# PRECAMBRIAN PALAEOMAGNETISM OF AUSTRALIA

*by*

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# DECLARATION

The studies described in this thesis were carried out while I was a full-time Research Scholar in the Research School of Earth Sciences of the Australian National University. The stability index of remanent magnetization described in Chapter 2 is the result of a collaborative research program with Dr. M.W. McElhinny. The measurements of Natural Remanent Magnetization of the Cambrian sediments (Chapter 5) were made by Dr. B.J.J. Embleton, but other measurements and the analysis of the cleaned directions were made by myself. The choice between possible interpretations of the late Precambrian to Early Palaeozoic apparent polar wander path for Gondwanaland (Chapter 7) was made using the suggestion of Dr. M.W. McElhinny of relating the path to the evidence for glaciation in the late Precambrian. All other work is my own. No part of this work has been submitted to any other University or similar institution.

J.W.G. Giddings
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J.W.G. Giddings

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SUPPORTING PAPERS (in back pocket)

M.W. McElhinny, J.W. Giddings and B.J.J. Embleton (1974)
'Palaeomagnetic results and late Precambrian glaciations'.
Nature, 248, 557-561.

B.J.J. Embleton and J.W. Giddings (1974)
'Late Precambrian and Lower Palaeozoic palaeomagnetic results from South Australia and Western Australia'.
Earth Planet. Sci. Letters, 22, 355-365.

J.W. Giddings and B.J.J. Embleton (1974)
'Large scale horizontal displacements in southern Australia — contrary evidence from palaeomagnetism'.
J. Geol. Soc. Aust., in press.

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# SYMBOLS

The following symbols have been employed in this thesis:

(a) Text symbols

| | |
|---|---|
| NRM | Natural Remanent Magnetization — the magnetization measured prior to the application of cleaning techniques. |
| TRM | Thermoremanent Magnetization. |
| PTRM | Partial Thermoremanent Magnetization. |
| VRM | Viscous Remanent Magnetization. |
| ARM | Anhysteretic Remanent Magnetization. |
| D | Declination of the remanent magnetization vector (east of geographic north). |
| I | Inclination of the remanent magnetization vector (treated as positive if pointing below the local horizontal and negative if pointing above). |
| Int | Intensity of remanent magnetization in $mA.m^{-1}$. |
| N | Number of unit vectors used in calculating a mean direction of magnetization or pole position. |
| R | Resultant of N unit vectors (not applicable to Chapter 2). |
| k | Estimate of the precision parameter, kappa (from Fisher, 1953), which describes the grouping of points about their mean. $k = (N-1)/(N-R)$. |
| A | Semi-angle of the cone, whose axis lies along the mean pole position and within which the true mean lies with a probability of 95%. (Due to a statistical procedure developed by Fisher (1953) for the analysis of a set of vectors regarded as points on a unit sphere. In this case, the analysis refers to site or sample pole positions.) |
| a | As for A, but the statistical analysis relates to directions of magnetization. |
| dp,dm | Semi-axes of the elliptical error around the pole position at the 95% probability level, dp in the colatitude direction and dm perpendicular to it. (The circle of confidence, radius 'a', round the mean direction of magnetization, transforms to an ellipse about the corresponding pole position — see McElhinny (1973, p. 83).) |

| | |
|---|---|
| Palaeomagnetic Pole | Represents the palaeomagnetic field averaged over a period of time regarded as sufficiently long (0.01 My to 1 My) that the field is free of palaeosecular variation effects. It is the point where the dipole axis corresponding to that field (assuming an axial geocentric dipole model — McElhinny, 1973) cuts the Earth's surface. It is therefore an estimate of the geographic pole position. |
| VGP | Virtual Geomagnetic Pole. It represents a spot reading of the palaeomagnetic field and as such, is not free of the effects of palaeosecular variation. |
| My | Million years. |

### (b) Illustration symbols

Directions of remanent magnetization have been plotted exclusively on an equal angle (Wulff) stereographic net. Symbols denoting those directions are shown solid if inclinations of magnetization are positive (downward pointing) and open, if negative (upward pointing). The present field direction at the localities sampled is shown as an open star. Pole positions are shown as solid symbols if they fall on the outward-facing hemisphere and as open symbols if they plot on the concealed hemisphere.

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# ABSTRACT

The primary object of the research program was to establish a Precambrian apparent polar wander path for Australia. Prior to the results reported herein, only two reliable and radiometrically dated palaeomagnetic poles were available. Pole positions based on reliable magnetic directions from some haematite ore bodies lacked necessary age control for their interpretation in terms of polar wander. The palaeomagnetic data was therefore insufficient to define an unambiguous apparent polar wander path. A pre-requisite to achieve that aim was further reliable and radiometrically dated poles. The results in this thesis, from Precambrian dykes and lavas of the Yilgarn Block, Western Australia, Precambrian dykes of the Gawler Block, South Australia and Precambrian-Cambrian sediments of the Adelaide Geosyncline, South Australia, fulfil this requirement.

An apparent polar wander curve covering the period 2500 My to the Cambrian is presented which incorporates all previously published Precambrian data and that published independantly of, but during the course of, the present investigation. As a result it has been possible to propose dates of formation of the various haematite ore bodies which outcrop in Western Australia and South Australia. The most reliable section of the Precambrian apparent polar wander curve for Australia is defined for the interval 1800 My - 1300 My. During this time the pole migrated through an angular distance of about 230°. The palaeomagnetic data indicate that Australia remained essentially in equatorial latitudes. This is in good agreement with palaeoclimatic evidence suggesting the prevalence of tropical conditions at that time. The oldest poles lie in the time range 2500 My - 2400 My. There is a lack of reliable palaeomagnetic data for the interval 2400 My - 1800 My

and this section remains to be clearly defined. Similarly, relatively few data exist between 1300 My and 750 My — this again represents a time range for which further data are required. The total arc length of the Precambrian apparent polar wander path defined is 620°. Since this represents a time span of 1900 My, between 2500 My and the base of the Cambrian, the average rate of apparent polar wander, 0.3° per My, is the same as that found from Precambrian and Phanerozoic apparent polar wander paths of other continents.

Precambrian palaeomagnetic data from the other constituent continents of Gondwanaland complement the Australian curve and enable a model curve to be proposed. This reveals that the concept of a unified Gondwanaland is valid back to at least 750 My, and suggests that the concept may be applicable as far back as c1800 My. However, pending further data for the interval 1800 My - 1300 My for Africa, extension of the concept to the older Precambrian must be considered a tentative conclusion at this stage. Preliminary indications from data older than 1800 My may be consistent with a model invoking relative motion between a proto-Africa and a proto-Australia.

The implication of these conclusions is that the various Precambrian mobile belts that form a network across Gondwanaland may not result from episodes of major ocean closure and suturing between once widely separated cratonic nuclei. Rather, the data support the contention that they are of ensialic origin, generated between contiguous crustal nuclei. This does not argue against the existence, at that time, of some sort of plate régime but questions the premise that all orogenic belts result from plate interaction.

The model apparent polar wander path defined for Gondwanaland for the interval 1400 My - 1000 My shows a more striking similarity to the similar aged section of the North American curve than has been previously noted. A proto-'Pangaea' for that time interval becomes a distinct possibility provided that the late Precambrian to Cambrian section of the North American curve is more complex than originally believed.

During routine alternating field demagnetization of pilot specimens from the Precambrian dykes it became evident that the magnetic properties of the dykes represented a wide spectrum of magnetic stability. Presentation of this spectrum in a concise and objective form led to a review of published stability indices which attempt to quantify magnetic stability. In the light of this review, which demonstrated the inadequacy of published proposals, a new stability index has been defined which successfully quantifies that property.

# CHAPTER 1

# INTRODUCTION

## 1.1 BACKGROUND AND AIM OF THE PROJECT

Plate tectonics, unlike any other theory of global tectonic processes, has met with unqualified success in providing an explanation of observations from many different branches of the Earth Sciences. In terms of this theory (Morgan, 1968; Le Pichon, 1968) the outer surface of the Earth, or lithosphere, comprises a number of rigid plates of average thickness 50 Kms - 100 Kms. These plates are in relative motion and move, in a normal direction, away from the system of oceanic ridges which are the locii of plate creation, towards the system of trenches and young fold mountains which are the sites of plate consumption. The continents may be regarded as passive passengers on the plates. Ocean basins are ephemeral features, developed during the rifting apart of continental crust and destroyed during its convergence. The buoyancy of the less dense continental crust compared with the oceanic crust ensures that once created (from fractionated mantle material) continental material cannot be consumed (McKenzie, 1969). Consumptive plate margins are thus the sites of accretion and deformation of continental material during its collision. In terms of plate theory therefore, an orogen can be understood as the culmination of an episode of ocean basin closure between blocks of continental material which were once widely separated (Mitchell and Reading, 1969; Dewey and Bird, 1970).

The question that arises, and one which is currently very controversial, is how far back in geological history can plate theory be extrapolated as a viable explanation of tectonic processes? Are ancient mountain belts and mobile zones the legacy of plate interaction or was some other process involved? Detailed studies of the linear magnetic anomaly patterns preserved in the rocks of the oceanic crust demonstrate the applicability of the theory to the last 200 My of Earth history (Heirtzler *et al*, 1968; Le Pichon, 1968; Dietz and Holden, 1970). Prior to 200 My ago however, support from this source is not forthcoming because the records of ancient ocean basins have been obliterated by post-Palaeozoic ocean basin development related to the break-up and dispersal of the constituent continents of the supercontinent Pangaea. Evidence therefore rests on the analysis of the orogenic zones themselves. This involves adoption of a uniformitarian approach in which it is assumed that rocks and structures found in ancient orogenic belts will be similar to those found in present day orogens if the same deformation process was then operative (Burke and Dewey, 1973a). Such analyses and the recognition of ancient triple junction structures have led some to conclude that the plate tectonic regime, as currently conceived, is applicable back to about 2500 My - 2000 My (Dewey and Horsefield, 1970; Burke and Dewey, 1973a,b), but this has involved the introduction of such terms as 'cryptic sutures', 'pseudo-ophiolites' and 'phantom junctions' in analyses of some pre-Phanerozoic orogens. On the other hand, there is a considerable body of evidence that the mobile belts of the Precambrian do not represent the eroded roots of collision orogeny resulting from closure of major ocean basins between once widely separated but now adjacent cratons (Shackleton, 1969; Clifford, 1970; Hurley, 1972). Rather the evidence supports the view that the belts were generated *in situ* between contiguous cratons.

Clearly, ultimate acceptance of plate theory as a viable explanation of tectonic processes back to the late Archaean or early Proterozoic is going to depend on quantitative confirmation of the scale of relative motion implied. Palaeomagnetism is the only research technique potentially able to supply such evidence. Each continental crustal unit, in theory, will have an associated apparent polar wander path whose shape may be ascertained by performing palaeomagnetic measurements on the outcropping rocks and expressing the results in terms of a chronological sequence of pole positions, which will define the path. If an expanse of continental crust comprises a number of crustal units separated by orogenic zones then in terms of the plate tectonic model, the crustal units will once have been widely dispersed. The apparent polar wander path for the 'continent' will therefore initially comprise a number of unrelated apparent polar wander paths belonging to the separate crustal units. Subsequent suturing of those units will result in the coalescing of the individual paths into a single common path. It is evident that the alternative model i.e. *in situ* development of the orogens, will manifest itself as a single common path (allowing for minor jostling and separation of the cratons not detectable palaeomagnetically).

Analysis of actual apparent polar wander paths in this fashion has provided critical support for plate tectonic interpretations of older Phanerozoic orogens as sites of consumed oceans. Such support is forthcoming for the Late Palaeozoic Ural Mountains and various younger mountain ranges of easternmost Siberia (Hamilton, 1970; McElhinny, 1973), the Early to Middle Palaeozoic Caledonian-Appalachian orogen (Dewey, 1969; Bird and Dewey, 1970; McElhinny and Opdyke, 1973) and the Palaeozoic Tasman orogenic zone of Australia (Oversby, 1971; Solomon and Griffiths, 1972; McElhinny and Embleton, 1974). To determine the relevance of plate theory to Precambrian orogens requires similar analyses to be performed on Precambrian apparent polar wander paths.

