>Map No.</u>	<u>Symbol</u>	<u>Locality</u>	<u>Reference No. In List A</u>
1	○	Cape Verde	92
2	●	Liberia - Coast	13
	●	Inland	13
3	○	Central Atlas	32
4	●	Foum Zguid	32
5	●	Pilansberg	30, 52
6	●	Crystal Springs	40
7	●	Bubi	40
8	●	Satellite - Both	52
	●	East Satellite	40
	●	Umvineela	40
9	●	Sebanga Poort	40
10	●	Ethiopia- East Plateau	56
	●	West Plateau	56
11	○	Madagascar	78

Figure 7.5:
Reference Map of Australia

Figure 7.6:
Reference Map of South America and Caribbean

Figure 7.7:
Reference Map of Antarctica

Legend to Figures 7.5, 7.6 and 7.7

<u>Map No.</u>	<u>Symbol</u>	<u>Locality</u>	<u>Reference No. In List A</u>
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Figure 7.5 (Australia)

1	●	Widgiemooltha	19
2	○	Yilgarn - "A", Old	28
	xx	"D", Intermediate	28
	●	"F", Intermediate	28
	▽	"C", Young	28
3	xx	Gawler - "B", Older	29
	●	"A", Younger	29
4	○	Queensland	35

Figure 7.6 (South America and Carribean)

5	○	Jamaica	93
6	●	Bolivar	51
7	●	Minor	33
8	●	Surinam	90

Figure 7.7 (Antarctica)

9	○	Vestfold	17
10	○	Theron	9

Maimecha - Kotuy (variation in strike) no. 6, Figure 7.3,
Liberia (variation in magnetization) no. 2, Figure 7.4,
Yilgarn (variation in age) no. 2, Figure 7.5.

7.2 Time Distribution

The distribution of dyke intrusion through time is also of interest, because a periodicity or a change of pattern could be related to the evolution in time of lithospheric dynamics. The time distribution of the 149 dyke measurements is shown in Figure 7.8. The horizontal scale ranges from 0 to 2800 Ma b.p., and is subdivided into 40 Ma intervals for convenience of plotting. There is no implication of an age error in the 40 Ma subdivision. The assigning of an age error to each swarm was deemed unnecessary for the reasons previously discussed (see Section 5.3).

As North America supplies half of the world data, a division was made into North American data, and world data excluding North America: Figures 7.9a and 7.9b. In the Precambrian both distributions appear to be random, though 49% of the data comes from North America. This is largely due to the good exposure and accessibility of the Canadian Shield. Other continents may contain equally abundant dyke swarms, a great number of which are undiscovered or unstudied due to geographical inaccessibility.

The general scarcity of data in the Paleozoic can be attributed to the abundant sedimentary cover, which may be concealing existing dyke swarms in the lower sections of the crust. In the Precambrian terrains, the sedimentary cover has been stripped off, but the ancient crust has been affected by orogenetic processes which have obliterated much of the

Figure 7.8: Distribution of all Data with Respect to Time

Figure 7.9a: Distribution of Data with Respect to Time -
World Excluding North America

Figure 7.9b:- Distribution of Data with Respect to Time -
North America

evidence. The abundance of data in the Meso-Cenozoic is a reflection of the well-preserved geologic record.

A difference can be detected between the data point distribution of North America and that of the rest of the world in the past 200 Ma. Most of the data seems to originate outside North America. About 180 Ma a sharp peak occurs in the North American distribution. The abundance is due to the young dyke swarms along the Atlantic coast, and the Coast Parallel dykes of Greenland. These swarms are related to the tensional stresses which built up prior to the rifting of the Atlantic Ocean (McHone, 1978). The separation of the Atlantic was complete by 150 Ma (Irving, 1977). Thus North America was involved in a major rifting episode in the Late Jurassic, while in the rest of the world continental breakup continued into the Tertiary. For instance, the separation of South America and Africa (Irving, 1977) and of India and Australia (Athavale et al., 1970) occurred in the Cretaceous. The spreading of the North Atlantic in the Tertiary was concentrated between Europe and Greenland, and generated the extensive British Tertiary igneous province (Hall, Wilson and Dagley, 1977). Plate motions throughout the world can explain the high concentration of data points outside North America in the Meso - Cenozoic.

Chapter 8. PALEOAZIMUTH AND PALEOLATITUDE ANALYSIS

8.1 Time Subdivisions

The paleoazimuths and paleolatitudes were examined for all geologic time and then for the following three time intervals:

- . . . Pre - 1300 Ma,
- . . . 1300 - 190 Ma,
- . . . Post - 190 Ma.

The boundaries of the intervals were determined empirically after many time combinations of the data were attempted. A division into more than 3 intervals resulted in an insufficient number of data points in each. It will be shown that paleoazimuths exhibit a preferred orientation before 1300 Ma and after 190 Ma. In the intermediate interval of 1300 - 190 Ma the paleoazimuths are randomly distributed. If the time boundaries are placed elsewhere, this pattern is not so clear. Any further time subdivisions of paleoazimuths in the 1300 - 190 Ma interval fail to detect any preferred directions.

It may be significant that the 1300 Ma and 190 Ma boundaries, determined independently on the basis of the dyke data, closely pre-date two major episodes of extension in the lithosphere. The Mackenzie-Gardar igneous phase took place between ca. 1260 and 1190 Ma (Patchett, Bylund and Upton, 1978). The occurrence of Mackenzie diabases over most of the Canadian Shield indicates that extension was distributed over a very large area. If the stress was thus dissipated, a complete continental breakup may not have occurred (Fahrig and Jones, 1969).

On the other hand, the post-190 Ma interval encompasses a well documented rifting phase. After 180 Ma, dyke systems preceding the opening of the Atlantic began to appear along the east coast of North America (Smith, 1976), west coast of Africa (Dalrymple, Gromme and White, 1975), and south-west coast of Greenland (Piper, 1975). At the same time Karroo basaltic activity (Sutton, 1977) evidenced the impending breakup of Gondwana. The grouping of dyke swarms pertaining to the latest major plate tectonic events resulted in a preferred orientation of paleoazimuths.

8.2 Paleoazimuths and the Turkey χ^2 Test

Paleoazimuths are plotted on semi-circular rose diagrams. A 20° interval is used because of the large error in A : strike errors of up to $\pm 10^\circ$ were sometimes allowed, and therefore the interval could be no less than 20° .

A perfectly uniform rose diagram would have the same number of data points in each class (20° interval). The paleoazimuths presented in the following figures deviate from this distribution. If the degree of deviation is statistically significant, the distribution is non-uniform. A χ^2 test for directional data was applied to determine the presence or absence of preferred directions.

The Tukey χ^2 test (Middleton, 1965) generates a χ^2 distribution using vector components. The number of observations in a given directional class interval j can be regarded as the magnitude of a vector x_j . The direction of x_j in two dimensions is given by θ_j , the angle to the mid-point of the class interval with respect to the north-south axis; the components of x_j are $x_j \sin \theta_j$ and $x_j \cos \theta_j$. The observed total lengths

of the components of the frequency vector are then

$$Z_1 = \sum_{j=1}^n x_j \sin \theta_j \text{ in the east-west direction, and} \quad (8.1)$$

$$Z_2 = \sum_{j=1}^n x_j \cos \theta_j \text{ in the north-south direction,} \quad (8.2)$$

where n is the number of classes.

On the assumption of a uniform distribution the expected variances of the two components Z_1 and Z_2 are defined as

$$\sigma_1^2 = \bar{x} \sum_{j=1}^n \sin^2 \theta_j, \text{ and} \quad (8.3)$$

$$\sigma_2^2 = \bar{x} \sum_{j=1}^n \cos^2 \theta_j, \quad (8.4)$$

where $\bar{x}$ is the expected value of x_j , and is defined as

$$\bar{x} = \frac{\sum_{j=1}^n x_j}{n} \quad (8.5)$$

The χ^2 distribution is then given by

$$\chi^2 = \frac{Z_1^2}{\sigma_1^2} + \frac{Z_2^2}{\sigma_2^2} \quad (8.6)$$

and has two degrees of freedom. At the 95% confidence limit this yields a maximum acceptable χ^2 value of 5.99. If the observed χ^2 value exceeds this, the null hypothesis is rejected and the presence of significant departures from uniformity is accepted.