In this respect, Gondwanaland is potentially a decisive testing ground. At the start of the project described herein, there was sufficient evidence to reasonably assume that the supercontinent existed at least since the Early Palaeozoic (McElhinny and Luck, 1970a). However, the presence of a network of mobile belts with ages peaking at 550 ± 100 My made it speculation as to whether the concept of a unified supercontinent could be sustained beyond this time since, in terms of plate theory, those belts would be the legacy of the formation of Gondwanaland. In order to investigate this problem and the nature of similar but older mobile belts within Gondwanaland there was a need for Precambrian apparent polar wander paths for the constituent continents of Gondwanaland. Only for Africa was such a path available, even though of a preliminary nature (McElhinny *et al*, 1968). The aim of this project was therefore to establish a 'first-order' Precambrian apparent polar wander path for Australia.

## 1.2 THE PROJECT

Fig. 1.1 gives a map showing the main structural elements of Australia in order to illustrate the tectonic setting of rocks which have been subjected to palaeomagnetic investigation. Briefly, Australia may be divided into two broad structural zones:

(i) Occupying the western and central parts of the continent as far east as approximately longitude 138°E is the Australian Platform. This comprises a number of distinct Precambrian shield nucleii separated by mobile belts and intercratonic sedimentary basins of Precambrian age (Hills, 1965). Since the latest Precambrian, sediments of various ages up to the Tertiary have been deposited on the Platform in a number of basins.

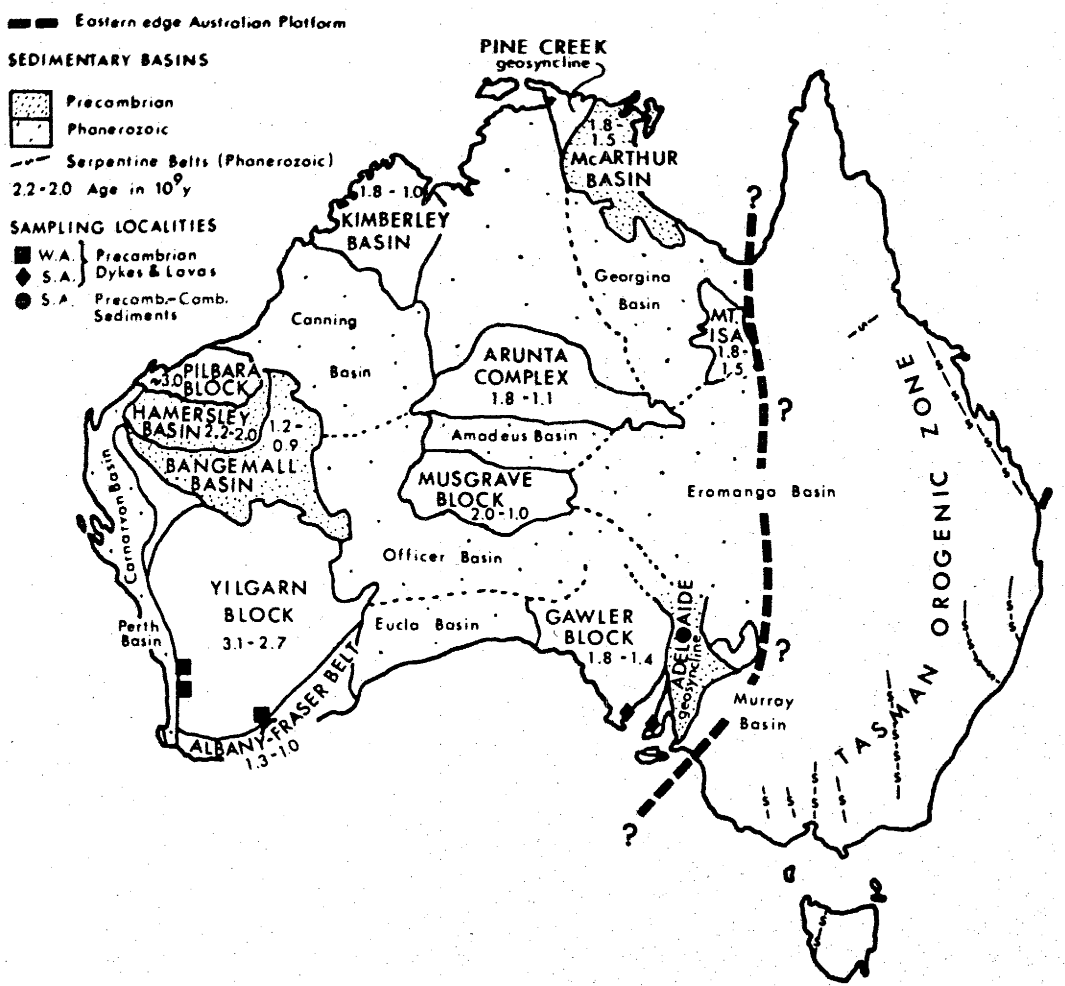


FIGURE 1.1 The main structural elements of Australia. Age information is taken from Compston and Arriens (1968).

(ii) East of the Australian Platform and occupying what is now eastern Australia is the broad Tasman orogenic zone — a feature which, in terms of plate theory (Oversby, 1971; Solomon and Griffiths, 1972), appears to be a zone of island arc complexes and small plates of continental material which have been accreted onto the Australian Platform throughout the Phanerozoic.

At the commencement of the project the only Precambrian poles available for Australia, based on cleaned magnetic remanence, were those for the 1800 ± 25 My Hart Dolerite (Kimberley Block) and 2420 ± 30 My Widgiemooltha Dykes (Yilgarn Block) reported by Evans (1969) and nine poles obtained by Porath (1967a) from various haematite ore bodies located in the Pilbara, Yilgarn and Gawler Blocks and the Hamersley Basin. The haematite ore body poles lacked absolute (radiometric) ages but were concluded to be of Precambrian age from a comparison of their pole positions with the Phanerozoic apparent polar wander path of Australia as then defined (Chamalaun and Porath, 1968; Porath and Chamalaun, 1968). Other work on Precambrian rocks comprised the pilot studies of Irving and Green (1958) and Briden (1964). The three poles reported by Irving and Green were based on uncleaned remanence and are considered unreliable by present day standards (McElhinny, 1973). The unreliability of one of those poles, that for the 1760 My Edith River Volcanics, which gave a positive fold test (Irving, 1964), also stems from the possibility that many of the sites sampled are not within the Edith River Volcanics but within the latest Precambrian or Early Cambrian Antrim Plateau Volcanics. They are also extensively developed in the area and have a very similar pole position (McElhinny and Luck, 1970b). The investigation of Briden (1964) provided miscellaneous results from some late Precambrian to Cambrian sediments from the Adelaide Geosyncline, South Australia. The data included a series of measurements of magnetic inclination in sediments penetrated by a number of borecores. The investigation produced disappointing results with scant indication of the retention of primary remanence and the likelihood of remagnetization of some sediments in the Tertiary. However, Briden (1964) reported the results in detail in anticipation that some of the results would become more intelligible in the light of further work carried out on similar aged rocks from Australia.

The locations of material sampled for palaeomagnetic work for the present investigation are shown in Fig. 1.1. The rocks comprised:

(a) 54 Precambrian dykes and the 1390 ± 140 My Morawa Lavas, both of the Yilgarn Block.

(b) 35 Precambrian dykes from the Gawler Block.

(c) A sequence of late Precambrian to Cambrian sediments from the Adelaide Geosyncline.

Radiometric dating of the dykes, using the Rb-Sr technique, was undertaken by Drs A.R. Crawford and W. Compston of this Research School. The results of that work are to be published elsewhere. The dates quoted were obtained when the thesis was in an advanced stage of preparation.

The establishment of a preliminary Precambrian apparent polar wander path for Australia was expected to yield information on:

(i) The structural integrity of Australia during the Precambrian

(ii) The age of formation of the various haematite ore bodies studied by Porath (1967a)

(iii) The history of Australia in Gondwanaland and, by implication, the origin of the intercratonic mobile belts.

The results of the palaeomagnetic work undertaken on the rocks of the Yilgarn Block, Gawler Block and Adelaide Geosyncline are reported in Chapters 3, 4 and 5 respectively. Definition of the apparent polar wander path using this new data and incorporating previously published data and other Precambrian data that became available independently of, but during the course of, this project (Facer, 1971; Embleton, 1972a; Duff and Embleton, 1974) is given in Chapter 6. Dating of the haematite ore bodies, by comparison of their poles with the path defined, and the question of the structural unity of Australia, are points that are also considered in this chapter. Chapter 7 deals with the data in the context of Gondwanaland and a brief comparison with North America is also attempted.

During the routine stepwise alternating field demagnetization of the pilot specimens selected from the dykes, it became evident that the pilot specimens represented a wide spectrum of magnetic stability. Presentation of this information in a concise and readily comprehendable form required this information to be quantified. Various indices of magnetic stability have been published to date which claim to achieve that object. To determine which, if any, was the most suitable, the indices were subjected to a detailed investigation. The results of that investigation and the definition of a new stability index form the subject matter of Chapter 2.

## 1.3 EXPERIMENTAL METHODS

The field and laboratory techniques generally employed in palaeomagnetic investigations have been extensively reviewed elsewhere e.g. 'Methods in Palaeomagnetism', eds. Collinson *et al* (1967). Apart from the techniques of thermal and alternating field demagnetization and the measurement of initial susceptibility, other techniques such as the collection, orientation and preparation of samples, the measurement of remanent magnetization, the statistical procedure employed in the analysis of palaeomagnetic data, are not considered in detail. All measurements of magnetic intensity and direction were performed on a PAR model SMI spinner magnetometer (the data is stored on file in the Research School). The useful measuring limit of this instrument was found to be about 0.4 $mA.m^{-1}$.

Demagnetization Techniques: In general, the NRM of a rock may be considered to be the resultant of two components of magnetization.

(i) A primary magnetization acquired at the time of formation of the rock,

(ii) A secondary magnetization acquired at some later time.

The remanence of a rock is only of palaeomagnetic significance if its primary component can be isolated. Two methods of demagnetization have been employed to remove the secondary component of remanence — alternating field demagnetization (applied to the Precambrian dykes and lavas) and thermal demagnetization (applied to sediments).

Magnetically a rock specimen may be regarded as a system of single domain and multidomain magnetic particles. In igneous rocks, those particles are generally members of the ferrimagnetic, titanomagnetite solid-solution series and its derivatives, whilst in sediments they are generally haematite, whose magnetization results from canting of the individual magnetic moments of an otherwise antiferromagnetic lattice (Nagata, 1961). The remanent magnetization of the system of magnetic particles in a rock is time-dependent because the energy associated with thermal fluctuations permits magnetic transitions to take place within the particles which may change the direction of magnetization or its magnitude or both. Such thermally activated transitions over intervening energy barriers separating two adjacent magnetic states may involve the motion of a domain-wall in a multidomain particle, or the reorientation of the individual magnetic moments within a single domain particle. This time-dependancy of magnetization is a relaxation process and may be described by a relaxation time, $\tau$:

$$\tau = A \exp \frac{E}{KT} \qquad 1.1$$

where A = constant (frequency factor)

E = Energy barrier to be surmounted

K = Boltzmann's constant

T = Absolute temperature.

For magnetically uniaxial single domain grains

$$E = \frac{v\, J_s\, H_c}{2} \qquad \text{(Néel, 1955)} \qquad 1.2$$

and for domain-wall motion in a multidomain

$$E = cS\, \lambda\, J_s\, H_c \qquad \text{(Everitt, 1962)} \qquad 1.3$$

where v = Grain volume

$J_s$ = Spontaneous magnetization

$H_c$ = Coercive force

c = Shape factor

S = Wall area

$\lambda$ = Barrier width.

For both single domain and multidomain particles of the same magnetic material at a fixed temperature T, the important point to note from equations 1.1 to 1.3 in that the relaxation time $\tau$, is a direct function of coercive force $H_c$. $H_c$ will vary greatly from particle to particle so that each rock will have a spectrum of relaxation times. Grains with the shorter relaxation times will tend to be the seat of secondary magnetization and from the direct relationship between $\tau$ and $H_c$ will be those with the lowest coercivities. This result is the basis of demagnetization by alternating magnetic fields.

In alternating field demagnetization, a rock, in zero ambient steady field, is subjected to an alternating magnetic field intensity whose value is slowly increased from zero to a predetermined peak value of $H_p$ A.m$^{-1}$. At the peak field, the moments of all grains for which $H_c \leqslant H_p$ follow the field. As this is slowly reduced to zero, the moments of those grains with progressively lower coercivities will be left in random orientations. At zero field, the remanent magnetization remaining in the rock will be contained in grains whose coercivities lie in the range $H_p$ to $H_{max}$. By repeating the process any number of times until $H_{applied} = H_{max}$, it is evident that grains with longer and longer relaxation times will be demagnetized. The secondary magnetization is thus preferentially destroyed leaving a primary magnetization in grains with the highest coercivities. Tumbling of the rock specimen ensures that all directions in the rock are exposed to the peak field. The equipment used in the present study was built and tested by Evans (1969) and is similar to that described by McElhinny (1966).

The technique of thermal demagnetization is based on the inverse relationship between relaxation time and T expressed by Equation 1.1. At a particular temperature $T_o$ and for a system of grains with a given set of wall characteristics (multidomains) or a particular volume (single domains), the magnetization of the system will have a particular relaxation time. It is evident from Equation 1.1 that by heating the system it is possible to reach a temperature, $T_B$, at which the relaxation time becomes very short (say of the order 100 secs). At this temperature the magnetization of the system, in the absence of an external applied field, becomes unstable and is lost, as the system adjusts itself to a state of minimum magnetic energy. If the temperature is now reduced, and the system maintained in zero field, the exponential increase in relaxation time causes the random orientations of the grain moments to become 'frozen-in' or 'blocked'. The system has been demagnetized.

As a result of the variation in physical parameters between the magnetic grains of a rock, the remanent magnetization is contained in grains which cover a spectrum of blocking temperatures. Secondary magnetization will generally reside in those grains with the shortest relaxation times which will generally be those with the lowest blocking temperatures (Equation 1.1). Thermal demagnetization therefore involves successive cycles of heating and cooling of a rock in zero field. The peak temperature is increased each time, so that each cycle demagnetizes grains with successively higher blocking temperatures. Ultimately, magnetic remanence remains only in those grains with the highest blocking temperatures and hence longest relaxation times. In this way the secondary magnetization is preferentially randomized leaving a magnetization which progressively approximates to the primary direction.

The alternating field demagnetizer and the furnace of the thermal demagnetizer were each situated in nominal field-free space at the centre of a helmholtz coil system. In practice the residual field could be maintained within about ± 20 nT.

Measurement of Initial Susceptibility: The problem that arises with thermal demagnetization is that the magnetic mineralogy, in response to heating, may undergo physico-chemical changes which may affect the remanent magnetization. For example, magnetite may oxidize to haematite, titanomagnetites may oxidize to two phase intergrowths whose composition and structure approach magnetite and ilmenite, metastable phases may invert to more stable structures (e.g. maghaemite to haematite) and iron hydroxides may dehydrate and produce secondary haematite (Nagata, 1961). Magnetic susceptibility is a parameter which is sensitive to such changes. Therefore, during stepwise thermal demagnetization of the sediments (Chapter 5) this parameter was monitored.

The instrument used for the measurement of the initial or 'reversible' susceptibility (i.e. that measured in low magnetic fields) of specimens was similar to that described by Collinson and Molyneux (1967). It comprises a pair of identical ferrite-ring cores each with an air gap. Each core is wound with a similar primary winding and a split secondary winding. The primary coils are connected to a low frequency oscillator. The secondary coils are wound in series opposition so that when the coil circuit is balanced and the primary coils excited, there is no output from the secondary coils. Because of the presence of susceptible material in a rock specimen, insertion of the specimen in one of the air gaps changes the reluctance of the gap and unbalances the circuit. The signal thus received from the secondary coil circuit is amplified and calibrated in terms of susceptibility.

Analysis of Directions: Directions of remanent magnetization have been analyzed using the statistics developed by Fisher (1953). The randomness test (Watson, 1956; Vincenz and Bruckshaw, 1960) has been employed to allow objective determination of whether a set of directions was randomly distributed. Application of the test involves comparison of the observed vector resultant R of the N unit vectors of the set with a value $R_o(N)$ which is exceeded in only 5% of cases by a set of randomly directed vectors. Where $R > R_o(N)$, the distribution of directions was accepted as non-random with a significant mean (5% level).

Computer programs related to the stability index investigation (Chapter 2) were written by the author. All others used were written by Dr F.H. Chamalaun formerly of this School.

# CHAPTER 2

# A STABILITY INDEX OF NATURAL REMANENT MAGNETIZATION

## 2.1 INTRODUCTION

The technique of alternating field demagnetization (As and Zijderveld, 1958; Creer, 1958) is now routinely used in palaeomagnetic studies involving igneous rocks. It permits the natural remanent magnetization of a rock to be discriminated into its various components and shows how these are distributed within the coercivity spectrum of the magnetic grains in the rock. Depending on the overall behaviour of the remanence to demagnetization in progressively higher fields, rocks are generally qualitatively classified as 'stable', 'partially stable', or 'unstable'. The term 'stability' has no formal definition and as a result has been loosely and ambiguously used in the literature, meaning different things to different workers.

A full description of the magnetic stability of a rock for palaeomagnetic and rock-magnetic purposes must necessarily include consideration of the following variables:

(i) Maximum coercivity of remanent magnetization

(ii) The range of alternating field values over which the direction of cleaned remanence remains grouped

(iii) The precision with which the cleaned direction is reproduced in higher alternating fields

(iv) The rate at which the natural remanent magnetization reduces on application of progressively higher alternating fields.

The meanings of these terms and their relevance to a definition of stability are described using the illustrations in Fig. 2.1. It

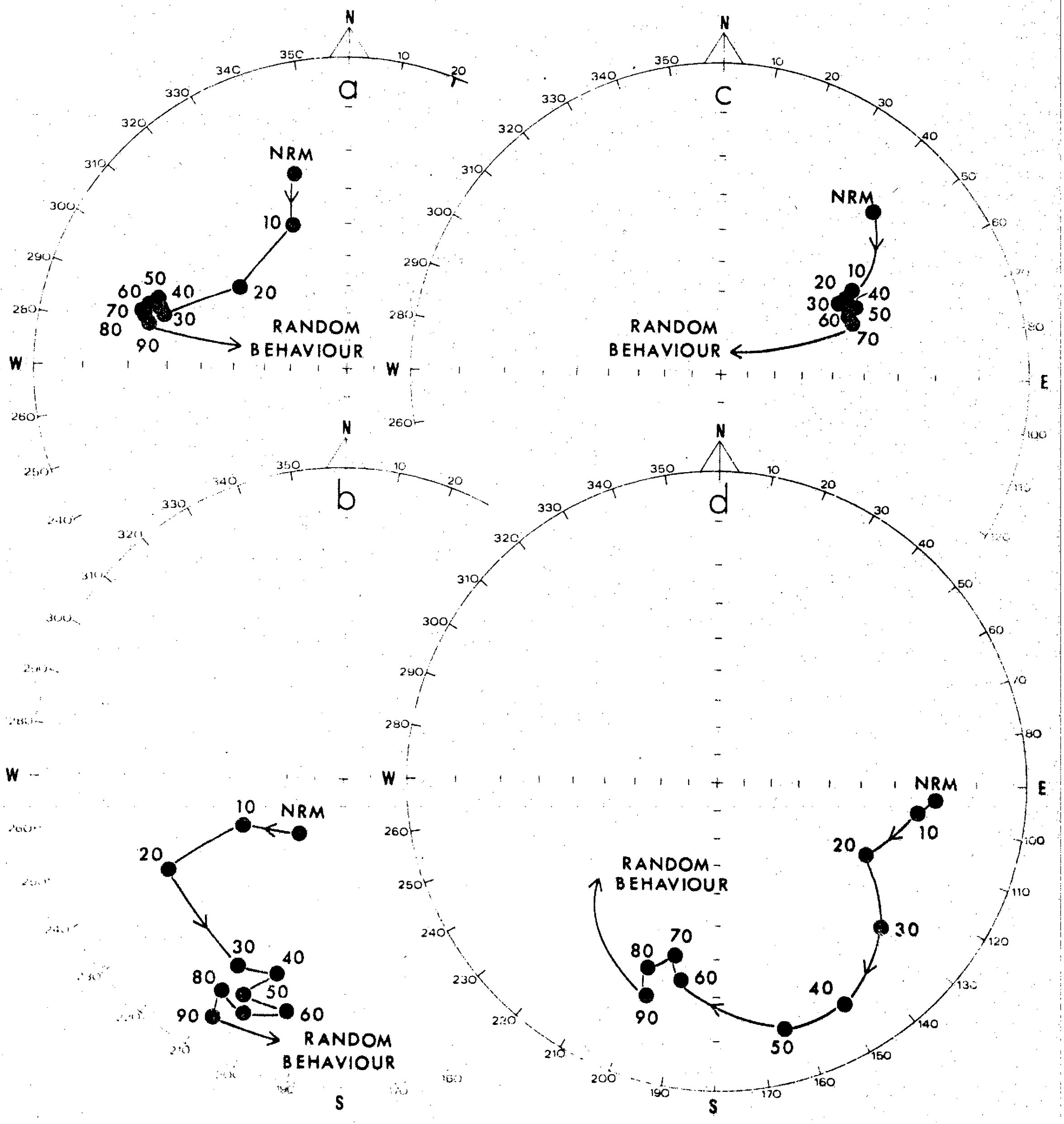


FIGURE 2.1 The directional behaviour of the four hypothetical pilot specimens used to illustrate different aspects of magnetic stability. The numbers refer to alternating demagnetizing fields (in mT).

shows four examples of demagnetization behaviour of simple two-component systems in which the directions of primary and secondary magnetizations (assumed to consist of various viscously acquired components) constituting the natural remanence, are different. In all four examples, the remanent vector undergoes an initial rotation in response to the destruction of the secondary component of remanence. Eventually a point is reached where the remanent vector ceases to rotate systematically and its direction remains essentially the same in response to increasing applied field. That direction is termed the endpoint, and signifies that the hardest component i.e. that most resistant to demagnetization, has been isolated. Until the maximum coercivity of this component is exceeded, directions stay grouped (the endpoint grouping) although its intensity may decrease. For fields higher than the maximum coercivity, the remanent vector will undergo large angular changes haphazardly and its magnitude may vary erratically. The behaviour at this stage of the demagnetization merely reflects the random orientations of the minimum moment of the rock (Irving *et al*, 1961; Dickson, 1962).

Fig. 2.1a shows an example of the hard component of magnetization revealed after treatment at 30 mT. Its direction is regarded as unchanged over a range of 60 mT. Fig. 2.1c however also shows an example where the cleaned direction is stable over 60 mT but only within the range 10 - 70 mT. Therefore the specimen referred to in Fig. 2.1a could be regarded as more stable since the cleaned component has a greater maximum coercivity of remanent magnetization — point (i) above. The range of field values over which the endpoint grouping extends is another aspect of magnetic stability — point (ii). Again comparing Figs. 2.1a and 2.1c, the range is the same in both cases, so that on this criterion alone, they are equally stable. However comparing Figs. 2.1b and 2.1d, although they have the same maximum value of coercivity (90 mT) the range of fields over which the cleaned direction is repeated is higher in the example of Fig. 2.1b.