The Tukey χ^2 test must be applied to directional data distributed about 360° . This stems from a requirement of the test that (see Middleton, 1965)

$$\sum_{j=1}^n \sin \theta_j = \sum_{j=1}^n \cos \theta_j = 0. \quad (8.7)$$

Data such as paleoazimuths do not satisfy this condition. The distribution is semi-circular, as the data are bimodal with a periodicity of 180° . If the rose diagram is reflected about the east-west axis, the Tukey χ^2 test will fail, because for every vector x_j there will be another x_j of equal magnitude and opposite direction. The χ^2 will always add up to zero regardless of how non-uniform the data actually are. Therefore, the data in the semi-circle must be expressed over 360° without making them bimodal. This is achieved by doubling the class interval, i.e. multiplying all θ 's by 2 (Middleton, 1965). The χ^2 is now expressed as

$$\chi^2 = \frac{\sum_{j=1}^n x_j \sin 2\theta_j)^2}{n \sum_{j=1}^n \sin^2 2\theta_j} + \frac{\sum_{j=1}^n x_j \cos 2\theta_j)^2}{n \sum_{j=1}^n \cos^2 2\theta_j} \quad (8.8)$$

A sample calculation of a χ^2 value from equation 8.8 is given in Appendix 1. The Tukey χ^2 test is particularly well suited for the present analysis because it detects only departures from uniformity that lead to non-zero mean vector components, i.e. departures due to preferred orientation, not to random deviations from uniformity.

Paleoazimuths were plotted using tensional dykes only, and tensional and shear dykes together. A comparison of χ^2 values shows that a more consistent data set is achieved by eliminating shear dykes. Therefore

Figures 8.1 to 8.4 show plots of only the tensional dykes for all geologic time and for the three previously discussed time subdivisions. In the figures, N is the total number of data points.

The most distinctly non-uniform distribution was picked up in the pre-1300 Ma interval, implying the existence of a single preferred orientation of tension on a world-wide scale, centred on $350 \pm 20^\circ$. The inclusion of shear dykes in this time interval would raise the number of observations to $N = 38$, and lower the χ^2 value to 7.33, which is still non-uniform; the position of the peak at 350° remains the same.

A significantly different pattern is observed in the following time interval of 1300 - 190 Ma. Here the null hypothesis that the distribution of paleoazimuths does not depart significantly from uniformity must be accepted. The inclusion of shear dykes does not alter this conclusion. Apparently during this time interval there was no preferred orientation on the global scale of the stress that gave rise to dyke formation.

In the post-190 Ma interval a broad peak centred on $340^\circ \pm 30^\circ$ is evident. As this time interval is much shorter in duration than the previous two, only one major global tectonic episode is represented, namely the opening of the Atlantic and the breakup of Gondwana. The ensuing plate motions are continuing to the present.

When paleoazimuths for all time are plotted together (Figures 8.4 and 8.5), it becomes apparent why shear dykes increase the scatter when superimposed on tensional dykes. The latter alone (Figure 8.4) are not uniform, but the former are (Figure 8.5). If there is one prevailing direction of tension, two conjugate shear directions are to be expected. The observed uniformity of shear dykes is also affected by the small

Figure 8.1: Pre-1300 Ma Paleoazimuths

N = 24

$$\chi^2 = 12.16 \quad (\chi^2_{0.05} = 5.99)$$

Figure 8.2: 1300 - 190 Ma Paleoazimuths

N = 32

$$\chi^2 = 0.89 \quad (\chi^2_{0.05} = 5.99)$$

Figure 8.3: Post-190 Ma Paleozoazimuths
N = 23
 $\chi^2 = 7.82$ ($\chi^2_{0.05} = 5.99$)

Figure 8.4: All Time Paleoazimuths

N = 79

$$\chi^2 = 14.58 \quad (\chi^2_{0.05} = 5.99)$$

Figure 8.5: All Time Paleoazimuths of Shear Dykes

N = 27

$$\chi^2 = 0.35 \quad (\chi^2_{0.05} = 5.99)$$

number of samples ($N = 27$), when compared to tensional dykes ($N = 79$).

In the simplest mechanical model there are two possible orientations for shear, while for tension there is only one. The noise on the shear rose diagram would be twice as great. It would therefore be more difficult to identify non-uniformity in shear dykes than in tensional dykes, even if the number of samples in each set were comparable.

Tensional dykes are characterized by a non-uniformity in the north to northwest orientations. The observed peak for all time is at $0 \pm 10^\circ$, and the number of observations west of north exceeds the number in the northeast quadrant. It is difficult to assess the significance of these observations from the Tukey χ^2 test beyond the recognition of non-uniformity.

8.3. Paleolatitudes and the Uniform Model

Dyke occurrences with respect to paleolatitude were plotted in histograms using 10° intervals from 0° to 90° . Both hemispheres were combined in one, so that in fact two 10° -wide latitudinal bands, symmetric with respect to the equator, are represented in each class. In paleomagnetism the distinction between the northern and southern hemispheres is usually lost, because a reversed geomagnetic field would give rise to a negative paleolatitude for a sampling site that was in the northern hemisphere at the time of magnetization (see e.g. Wilson et al., 1974). Therefore, when normal and reversed directions occur throughout the same rock unit, they are often averaged together regardless of sign (e.g. Piper, 1975).

Paleolatitudinal distributions can be statistically tested against a model which assumes a constant areal density of dykes in each latitudinal

band, i.e. a uniform distribution. The number of occurrences will gradually decrease towards the poles as a result of decrease in area of each successive latitudinal band. The percentage of area in each band can be related to the expected percentage of dyke occurrences.

On the surface of a sphere, a zone is a strip limited by two parallels. The area of such a zone is

$$A = 2 \pi r h \quad (8.9)$$

where r is the radius of the sphere, and h is the altitude of the zone measured on the rotational axis. For 10° paleolatitudinal intervals the altitude will be

$$h = r [\sin (\lambda + 10^\circ) - \sin \lambda]. \quad (8.10)$$

Substituting (8.10) in (8.9) and multiplying by 2 gives the area of the two combined 10° latitudinal bands from both hemispheres

$$A = 4 \pi r^2 [\sin (\lambda + 10^\circ) - \sin \lambda]. \quad (8.11)$$

As the area of a sphere is

$$S = 4 \pi r^2, \quad (8.12)$$

the percentage of area in each band is

$$A \% = \frac{A}{S} \times 100\% = [\sin (\lambda + 10^\circ) - \sin \lambda] \times 100\%. \quad (8.13)$$

Equation 8.13 represents a uniform distribution of dyke density with latitude. The percentages for 10° intervals are given in Appendix 2.

The observed distributions are tested for agreement with the uniform model by the χ^2 test (Huntsberger and Billingsley, 1973)

$$\chi^2 = \sum_{i=1}^n \frac{(O_i - E_i)^2}{E_i} \quad (8.14)$$

where O_i = observed frequency

E_i = expected frequency, and

n = number of classes.

The usually good fit to the model shows the absence of a preferred paleolatitude of intrusion. The model was converted from 100% to fractions of N , the total number of observations, depending on the data. An example of such a conversion is found in Appendix 2. As the number of observations in a class can be no less than 5, some 10° intervals have to be combined, and the number of classes is always less than 9. The number of degrees of freedom is thus different for each data set, as

$$\begin{array}{l} \text{number of degrees} \\ \text{of freedom} \end{array} = n - 1 \quad (8.15)$$

where n = number of classes (Huntsberger and Billingsley, 1973).