Use of cleaning procedures brings the problem of deciding when the cleaning process is complete. The ability of the process to reproduce the cleaned direction is also called stability — point (iii). For example, a rock with an endpoint grouping which is very tight (Fig. 2.1a) could be regarded more stable than a rock in which the dispersion within the cleaned group is higher (Fig. 2.1b). On this criterion, the most stable rocks are those that clean 'best'.

The rate at which the intensity drops during AF demagnetization has also been considered a measure of magnetic stability — point (iv). A specimen whose intensity continues falling after treatment in altering fields (and after the endpoint has been attained) may be regarded less stable than a specimen which maintains a particular intensity level with repeatedly uniform directions.

To put studies aimed at elucidating the factors which affect or control the stability of rocks (Akimoto and Kushiro, 1960; Powell, 1963; Larson *et al*, 1969; Larson and Strangway, 1969; Watkins and Cambray, 1971; Watkins *et al*, 1971) on a more rigorous basis and to facilitate comparison of the magnetic characteristics of one collection with those of another (Tarling and Symons, 1967; Symons and Stupavsky, 1974), the need has arisen to make the classification of stability objective. This has therefore led to several attempts aimed at obtaining a quantitative measure of this property (Tarling and Symons, 1967; Wilson *et al*, 1968; Murthy, 1971; Briden, 1972; Symons and Stupavsky, 1974). To quantify stability, the raw data from stepwise, alternating field demagnetization is used to evaluate some sort of index. The formulation of a so-called Stability Index however, depends on (a) how the designer views stability and (b) the purpose for which it was developed. No index defined to date has accounted for all aspects here considered relevant to a full description of magnetic stability. A review of the five published indices is given in the following section.

In this chapter, a new stability index is defined which is applicable to magnetite-bearing igneous rocks. It takes into account, in a single formulation, all aspects of magnetic stability discussed above. Investigation of this problem arose from the palaeomagnetic work undertaken on dyke swarms from Western Australia and South Australia and was prompted by,

(a) The presence of a wide range of values of the variables considered relevant to a full description of magnetic stability. This provided the opportunity to test thoroughly the new index and its performance compared with the other published indices.

(b) The desire to classify quantitatively the magnetic stability characteristics of the rock collection, so facilitating a description of the results.

## 2.2 A REVIEW OF PUBLISHED STABILITY INDICES

Stability indices published to date fall into two categories:

(i) Attempts to put cleaning procedures on an objective basis has led to the definition of three stability indices (Tarling and Symons, 1967; Briden, 1972; Symons and Stupavsky, 1974). They are such that they define (by the magnitude of the index) the relative ability of each sample to define the optimum cleaning field. They are here regarded as 'optimum cleaning indices'.

(ii) Two further indices (Wilson *et al*, 1968; Murthy, 1971) estimate stability in terms of the degree of soft magnetization present. They are classed as 'relative stability indices'. Although intended to describe the spectrum of total magnetic stability, it is argued that their definitions are incomplete for this purpose.

### 2.2.1 Optimum Cleaning Indices

The main function of this type of index is to determine objectively, the optimum cleaning field required to remove unwanted secondary magnetization from a sample. As and Zijderveld (1958) originally argued that the cleaning process was complete when the remanent vector ceased to rotate from the secondary remanence direction with increasing demagnetizing fields. However, as previously noted, this situation is only found in the case of extremely stable remanence; in most cases, the remanent vector never stops moving within the stable endpoint region so that choice of optimum field becomes rather subjective.

Prior to the advent of optimum cleaning indices, schemes to overcome this uncertainty revolved around a minimum dispersion criterion. Thus Irving *et al* (1961) and McElhinny and Gough (1963) argued that, for a series of test specimens washed at different fields, the optimum cleaning field was that giving the best grouping of directions. To allow for a variation in magnetic properties between specimens Watkins and Richardson (1968) and Dagley and Ade-Hall (1970) used modifications of the Irving *et al* procedure. Essentially, *all* specimens were washed at a number of different fields and an optimum cleaned mean-direction was chosen to be the mean of that combination of directions (not necessarily belonging to the same field value) which gave the least dispersion compared with all other possible combinations. However, both Storetvedt (1970) and Briden (1972) have criticised the ability of the minimum dispersion method to isolate meaningful palaeomagnetic directions in certain situations.

Tarling and Symons (1967) were the first to introduce a stability index to put the determination of the optimum cleaning field onto an objective basis. The rationale behind this index, and other optimum cleaning indices, is to select that part of the stable range in which the remanent vector undergoes the least amount of change between adjacent cleaning fields (suggesting complete removal or optimum minimization of the secondary magnetization). Their index (Table 2.1.a) is a function of the directional change undergone by the remanence vector after two or more successive increases in alternating field strength, expressed in terms of the circular standard deviation (Fisher, 1953), and the range of field over which this takes place. The optimum cleaning fields occur in that range for which the index has its maximum value. Their formulation is thus independent of intensity change, as is the most recent proposal of Symons and Stupavsky (1974). Physically, their parameter (Table 2.1.b) expresses the rate of angular change in remanence direction with field at each demagnetization step. The optimum cleaning field, by definition, is the field at which the minimum value of the rate occurs. The Symons-Stupavsky index can be criticized on the grounds that to be mathematically rigorous, experimental changes of declination and inclination with increasing field should be simulated by smooth and continuous functions, otherwise evaluation of their index in the way they suggest is only approximate.

Symons and Stupavsky justified their approach in disregarding intensity data by arguing that directional data alone were the most important in palaeomagnetic studies. Earlier studies by Ade-Hall (1969), Murthy (1971) and Briden (1972) argued that to give an adequate representation of magnetic stability both intensity and directional data were essential ingredients. Briden (1972) designed an index (Table 2.1.c) which was a function of both directional and intensity change at each demagnetization step. It is formulated in terms of the

TABLE 2.1

Mathematical definitions of published Stability Indices

| Authors | Formulation* |
|---|---|
| a. Tarling and Symons (1967) | $\mathrm{SI} = \max[(r)^{\frac{1}{2}}/\Theta_{63}]$ |
| b. Symons and Stupavsky (1974) | $\mathrm{PSI} = 57.296 \times 10^{4} \times \lvert d\underline{j}(B)/dB \rvert$ mdeg.mT$^{-1}$ |
| c. Briden (1972) | $S_{n+1} = 1.0 - \left\lvert \frac{j_{n+1}}{J_n} \right\rvert$ |
| d. Wilson *et al* (1968) | $S_{20} = J_{20}/(J_{20} + j_{0,20})$ |
| e. Ade-Hall (1969) | $S_n = J_n/(J_n + \sum_{i=1}^{i=n} j_i)$ |
| f. Murthy (1971) | $\mathrm{SF} = (J_{opt}/J_o)/\Theta_{63}$ |

*Symbol notes:

A full explanation of how each index operates is given in the text. The magnitude and direction of the remanent magnetization in a specimen is denoted by the vector $\underline{J}$. The intensity of magnetization is denoted by $J$ (= $|\underline{J}|$).

$r$ = Difference between the maximum and minimum values of the demagnetizing field represented by three or more consecutive remanence directions during a stepwise alternating field demagnetization.

$\Theta_{63}$ = Circular standard deviation (Fisher, 1953).

$\underline{j}(B)$ = $\underline{J}(B)/J(B)$. $\underline{J}(B)$ is the remanent vector after demagnetization in a field B and $\underline{j}(B)$ is the unit vector along $\underline{J}(B)$

$J_n$ = Intensity of magnetization at the nth demagnetization step.

$J_o$ = Intensity of magnetization of NRM.

$J_{opt}$ = Intensity of magnetization at the optimum cleaning field.

$J_{20}$ = Intensity of magnetization at a field of 20 mT.

$j_{n+1}, j_i$ = Magnitude of the difference vector between successive measurements of the remanent magnetization vector during stepwise alternating field demagnetization i.e. $j_{n+1} = |\underline{J}_n - \underline{J}_{n+1}|$ and $j_i = |\underline{J}_i - \underline{J}_{i-1}|$

$j_{0,20}$ = $\sum_{i=1}^{n} j_i$, where n is the number of difference vectors between $\underline{J}_0$ and $\underline{J}_{20}$.

magnitude of the difference vector between two adjacent vectors expressed as a fraction of the magnitude of the first of the two vectors. The index is evaluated at regular intervals of the demagnetizing field and has been so designed that if direction and intensity conspire to produce the smallest change between two adjacent vectors, the index reaches its maximum value. The field values at which the minimum change occurs define the limits of the optimum cleaning field.

The change undergone by the remanent vector during demagnetization is a function of its magnitude and direction. Therefore, the Briden index gives a physically more complete description of that change than intensity independent indices described by Tarling and Symons (1967) and Symons and Stupavsky (1974). The Briden index was chosen to define the optimum cleaning fields employed in routine magnetic cleaning of the dykes (Chapters 3 and 4). In practice, a visual inspection of the demagnetization data during routine cleaning was sometimes necessary to check that the minimum change isolated by the index referred to the primary magnetization rather than a hard secondary magnetization.

### 2.2.2 Indices of Relative Magnetic Stability

Workers who have formulated such indices (Wilson *et al*, 1968, generalized by Ade-Hall, 1969 and Murthy, 1971) have been motivated by the need to compare magnetic stability with a number of other magnetic and opaque petrological parameters (e.g. Wilson *et al*, 1968; Ade-Hall *et al*, 1968; Ade-Hall, 1969; Lawley and Ade-Hall, 1971; Murthy, 1971; Ade-Hall *et al*, 1972) in order to define and experimentally demonstrate the factors governing magnetic stability.

Two different indices have been proposed to date. The Wilson *et al* (1968) index (Table 2.1.d) measures stability in terms of the ratio of the magnitude of the remanent vector at a field of 20 mT to the magnitude of the same vector and the cumulative sum of the magnitudes of all difference vectors between the original NRM direction and the 20 mT direction. It is thus a function of both intensity and directional change. As the difference vectors become smaller and the rock, therefore, more stable, so the value of the index approaches its maximum of 1. Ade-Hall (1969) has generalized this formulation (Table 2.1.e) so that the index can be evaluated at any one of the steps employed during demagnetization. It is evident though, that because of the cumulative term in the denominator of both formulations, the index measures stability in terms of the low coercivity components (Briden, 1972) and is dependent upon the angle these make with the primary direction (Murthy, 1971).

Murthy (1971) therefore proposed an index (Table 2.1.f) which he felt might '...better reflect the stability of a specimen' (Murthy, 1971, p.809). It measures stability in terms of the ratio of the fraction of the original intensity remaining at the optimum cleaning field (determined by some other method) to the grouping of endpoint directions taken by the remanent vector between its NRM and optimum cleaned direction inclusive, expressed in terms of the circular standard deviation. One disadvantage of this formulation is that it is numerically indeterminate for unstable rocks and those which are highly stable and require no cleaning. However, the index is still essentially a measure of the low coercivity component.

## 2.3 DEFINITION OF THE STABLE RANGE

This is described as the range of demagnetizing field values over which the directions at the endpoint remain grouped. The problem which arose in defining this characteristic was how to determine its field limits objectively. Obviously, the lower field value at which the vector endpoint ceases to move after removal of secondary remanence and the higher field value at which it starts moving haphazardly, is hardly a practical criterion for judging the lower and upper limits, respectively, of the stable range except in those cases of highly stable remanence. In most cases, the remanent vector never actually stops moving in the stable range. Its direction tends to plot in a restricted zone of the stereographic net. The uncertainty is whether particular directions should be included within the stable range or omitted. Subjective assessment would inevitably lead to different range limits from different individuals. An account is therefore given of the methods employed in defining this entity more rigorously.

Two methods were investigated, one statistical, the other 'geometrical'. In each case, success has been judged by the ability of the method, using a computer and set criteria, to select from unscrutinized pilot data, the limits and value of the stable range which correspond most closely with those considered intuitively realistic.

The statistical approach was based on the statistical test for serial correlation of a sequence of unit vectors devised by Watson and Beran (1967). The attractiveness of this test lay in the fact that it makes no assumptions concerning the nature of the directional and statistic distributions involved. For an ordered sequence of N unit vectors $(\underline{X}_1, \underline{X}_2 \ldots \underline{X}_N)$ the statistic they used to characterize correlation was:

$$L(OB) = \sum_{i=1}^{i=N-1} \underline{X}_i \cdot \underline{X}_{i+1}$$

where L(OB) is the path length obtained by joining the $\underline{X}_i$ in order and each $\underline{X}_i \cdot \underline{X}_{i+1}$ is a link in the path. Thus, large values of the path length indicate significance. The test was completed by determining the randomization distribution of L with which the observed value L(OB) could be compared to determine its significance level. Use of Monte Carlo methods showed the randomization distribution of L to be approximately normal. Denoting the mean of this distribution by L'(L) and its variance by V(L), and reducing the curve to a standard normal curve by transformation of the values to a new variable T (Hoel, 1962), L(OB) is significant at the P% level if

$$T > Z \quad \text{or} \quad T/Z > 1$$

where $$T = \frac{L(OB) - L'(L)}{[V(L)]^{\frac{1}{2}}} \qquad 2.1$$

and Z = ordinate value of the standard normal curve at the significance level P.

To obviate the necessity of using Monte Carlo methods for the calculation of L'(L) and V(L) in each new situation, Watson and Beran (1967) give theoretically derived formulae for the calculation of these parameters.

The test was originally envisaged to be suitable for the analysis of short-range correlation of magnetic directions along deep-sea cores or in lava sequences. However, the present problem appeared eminently suited for application of the test. The stepwise demagnetization is an ordered sequence of vectors and in the case of a stable rock, the stable range vectors must be correlated. It was believed therefore, that by applying the test to a complete demagnetization sequence it might be possible to isolate a sequential subset of vectors for which it was significant at the 5% or 1% level. The range of field values of the subset thus selected would then be accepted as the stable range. For unstable rocks of course, the test should never be significant.

To determine its suitability, the test was applied in three ways to the results from seven pilot specimens representing a wide range of magnetic stability (Fig. 2.2). The results in each case were unsatisfactory. An adopted procedure in the three approaches

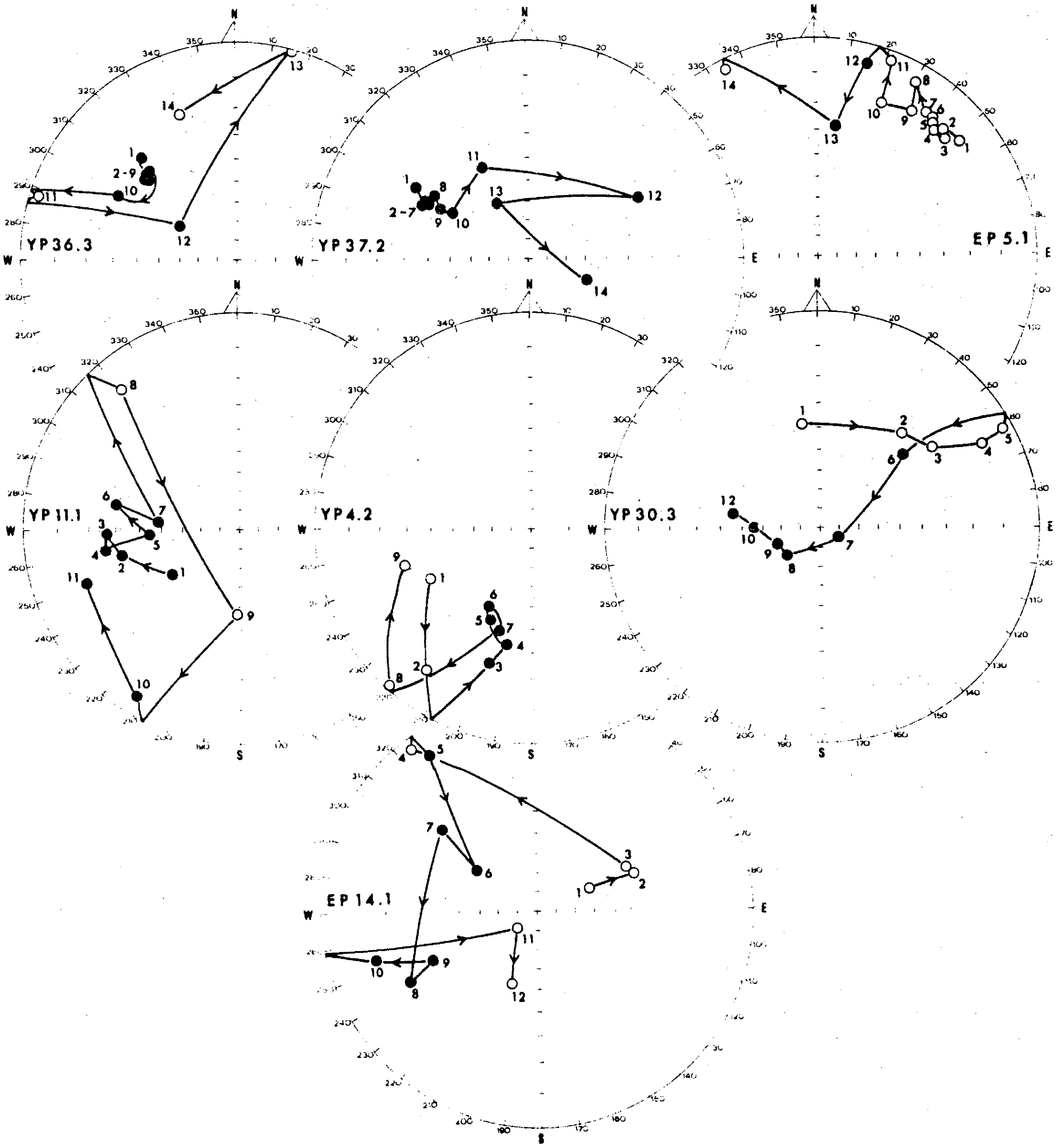


FIGURE 2.2 The directional behaviour of the seven test pilot specimens used for evaluating different methods for objective assessment of the stable range (R). The pilot specimens were subjected to alternating field demagnetization. The numbers 1 - 14 refer to the following demagnetizing fields (in mT) respectively: 0, 5, 10, 15, 20, 25, 32.5, 40, 50, 60, 75, 90, 110 & 130.

was that if the test proved negative ($T/Z < 1$) a procedure to home-in on the closest group of directions was initiated. The focus of the home-in procedure was the mean of the directions chosen by the Tarling-Symons stability index (see section 2.2.1). This index was used for locating the least dispersed group of directions because experience with it during subjective appraisal of the stable ranges of the 183 pilot specimens had demonstrated it to be very competent in this respect. The home-in procedure was terminated either when the test became positive, or, in the absence of this, at a semi-angle of 10° from the mean. In the latter case the test was taken to indicate the absence of a suitable stable range.

Approach 1. The results of applying the test to the complete demagnetization data sets of the seven pilot specimens showed the inability of the test to discriminate between pilots with well-grouped (YP 37.2 - Fig. 2.2) and scattered directions (YP 30.3 - Fig. 2.2). All pilots gave positive tests ($T/Z > 1$) at the 5% level (Table 2.2), while a more stringent test at the 1% level would still not have initiated a home-in procedure for the less stable pilots. Therefore, use of the test in this manner produced serious overestimates of the magnitude of the stable range. The reason for this failure is evident from the values of the individual parameters (Table 2.2) used in the test. For a directionally well-grouped pilot specimen, they reflect a distribution of randomized L values which approaches a spike in shape, while for a directionally scattered pilot, with possible path lengths, L, differing greatly in value, they reflect a flattened distribution. From the definition of T (equation 2.1), a spike-shaped distribution will produce a small value for both numerator and denominator and a value of T, therefore, of the order of unity. For a flattened distribution, however, the large standard deviation is offset by a large difference between the mean and observed path lengths, thus producing again a value

TABLE 2.2

Results of the Watson-Beran statistical test on the complete demagnetization data sets of the seven test pilot specimens

| Pilot Specimen | Value of test (T/Z) at given significance level: | | Theoretical mean path length, L'(L) | Observed path length, L(OB) | Variance |
|---|---|---|---|---|---|
| | 5% | 1% | | | |
| YP 36.3 | 1.212 | .857 | 10.4119 | 11.2456 | .1748 |
| YP 37.2 | 1.509 | 1.067 | 9.3544 | 11.1717 | .5362 |
| EP 5.1 | 2.419 | 1.711 | 11.0313 | 12.5393 | .1435 |
| YP 11.1 | 1.225 | .866 | 5.4968 | 7.0004 | .5565 |
| YP 4.2 | 1.444 | 1.021 | 5.0907 | 6.9998 | .6459 |
| YP 30.3 | 2.334 | 1.650 | 1.0594 | 8.8820 | 4.1523 |
| EP 14.1 | 2.230 | 1.577 | .2922 | 7.6502 | 4.0221 |

of T around unity and the likelihood of a positive test, as observed.

To overcome the problem posed by the directionally scattered pilots, the data sets of the seven pilots were subjected to a preliminary discarding procedure. This eliminated directions outside a cone of semi-angle 40°, centred on the mean of the group located by the Tarling-Symons index. A procedure ensured that the 40°-subset thus retained was sequential, with no spurious higher field directions being kept if lower field directions had been discarded. The idea behind this initial sorting procedure was to eliminate the obviously erratic part of the demagnetization trend in order to reduce, artificially, the standard deviation of the distribution of randomized L values. The results obtained by applying the test to the 40° subsets (Table 2.3) demonstrate the efficacy of this idea. All four pilots (YP 11.1, YP 4.1, YP 30.3 and EP 14.1) which exhibited large amounts of endpoint movement are rejected by the test at the 1% level and require the home-in procedure to determine a stable range subset.

Using the 40° subset therefore, as the initial data set, the second and third approaches of using the serial correlation test were applied. Common to both, the home-in procedure produced subsets related to a cone whose semi-angle, when necessary, was reduced in increments of 5° from the initial 40° to a minimum of 10°.

Approach 2. T was recalculated for each new subset using the directions retained. The results are given in Table 2.4. A positive test was never produced from any of the pilots which gave a negative test with the 40° subset, suggesting the absence of any subset in these pilots suitable for definition as the stable range. Subjectively, however, such sets (Fig. 2.2) are observed to be present. For each new subset, recalculation of the values used in the test produces a distribution of L values which becomes more spiked. As a result the difference between L(OB) and L'(L) diminishes. The test fails because

## TABLE 2.3

Results of the Watson-Beran statistical test on the 40° semi-angle subsets of the seven pilot demagnetization data sets

| Pilot Specimen | Value of test (T/Z) at given significance level: | |
|---|---|---|
| | 5% | 1% |
| YP 36.3 | .958 | .678 |
| YP 37.2 | 1.931 | 1.366 |
| EP 5.1 | 2.173 | 1.537 |
| YP 11.1 | .954 | .675 |
| YP 4.2 | .909 | .643 |
| YP 30.3 | 1.330 | .941 |
| EP 14.1 | -.266 | -.188 |

TABLE 2.4

Values of the Watson-Beran statistical test during the home-in procedure from the initial 40° data set (parameters recalculated at each semi-angular distance)

| Pilot Specimen | Test values at a given significance level for each semi angular distance | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 5% | | | | | | | 1% | | | | | | |
| | 40° | 35° | 30° | 25° | 20° | 15° | 10° | 40° | 35° | 30° | 25° | 20° | 15° | 10° |
| YP 36.3 | .958 | .958 | .958 | .958 | .958 | .958 | .959 | .678 | .678 | .678 | .678 | .678 | .678 | .678 |
| YP 37.2 | 1.931 | .......... No Home-in Required ......... | | | | | | 1.366 | .......... No Home-in Required ......... | | | | | |
| EP 5.1 | 2.173 | .......... No Home-in Required ......... | | | | | | 1.537 | .......... No Home-in Required ......... | | | | | |
| YP 11.1 | .954 | .954 | .954 | .954 | .437 | .437 | .243 | .675 | .675 | .675 | .675 | .309 | .309 | .172 |
| YP 40.2 | .909 | .909 | .909 | .909 | .909 | .909 | .213 | .643 | .643 | .643 | .643 | .643 | .643 | .137 |
| YP 30.3 | 1.330 | .......... No Home-in Required ......... | | | | | | .941 | .941 | .781 | .781 | .781 | .534 | * |
| EP 14.1 | -.266 | -.266 | -.266 | -.266 | -.266 | -.266 | * | -.188 | -.188 | -.188 | -.188 | -.188 | -.188 | * |

*Only one direction remaining

this difference decreases at a faster rate than the standard deviation. Consequently, the numerical value yielded by the test using this method of application decreases rather than increases. A possible solution to this problem suggested the following method of application.