Figures 8.6 to 8.10 are histograms of paleolatitudinal distributions ~~in the same time subdivisions as those used for paleoazimuths.~~ Only tensional dykes are considered. The uniform model is represented by a dashed curve on Figures 8.6, 8.7, 8.8 and 8.10. As can be seen, the test is not very restrictive, but still the null hypothesis (i.e. uniform distribution) cannot be rejected at the 95% confidence level. In Figure 8.9 the following modification was made. The uniform model does not account for the fact that each latitudinal band is composed of both oceanic and continental lithosphere. As dyke occurrences are being sampled only on continents, a calculation of the percentage of continental area in each latitudinal band would be an improvement to the model. Paleogeographic maps of the world are available for the last 220 Ma (Smith and Briden, 1977). A continental correction was worked out for the post-190 Ma interval. This was done by averaging the percentage of continental

Figure 8.6: Pre-1300 Ma Paleolatitudes

N = 36

$$\chi^2 = 2.37 \quad (\chi^2_{0.05} = 7.81)$$

Figure 8.7: 1300 - 190 Ma Paleolatitudes

N = 44

$$\chi^2 = 4.55 \quad (\chi^2_{0.05} = 9.49)$$

Figure 8.8: Post-190 Ma Paleolatitudes

N = 39

 $\chi^2 = 2.19$ ($\chi^2_{0.05} = 9.49$)

Figure 8.9: Post-190 Ma Paleolatitudes with Continental Area Correction

N₂ = 39 $\chi^2 = 3.03$ ($\chi^2_{0.05} = 9.49$)

Figure 8.10: All Time Paleolatitudes

N = 119

$$\chi^2 = 4.47 \quad (\chi^2_{0.05} = 14.07)$$

Figure 8.11: β Distribution for Tensional Dykes

N = 79

$$\chi^2 = 6.34 \quad (\chi^2_{0.05} = 11.07)$$

area in each 10° latitudinal band for five 40 Ma intervals over the past 200 Ma. The correction was applied to the uniform model. The detailed calculation is given in Appendix 3. Figure 8.9 shows the post-190 Ma observed distribution in relation to the corrected uniform model, which is marked with a dashed line.

Tensional dykes do not show any dependence on latitude, as agreement with the uniform model is observed in all cases. The best fit is to the distribution over all time, where the number of samples is highest. It appears that a lack of a preferred latitude of intrusion has persisted through time.

It is impossible to conclude from the small number of measurements available whether shear dykes alone have any preferred latitude of formation. There is no obvious reason to suspect that they should. The inclusion of shear dykes in the data set has no significant effect on the results.

The fit of the post-190 Ma data to the uniform model corrected for continental area is marginally worse than the fit to the uncorrected model. The error involved in estimating the continental correction from paleogeographic maps is apparently too great to improve the results. Therefore it seems that the uncorrected uniform model is an adequate approximation to the observed distribution of dykes with latitude.

8.4 β Distribution

β angles were calculated from equation 2.4 for all tensional dykes which had a paleoazimuth. The resultant histogram (Figure 8.11) shows a satisfactory χ^2 fit to the theoretical β distribution as developed by Evans (1968), and denoted on the figure by a dashed line. Thus, when

the variations in A and λ are taken together, no deviation from Evans' model is observed, but when taken separately, A reveals preferred orientations while λ remains uniform.

Chapter 9. DISCUSSION AND CONCLUSIONS

9.1 Change in the Mechanics of the Lithosphere with Time

Dykes have preferred orientations of intrusion, but no preferred latitude, as the results of this work show. The pattern of overall paleo-azimuth orientations has changed with time, but paleolatitudes have shown no corresponding deviation from uniformity. The variation in the strikes of intrusion implies that changes either in the rheology of the lithosphere, or in the global stress field or in both, may have occurred. Although the data may be subject to different interpretations, the following speculations can be attempted.

In the pre-1300 Ma interval the relatively narrow peak centred at about $350^{\circ} \pm 20^{\circ}$ indicates that tensional fractures occurred approximately north-south, with a tendency to west of north. This would indicate a relative tension in approximately the east-west direction. By Bijlaard's theory (Nadai, 1950), decreasing the thickness of the deforming medium leads to an increased tendency for oblique fracture. The pre-1300 Ma lithosphere may have been thinner than that of later times (Baer, 1977), and plates could have had a tendency to be larger and mechanically less competent (Sutton and Watson, 1974). The effects of a global stress field could have been readily recorded in an environment where intra-plate deformation was an important process. A consistent fracture pattern, as evidenced by dykes, was likely to arise in such an environment. It is unlikely that the pre-1300 Ma peak is the result of only one tectonic event, because as shown in Figure 7.8, dyke intrusion took place continually throughout the time interval represented.

On the other hand, dyke paleoazimuths do not show a preferred or-

ientation in the 1300 - 190 Ma time interval. This suggests that either the tectonic stress field had no preferred orientation in this interval, or that the lithosphere reacted differently in response to the same stress. It is perhaps significant that a change in the style of global tectonics at ca. 1300 Ma has been suggested from other lines of evidence (Sutton and Watson, 1974). According to this hypothesis a transition from intraplate to interplate deformation occurred at some point in time, as the lithosphere became sufficiently rigid to dissipate stress by brittle fracture and relative motion of plates. Baer (1977) also suggested that plate tectonics emerged as a new global process, though at a later time (1000 Ma).

A link between this hypothesis and the results on dyke paleoazimuths is uncertain. It is unclear why a preferred orientation would be destroyed by the onset of plate tectonics. A possible explanation is that the complexity of plate interactions would tend to obscure the effects of the global stress field. This could happen if intense localized stress fields of different orientations at different times were set up at plate boundaries, and a number of these could give rise to a uniform distribution of dyke paleoazimuths. Each rifting event could produce a preferred orientation such as that observed in the post-190 Ma interval. It is likely that more than one episode of rifting occurred in the 1300-190 Ma interval. If the quantity of data had permitted, it might have been possible to resolve the uniform paleoazimuth distribution into several peaks, each representing a major phase of lithospheric breakup. However, the number of points was too small to be further subdivided.

The short post-190 Ma interval represents a single global tectonic event (i.e. the opening of the Atlantic and the contemporaneous breakup

of Gondwana (Irving, 1977), which is continuing to this day (Takin, 1972). There is more scatter in the non-uniform paleoazimuth distribution of these last 190 Ma than prior to 1300 Ma, an interval about seven times as long (2690 - 1300 Ma). It is therefore possible to envisage from the amount of noise on the post-190 Ma data how the superposition of a number of rifting events could have led to a random distribution such as that observed in the 1300 - 190 Ma interval. From this point of view it also seems unlikely that a plate tectonic environment such as that of the present, where several different plates interact, could have produced the strong peak of the pre-1300 Ma interval.

The hypothesis of commencement of plate tectonics after 1300 Ma can be supported by the evidence from dyke paleoazimuths if the post-190 Ma preferred orientation is indeed of secondary importance. This may not be the case. It is worth noting that the orientation of the post-190 Ma peak is similar to that of the pre-1300 Ma peak. It is therefore equally possible that a plate tectonic mechanism was operating prior to 1300 Ma, and that the stress field producing preferred orientations was similar in both cases. The 1300 - 190 Ma interval could have been characterized by a more complex system of stresses. Arguments can be made both for and against the commencement of plate tectonics after 1300 Ma on the basis of the dyke study. Nevertheless, the data strongly imply some change in the style of dyke intrusion ca. 1300 Ma. Another change after 190 Ma may have also occurred.