Approach 3. Using the 40°-subset directions, it is possible to calculate a critical value of L, L(CR), at any desired significance level such that T/Z = 1. A positive test results therefore if L(OB)/L(CR) > 1. Since any path length, L, is the sum of the cosines of the angles between successive, adjacent vectors, then by dividing the number of links in the path into L(CR) and L(OB), the critical average cosine value COS(CR) and the observed average cosine value COS(OB), are obtained respectively. Since COS(CR) at a particular significance level expresses the critical value that must be exceeded for a positive test, it is argued that if a subset could be isolated from the 40° set such that it had the characteristic that its $\mathrm{COS(OB)} > \mathrm{COS(CR)}_{40°}$ then its directional distribution was representative of a group which would give a positive test at a 40° semi-angle. By this token therefore, this subset would be accepted as the stable range.

For the seven pilots, the values of $\mathrm{COS(CR)}_{40°}$ at the 5% and 1% levels were calculated and compared with those of COS(OB), recalculated at each semi-angular distance during the home-in. The results are given in Table 2.5. Subsets were obtained for five of the seven pilots. For each, the limits of the stable range, corresponding to the highest and lowest field values present in the subset are given for comparison with subjective assessments. An obvious criticism is that in some cases (EP 5.1, YP 30.3), the test (5% level) gives rather generous limits to the stable range. Raising the significance level (1% level) for greater stringency has little material effect on these two, but causes the range for YP 11.1 to become rather narrow. The overriding shortcoming, however, is the fact that the method failed for two pilots, one of which

TABLE 2.5

Values of the statistical test COS (OB)/COS $(CR)_{40°}$ during the home-in procedure from the initial 40° data set (observed average cosine, COS (OB), recalculated at each semi-angular distance) and the stable range limits that the test and the geometrical method define

| Pilot Specimen | Test values COS (OB)/COS $(CR)_{40°}$ at a given significance level for each semi angular distance | | | | | | | | | | | | | | Stable Range (SR) limits (in mT), defined by various methods | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 5% | | | | | | | 1% | | | | | | | 5% SR | 1% SR | Estimated SR | Geometrical method SR |
| | 40° | 35° | 30° | 25° | 20° | 15° | 10° | 40° | 35° | 30° | 25° | 20° | 15° | 10° | | | | |
| YP 36.3 | .9999 | .9999 | .9999 | .9999 | .9999 | .9999 | 1.0043 | .9988 | .9988 | .9988 | .9988 | .9988 | .9988 | 1.0033 | 0-50 | 0-50 | 0-50 | 0-60 |
| YP 37.2 | 1.0075 | .......... No Home-in Required ......... | | | | | | 1.0042 | .......... No Home-in Required ......... | | | | | | 0-75 | 0-75 | 0-60 | 0-60 |
| EP 5.1 | 1.0223 | .......... No Home-in Required ......... | | | | | | 1.0143 | .......... No Home-in Required ......... | | | | | | 0-90 | 0-90 | 0-50 | 0-50 |
| YP 11.1 | .9989 | .9989 | .9989 | .9989 | 1.0070 | * | * | .9889 | .9889 | .9889 | .9889 | .9969 | .9969 | 1.0098 | 5-32.5 | 5-20 | 5-32.5 | 5-32.5 |
| YP 4.2 | .9986 | .9986 | .9986 | .9986 | .9986 | .9986 | .9987 | .9923 | .9923 | .9923 | .9923 | .9923 | .9923 | .9925 | 0 | 0 | 15-32.5 | 10-32.5 |
| YP 30.3 | 1.0237 | .......... No Home-in Required ......... | | | | | | .9941 | .9941 | 1.0191 | * | * | * | * | 32.5-90 | 40-90 | 40-50 | 40-60 |
| EP 14.1 | .9791 | .9791 | .9791 | .9791 | .9791 | .9862 | .9862 | .9725 | .9725 | .9725 | .9725 | .9725 | .9792 | .9795 | 0 | 0 | 40-60 | 40-60 |

*Test satisfied

(YP 4.2) had an obvious endpoint. This made it unsatisfactory for defining the stable range in precisely those cases where an objective method is most needed. Reducing the significance level to 10% in order to lower the value of $\text{COS(CR)}_{40^\circ}$ might have had the effect of making this method 100% successful, but under such circumstances, it is evident that the limits of the stable range defined would have been unreasonably large. The use of a variable significance level depending on the type of pilot, might also have produced greater success, but this is subject to the criticism of being unsystematic, the main argument levelled against subjective assessment.

On the basis of the unsatisfactory results thus far obtained, it was concluded that the Watson-Beran statistical test was unsuitable for defining the stable range; its use was abandoned in favour of a completely different approach.

The 'geometrical' method arose from the observation that during the routine homing-in procedure used in the statistical method, the subset of directions isolated by the 15° semi-angle cone often defined a stable range which was close to, or coincided with that selected subjectively. The method consisted, therefore, of homing in to a 15° semi-angle cone and accepting as the stable range the subset retained. The home-in was performed twice where necessary, using a different criterion each time for initially locating the least dispersed set of directions.

Firstly, the closest grouping of directions was chosen by use of the Tarling-Symons index. Home-in was initiated from the mean of that subset of directions within an arbitrarily chosen semi-angle of 40° of the mean provided by the Tarling-Symons index. Thereafter, for each new semi-angular distance, the mean was recalculated, using the subset remaining, before the next angular reduction. A procedure ensured that the subsets were sequential.

Secondly, the mean of the two closest successive directions was calculated for each pilot. This pair was defined to exist if the angular separation was less than 15°. If the mean was more than 40° away from the mean of directions selected by the Tarling-Symons stability index, the home-in procedure was repeated using, as a focus for all subsets, the mean of this pair. The reason for this second application lay in the fact that for partially stable rocks, the closest pair was sometimes found to be a better indication of the most stable region than the Tarling-Symons index which could miss it because of the index requiring a minimum of three vectors for its evaluation.

In the event of both home-in procedures isolating a 15° subset with at least two vectors less than 15° apart, the choice of subset as the stable range was based upon such considerations as the number of included vectors, closeness of the mean to the cleaned directions of other specimens from the same dyke and a general preference for directions isolated at higher alternating fields. The results of applying the method to the seven pilot specimens are shown in Table 2.5. Because of the good agreement between subjective and objective determinations of the stable range in all cases, this method was adopted to define the stable range of all 183 pilot specimens. A comparison with subjective assessment of all pilots showed that for 51.9% of the collection the magnitude of the objectively (or systematically) determined stable range was equal to that determined subjectively, while for 67.8% it was within ± 30% of the subjective value. The absence of 100% agreement is taken to reflect the unsystematic nature of the subjective determinations, particularly in rocks with partially stable magnetization.

The stable range of a specimen is therefore defined as that sequential set of directions which are within an angular distance of 15° of the mean of the most closely grouped part of the stable endpoint region. For partially stable rocks in which the number of directions is two, the stable range is considered to be defined only if these two directions are also less than 15° apart. The magnitude of the stable range, is denoted by R. It follows that the coercivity of primary remanent magnetization is the maximum demagnetizing field value represented in the stable range — denoted by $\tilde{B}_p$ (Fig. 2.3). It represents the field at which the primary component of magnetization is effectively destroyed and for palaeomagnetic purposes represents the practical upper limit of the coercivity spectrum. The coercivity of secondary remanence is the lowest demagnetizing field value represented in the stable range. It represents the field at which the secondary component of magnetization is effectively removed and is denoted by $\tilde{B}_s$ (Fig. 2.3).

## 2.4 A NEW STABILITY INDEX

Three independent parameters were considered necessary to give an adequate description of magnetic stability (the intensity aspect of (iv) in Section 2.1 is included in (i) below) and represent:

(i) Intensity and directional variation of the remanent vector within the stable range

(ii) The proportion of the remanent coercivity spectrum which is occupied by coercivities of the stable range

(iii) A gauge of the 'hardness' or maximum coercivity of remanence.

The formulation of each of these parameters is briefly described.

(i) The overall behaviour of the remanent vector within the stable range, has been expressed in terms of a parameter (MBI) based on the optimum cleaning index of Briden (1972). It is argued that, being intensity dependent, this index (BI) provides a better measure of the total change undergone by the vector within a particular field interval, i, than either of the two intensity independent cleaning indices (Tarling and Symons, 1967; Symons and Stupavsky, 1974). In the general case where the stable range spans several field intervals however, several values of the index ($BI_i$) are obtained. Since the general level of behaviour of the remanent vector within the stable range could not be truly represented by a single $BI_i$ value, it was decided that the best estimate of the overall level would be the arithmetic mean value of all $BI_i$ values within the stable range. Accordingly the parameter (MBI) is defined as:

$$MBI = \frac{\sum_{i=1}^{i=n} BI_i}{n}$$

where n is the number of $BI_i$ values in the stable range of magnitude R.

The maximum value of MBI is 1, corresponding to a rock in which there is neither change in direction nor intensity of the remanent vector in the stable range. With increasing dispersion and intensity fluctuation at the endpoint, the value decreases down to a defined minimum of 0 for an unstable rock.

(ii) The parameter which expresses the proportion of the coercive force spectrum in the stable range is defined as:

$$C_s = \frac{R}{\tilde{B}_p}$$

The importance of this aspect of stability is evident since different degrees of stability would be subjectively accorded to two rocks in which the same remanent coercivity spectrum was respectively fully, and partially, occupied by the stable range.

Since

$$\frac{R}{\tilde{B}_p} \equiv 1 - \frac{\tilde{B}_s}{\tilde{B}_p}$$

the parameter may be regarded as a measure of the importance of secondary remanence to the composite remanence in a rock. In this respect the property is essentially the same as that considered by the stability indices of Wilson *et al* (1968) and Murthy (1971). The parameter has its maximum value of 1 when secondary remanence is absent (stable) and minimum of 0 when remanence is purely secondary (unstable rock).

(iii) Every rock has its own characteristic remanent coercivity spectrum (Larson *et al*, 1969). The parameter, $C_p$, gauges the upper limit of this spectrum i.e. the ability of the primary magnetization to withstand higher and higher demagnetizing fields without destruction. It is defined as:

$$C_p = \frac{\tilde{B}_p}{80} \qquad 0 \leqslant \tilde{B}_p < 80 \text{ mT}$$

If $B_p \geqslant 80$ mT, $C_p = 1$.

It measures the coercivity of primary remanence in terms of the highest possible experimental value for the maximum coercivity of multidomain T.R.M. (Evans and McElhinny, 1968).

The stability index, SI, was defined by combining the three parameters expressing different aspects of stability into a single formulation. Thus:

$$SI = MBI \times C_s \times C_p$$

or

$$SI = MBI \times CI$$

where CI can be thought of as a coercivity index ($C_s \times C_p$). Consideration of the extreme values for each of the three parameters will show the value of SI to vary from 0 for a completely unstable rock and approaches a maximum of 1 with increasing stability.

## 2.5 EXPERIMENTAL EVALUATION OF SI

The stability index was tested using the demagnetization data from 183 pilot specimens of the Western and South Australian dykes collection. The range of magnetic stabilities exhibited by this collection, with $\tilde{B}_p$ ranging from 0 - 150 mT, made it eminently suitable for this purpose. The raw data for each pilot, in the majority of cases, consisted of a series of measurements of direction and intensity of remanence at every 5 mT in the range 0 - 25, 32.5, 40, 50, 60, 75, 90 mT and thereafter at intervals of 20 mT up to a peak value of 210 mT where necessary. Demagnetization of a pilot specimen was generally terminated two field increments above $\tilde{B}_p$, or for an unstable pilot, at 75 mT. A regularly spaced set of vectors at 5 mT intervals and starting at 0 mT, was derived from the raw data set by linear interpolation of the cartesian components of the remanent vector so that values of $BH_i$ could be calculated.

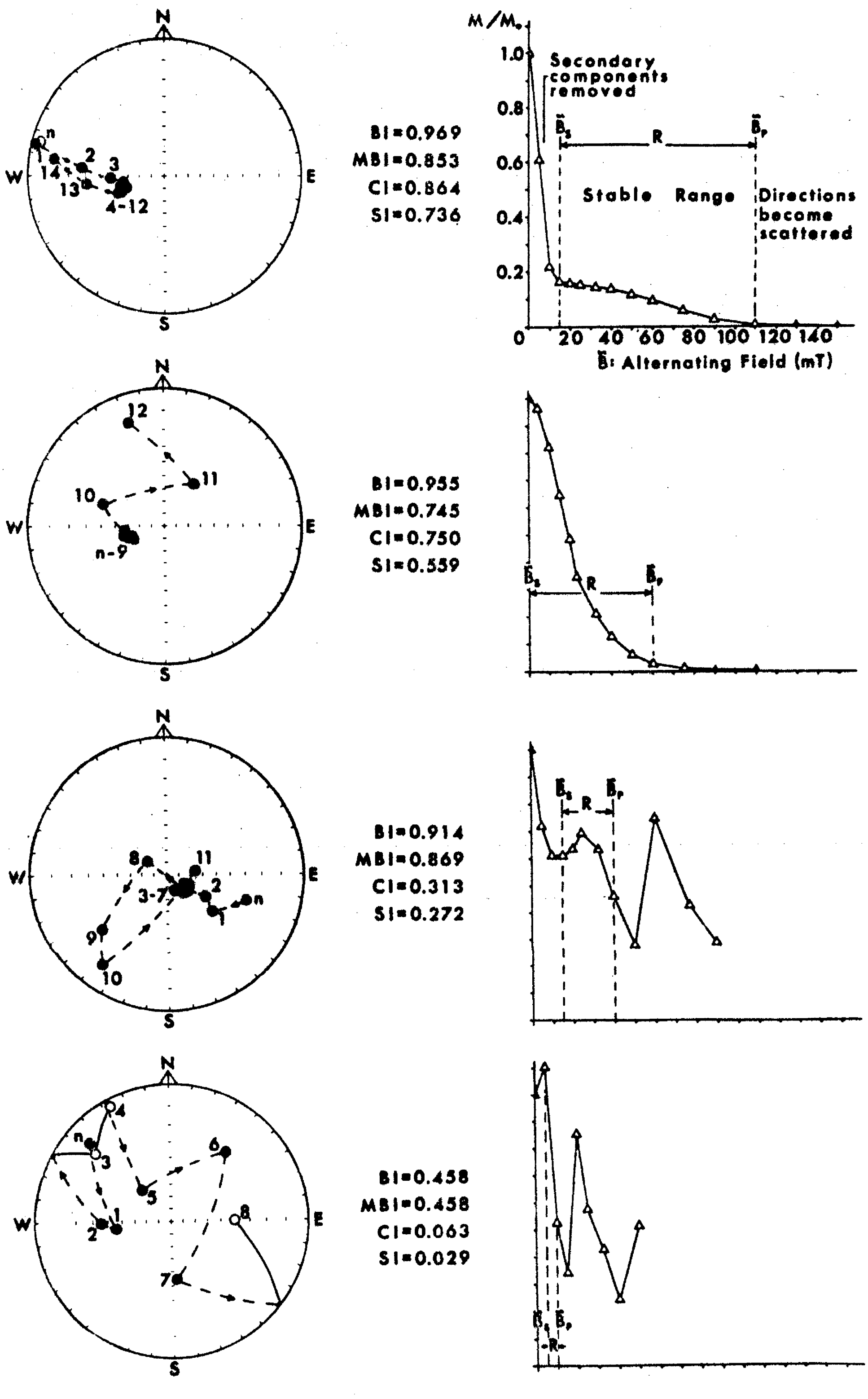
The spectrum of all possible magnetic stabilities was divided into five classes, three representing stable remanence, one for partially stable remanence and one for unstable remanence. Division of the stable remanence spectrum was made using the criterion which is generally employed by palaeomagnetists in classifying whether a rock is 'good' or 'not so good', that the greater the magnitude of the stable range, the more stable the rock. The classes thus defined are:

Class a : $R > 80$ mT. A typical member is shown in Fig. 2.3a

Class b : $40 \text{ mT} < R \leq 80$ mT (Fig. 2.3b)

Class c : $10 \text{ mT} \leq R \leq 40$ mT (Fig. 2.3c)

FIGURE 2.3


N
W
E
S
n
1
2
3
14
13
4-12
BI=0.969
MBI=0.853
CI=0.864
SI=0.736
M/M₀
1.0
0.8
0.6
0.4
0.2
0
Secondary components removed
B̃s
R
B̃p
Stable Range
Directions become scattered
20 40 60 80 100 120 140
B̃: Alternating Field (mT)
N
W
E
S
12
11
10
n-9
BI=0.955
MBI=0.745
CI=0.750
SI=0.559
B̃s
R
B̃p
N
W
E
S
8
11
3-7
2
n
1
9
10
BI=0.914
MBI=0.869
CI=0.313
SI=0.272
B̃s
R
B̃p
N
W
E
S
4
n
3
6
5
8
2
1
7
BI=0.458
MBI=0.458
CI=0.063
SI=0.029
B̃s
B̃p
R

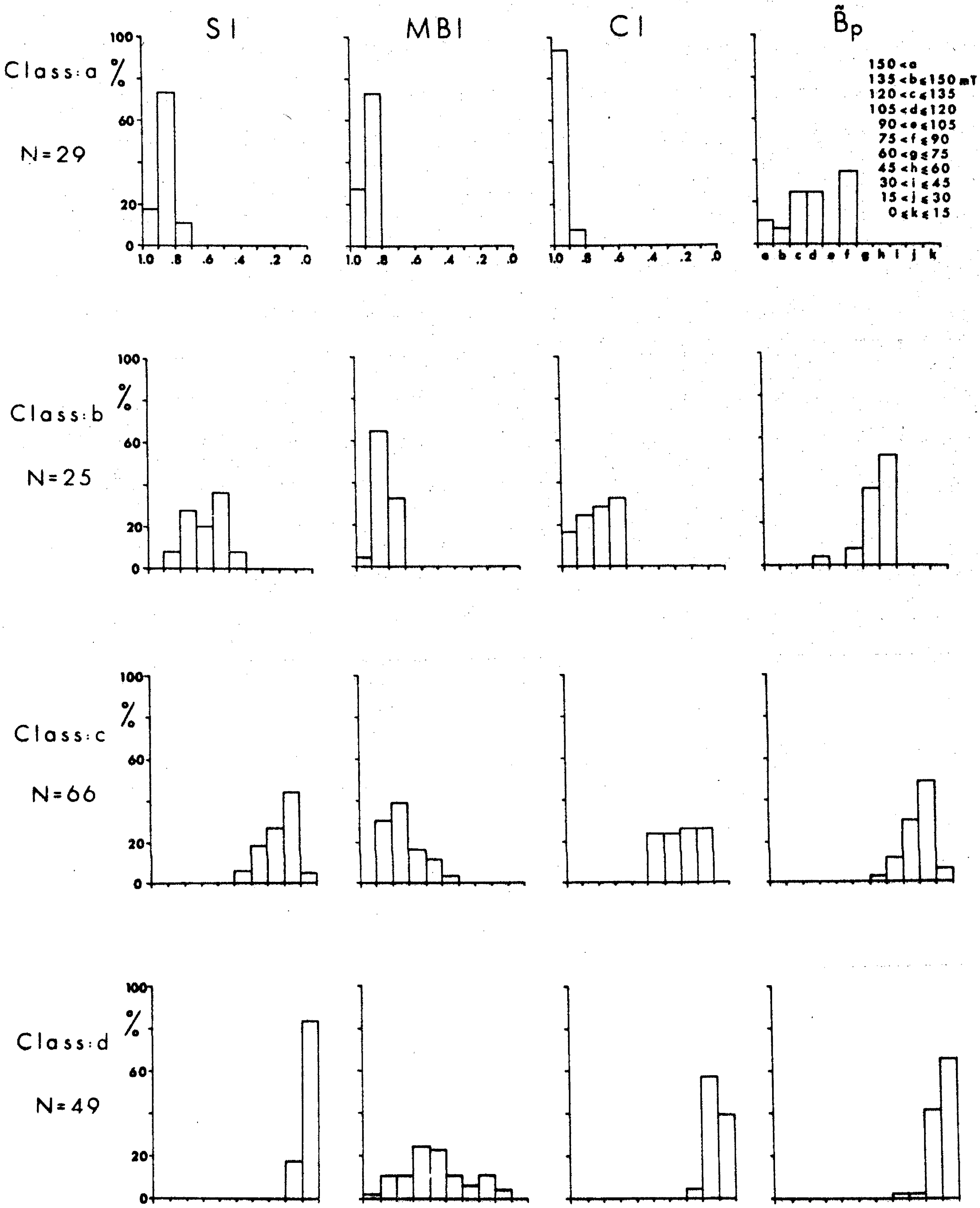


FIGURE 2.3 An illustration of typical pilot specimen behaviour observed for each of the stability classes a - d and histograms of SI, MBI, CI and $\tilde{B}_p$ values determined for pilot specimens belonging to each of those classes (N denotes the number of pilot specimens in each stability class). In the diagrams of the directional behaviour of the typical pilot specimens, n refers to the NRM direction and the numbers 1 - 14 refer to the following demagnetizing fields (in mT) respectively: 5, 10, 15, 20, 25, 32.5, 40, 50, 60, 75, 90, 110, 130 & 150. $M/M_o$ refers to the normalized decay of intensity of magnetization during demagnetization.

Class d : Partially stable remanence. The endpoint grouping in the stable range consisted of only two or three vectors generally separated by angular distances of 10° or more. In general $\tilde{B}_p < 30$ mT, and $R \lesssim 15$ mT (Fig. 2.3d)

Class e : Unstable remanence ($R = 0$ mT)

With respect to the definition of each class, the raw data from the 183 pilot specimens were inspected, classified and the values of SI calculated for the pilots in each. If SI were to do the task for which it was designed, the range of values of SI for each class ought to be unique, higher values being expected from a class of higher stability.

The results of the test are presented in the form of a series of histograms (Fig. 2.3) of the values of $\tilde{B}_p$, MBI, CI and SI found for each of the classes a - d. Class e has been omitted since all values are 0. Also shown are the values of these parameters for the particular pilots illustrated.

Three points are noted:

(i) The histograms of SI demonstrate clearly that the majority of pilots in each class are represented by a unique range of values. Furthermore, the values found in a particular class of stability are higher than those of the adjacent class of lower stability. SI thus fulfills precisely those conditions required of a stability index which is competent in the measurement of magnetic stability and its variation.

The minor amounts of overlap evident at class interfaces are not unexpected and arise from the creation of borderline pilots caused by the imposition of a number of discrete stability classes on a spectrum which is continuous.

(ii) The extensive overlap of values between adjacent classes in the histograms of MBI (the mean Briden index over the stable range) serve to demonstrate that it alone is inadequate to represent magnetic stability. The values of this parameter for the pilots illustrated for classes b and c, clearly demonstrate this point.