9.2 Global East - West Tension and the Earth's Ellipticity

A global stress field with a prevailing relative east-west tension

is implied by the overall north-south abundance of dyke paleoazimuths for all time. Observations of preferential east-west tension have been made previously. An example is the work by Moore (1973), who showed that 38% of the present mid-oceanic spreading axes are within 10° of north-south, accompanied by a similar preference of transform faults for the east-west direction (Figure 9.1). Moore explained the tendency of plates to move in the east-west direction by the effect of the tidal torque, which results in a net westward drift of the lithosphere. However, the magnitude of the torque has been proven to be too small to have an effect on tectonic processes (Jordan, 1974).

A preferred orientation of intraplate extensional features has been noted by Ranalli and Tanczyk (1975). Figure 9.2 shows a definite north-south peak for world Cenozoic grabens, showing that global east-west extension occurs. These two examples fall within the post-190 Ma interval. The non-uniform distribution of dyke paleoazimuths supports the presence of east-west tension in this period, and also suggests that a similar stress field characterized the pre-1300 Ma interval.

A possible explanation for the predominance of east-west tension can be found in the Earth's ellipticity. The Earth can be approximated to an oblate spheroid with ellipticity $e = 0.00335$ (Stacey, 1969). A meridionally moving plate must adapt to a change in the radius of curvature of the Earth, and as a result intraplate stresses are set up. These are known as membrane stresses. Turcotte (1974) showed that the magnitude of these stresses could be sufficiently great to fracture the lithosphere. The pattern of membrane stresses depends on the direction in which the plate is moving (Figure 9.3, Oxburgh and Turcotte, 1974).

Figure 9.1: Orientation of Global Spreading Lines and Transform Faults (After Moore, 1973)

Figure 9.2: Orientation of Cenozoic Grabens (After Ranalli and Tanczyk, 1975)

Figure 9.3: Membrane Stresses on Meridionally Moving Plates (After Oxburgh and Turcotte, 1974)

If motion is from the equator to the pole, the plate will experience tension at its boundaries and compression in the center, as the Earth's radius of curvature is increasing. The opposite occurs if a plate moves towards the equator. If a plate moves without changing latitude, i.e. in an east-west sense, the effects of membrane stresses are greatly reduced. It is therefore possible that plates move preferentially east-west, as north-south motion requires additional work to change the radius of curvature (Ranalli and Tanczyk, 1975).

The north-south preferred orientation of dyke paleoazimuths could thus be a consequence of the Earth's ellipticity, provided the majority of dykes were intruded into plates moving in a predominantly east-west sense in order to minimize membrane stress. The existence of this process cannot be verified for most of geologic history, as the present knowledge of the position and sense of motion of individual lithospheric plates is inadequate.

9.3 Concluding Remarks

The observed patterns of paleoazimuths have revealed a variation in the orientation of dyke intrusion with time. The preferred orientation of the pre-1300 Ma interval is approximately the north-south direction may reflect an environment where intra-plate deformation was the dominant response to a stress field with the minimum stress axis oriented east-west. The uniform distribution of the 1300 - 190 Ma interval can then be interpreted as evidence for a predominantly plate tectonic environment, in which each plate is subject to a different stress system transmitted from its boundaries. Within this line of reasoning, the preferred orientation of the post-190 Ma distribution, which resulted from one rifting phase, is simply the result of a short time frame. If, however, the post-190 Ma peak can be fairly compared to the pre-1300 Ma peak, the shift

to uniformity after 1300 Ma cannot be interpreted as evidence for the onset of plate tectonics.)

The preferred paleoazimuth orientations confirm previous studies concerning the existence of global east-west extension at certain times in the Earth's history. The ellipticity of the Earth could be considered as a possible explanation of this stress pattern, but its importance remains to be verified. As the change in the Earth's radius of curvature reaches a peak in mid-latitudes (Turcotte, 1974), uniformity in the latitudinal distribution of features related to membrane stress would not be expected. Thus there is no evidence that dyke formation results from membrane stresses, as the paleolatitude distributions are uniform throughout the sampled time span.

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APPENDICES

Appendix 1 - Sample Calculation of Tukey χ^2 Test (Example: All
Time Tensional and Shear Paleoazimuths)

x_j	θ_j	$2\theta_j$	$\sin 2\theta_j$	$\sin^2 2\theta_j$	$\cos 2\theta_j$	$\cos^2 2\theta_j$
10	280	560	-0.3420	0.1170	-0.9400	0.8830
12	300	600	-0.8660	0.7500	-0.5000	0.2500
15	320	640	-0.9848	0.9698	0.1736	0.0302
15	340	680	-0.6428	0.4132	0.7660	0.5868
20	0	0	0.0	0.0	1.0	1.0
10	20	40	0.6428	0.4132	0.7660	0.5868
9	40	80	0.9848	0.9698	0.1736	0.0302
6	60	120	0.8660	0.7500	-0.5000	0.2500
9	80	160	0.3420	0.1170	-0.9400	0.8830

N = 106

Total =
4.5000Total =
4.5000

$$Z_1^2 = \left(\sum_{j=1}^n x_j \sin 2\theta_j \right)^2 = 214.94$$

$$Z_2^2 = \left(\sum_{j=1}^n x_j \cos 2\theta_j \right)^2 = 270.81$$

$$\bar{x} = \frac{\sum_{j=1}^n x_j}{n} = \frac{106}{9} = 11.8$$

$$\sigma_1^2 = \frac{\sum_{j=1}^n x_j^2 \sin^2 2\theta_j}{n} = 53.1$$

$$\sigma_2^2 = \frac{\sum_{j=1}^n x_j^2 \cos^2 2\theta_j}{n} = 53.1$$

$$\chi^2 = \frac{Z_1^2}{\sigma_1^2} - \frac{Z_2^2}{\sigma_2^2} = 9.15$$

This paleoazimuth plot has a non-uniform distribution, as the χ^2 value
of 9.15 exceeds $\chi^2_{0.05} = 5.99$

Appendix 2 - Uniform Model for 10° Latitudinal Intervals

<u>Latitudinal Band</u>	<u>Model out of 100</u>	<u>Model out of 44</u> <u>(Example for Figure 8.7)</u>
$0^\circ - 10^\circ$	17.4%	7.7
$10^\circ - 20^\circ$	16.8	7.4
$20^\circ - 30^\circ$	15.8	7.0
$30^\circ - 40^\circ$	14.3	6.3
$40^\circ - 50^\circ$	12.3	5.4
$50^\circ - 60^\circ$	10.0	4.4
$60^\circ - 70^\circ$	7.4	3.3
$70^\circ - 80^\circ$	4.5	2.0
$80^\circ - 90^\circ$	1.5	0.7

Appendix 3 - Calculation of the Continental Area Correction

Latitudinal Band	C: Continental Correction	M: Uniform Model in 2 Hemispheres	M x C	M x C x 100 31.21	In One Hemisphere
90° to 80°	0.12	0.8	0.10	0.31	1.4
80° to 70°	0.38	2.3	0.87	2.80	5.4
70° to 60°	0.45	3.7	1.67	5.34	8.3
60° to 50°	0.51	5.0	2.55	8.17	12.3
50° to 40°	0.51	6.2	3.16	10.13	15.7
40° to 30°	0.41	7.2	2.95	9.46	15.7
30° to 20°	0.23	7.9	1.82	5.82	12.4
20° to 10°	0.24	8.4	2.02	6.46	12.9
10° to 0°	0.29	8.7	2.52	8.08	15.9
0° to -10°	0.28	8.7	2.44	7.81	--
-10° to -20°	0.24	8.4	2.02	6.46	--
-20° to -30°	0.26	7.9	2.05	6.58	--
-30° to -40°	0.27	7.2	1.94	6.23	--
-40° to -50°	0.28	6.2	1.74	5.56	--
-50° to -60°	0.25	5.0	1.30	4.17	--
-60° to -70°	0.25	3.7	0.93	2.96	--
-70° to -80°	0.35	2.3	0.81	2.58	--
-80° to -90°	0.42	0.8	0.34	1.08	--
		Total = 100%	Total = 31.21	Total = 100%	Total = 100%

END

29-12-80

FIN