(iii) The extent to which the CI values are class dependent, indicates the high degree of dependence of magnetic stability on a parameter using both coercivity-dependent variables ($\tilde{B}_p$ and $\tilde{B}_s$) together. This is a point which has been wholly neglected, or ineffectively used, in the stability indices published to date. Use of only $\tilde{B}_p$ (histogram in Fig. 2.3) produces less effective discrimination of stability.

A point that needs to be mentioned in connection with the CI histograms is that they tend to conceal the fact that the CI values do not form a continuous spectrum but are discrete. This argues against CI being a sole measure of magnetic stability.

On the basis of the competence of SI in classifying relative magnetic stability, the complete stability spectrum is divided into five classes each defined by a characteristic range of SI values:

Class A - Extremely Stable : $0.80 < SI \leqslant 1.00$
Class B - Very Stable : $0.45 < SI \leqslant 0.80$
Class C - Stable : $0.11 < SI \leqslant 0.45$
Class D - Partially Stable : $0.00 < SI \leqslant 0.11$
Class E - Unstable $SI = 0$

For each pilot specimen, the mean angular change of the vector endpoint within the stable range has been calculated. The average value of this quantity gradually increases for classes A to D. The respective values for the collection studied are 2.6°, 4.5°, 7.7° and

10.9°. This agrees with what is intuitively to be expected from a classification of relative stability.

The remanence of any class A rock is necessarily of single-domain or pseudo-single domain origin (Stacey, 1963; Stacey and Banerjee, 1974). Demonstration that a rock is class A will therefore have an important bearing on the history of its remanence (Johnson and Merrill, 1974) and its time-stability.

## 2.6 A COMPARISON OF SI WITH OTHER STABILITY INDICES

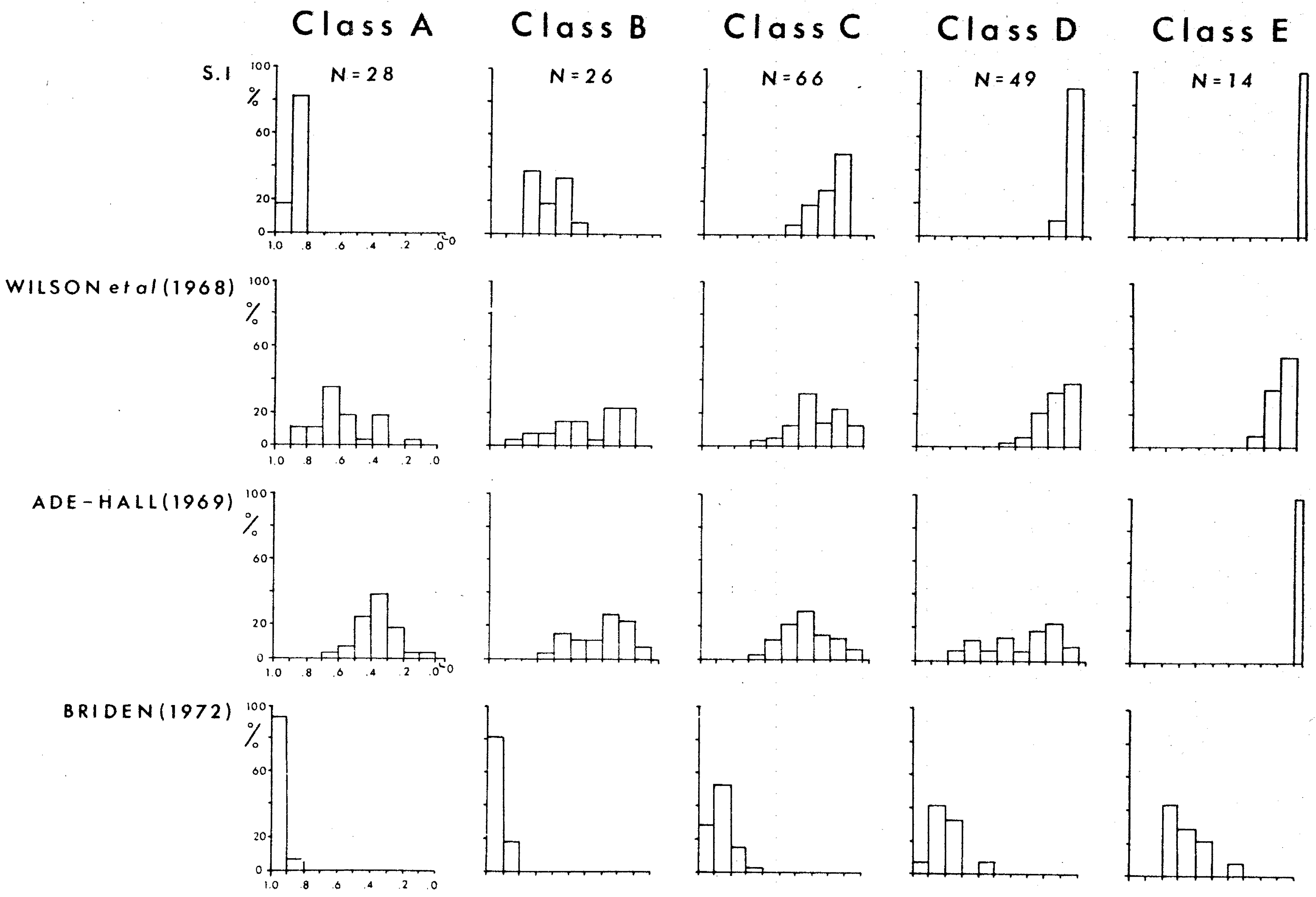
All published stability indices have been calculated using the same set of data as was used for calculating SI values. For each index, the values obtained for pilots in each of the classes A - E are shown as a series of histograms in Fig. 2.4. In obtaining this data three points need to be mentioned:

(i) For pilots with $\tilde{B}_s = 0$, the Murthy (1971) index could not be evaluated as defined (Table 2.1.f) because the circular standard deviation of a single direction is meaningless. In such cases therefore, the index has been calculated using the vector at the first demagnetizing field as the optimum cleaned direction.

(ii) The Murthy index is undefined for unstable rocks; the class E histogram is therefore omitted.

(iii) The Ade-Hall (1969) generalized version of the Wilson *et al* (1968) index (Table 2.1.e) is multivalued, each demagnetizing field having its own value. To facilitate its comparison with other indices therefore, a single value was derived for each pilot by calculating a mean value in exactly the same way that MBI was determined. It is here argued that a more stable rock should have a series of higher values of the index than a less stable rock, and would therefore be reflected in

FIGURE 2.4


Class A
Class B
Class C
Class D
Class E
S.I
N = 28
N = 26
N = 66
N = 49
N = 14
WILSON et al (1968)
ADE-HALL (1969)
BRIDEN (1972)
100
%
60
20
0
1.0
.8
.6
.4
.2
.0

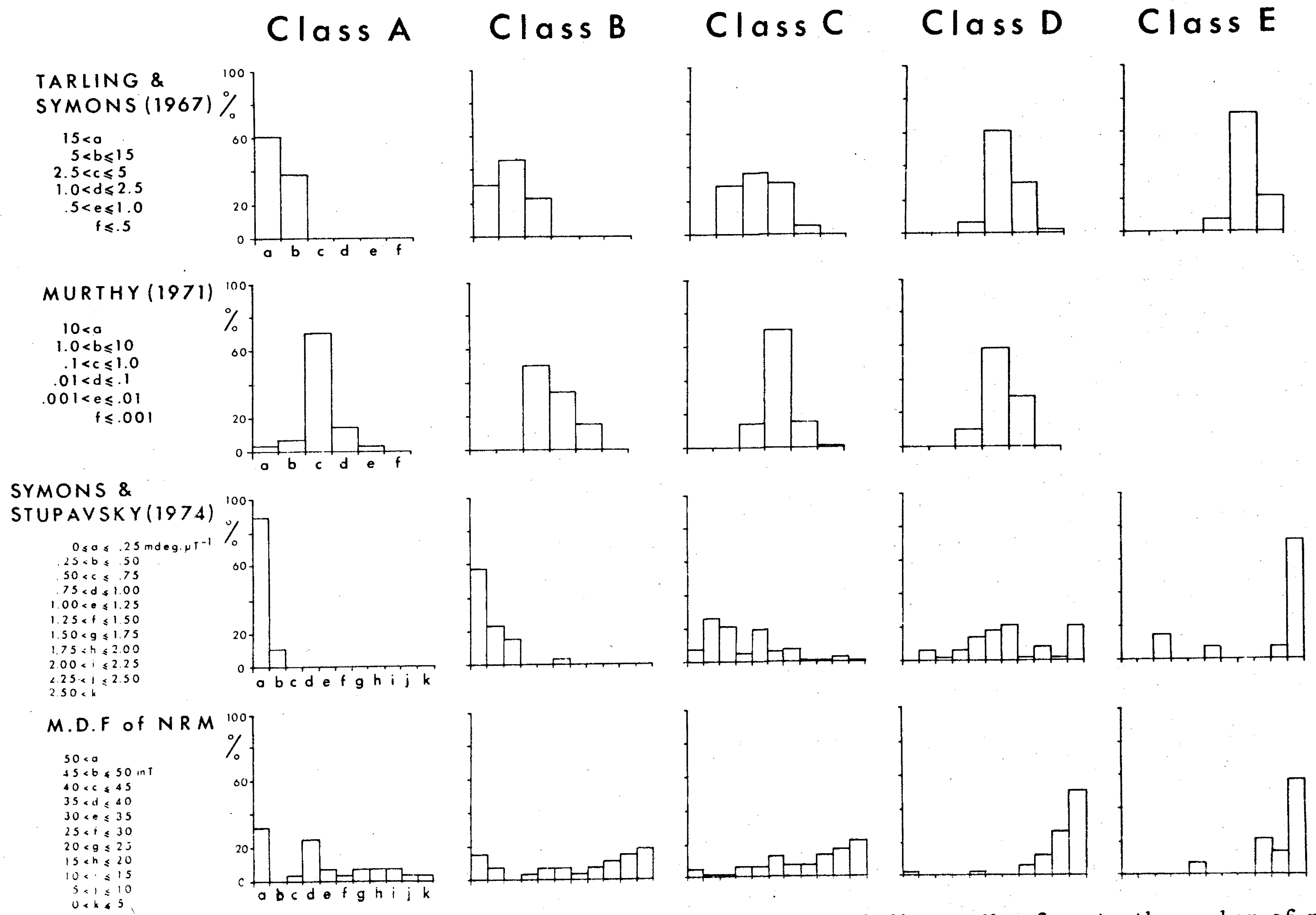


FIGURE 2.4 A comparison of SI with previously published stability indices. N refers to the number of pilot specimens in each stability class.

a higher mean value. Distortion of the information provided by the index would thus be minimal in all but unstable rocks, where the mean value is arbitrarily taken to be zero.

Examination of Fig. 2.4 clearly demonstrates that none of the proposed indices is as successful as SI in describing the stability spectrum. The most successful of them, in this respect, is the index of Tarling and Symons. It is the only one which gives a consistent variation of index values from one end of the stability spectrum to the other with no overlapping of histogram peaks between adjacent classes. It is more successful than the others because it acknowledges the role of involving a parameter related to coercivity, shown here to be an important consideration. The inefficient way it is used however, probably accounts for the impracticable amount of overlap of values between adjacent classes.

Except for the generalized version (Ade-Hall, 1969) of the Wilson *et al* (1968) index, the remaining indices provide adequate discrimination between the highly stable end of the spectrum and the partially or wholly unstable end. This is only to be expected however, since behavioural differences between rocks so classified is very great. Where adjacent classes are concerned, their ability to discriminate is poor.

One final measure of magnetic stability is considered for completeness. Although not specially designed to assess stability, the median destructive field of NRM (Park and Irving, 1970) has been used implicitly as such (Robertson and Fahrig, 1971; Ade-Hall *et al*, 1973). Its limited use in this respect is evident from Fig. 2.4.

The complete stability spectrum of the dykes is shown in terms of the new stability index (Fig. 2.5). The peak at low SI values is not the result of an intrinsic bias in the way SI has been defined.

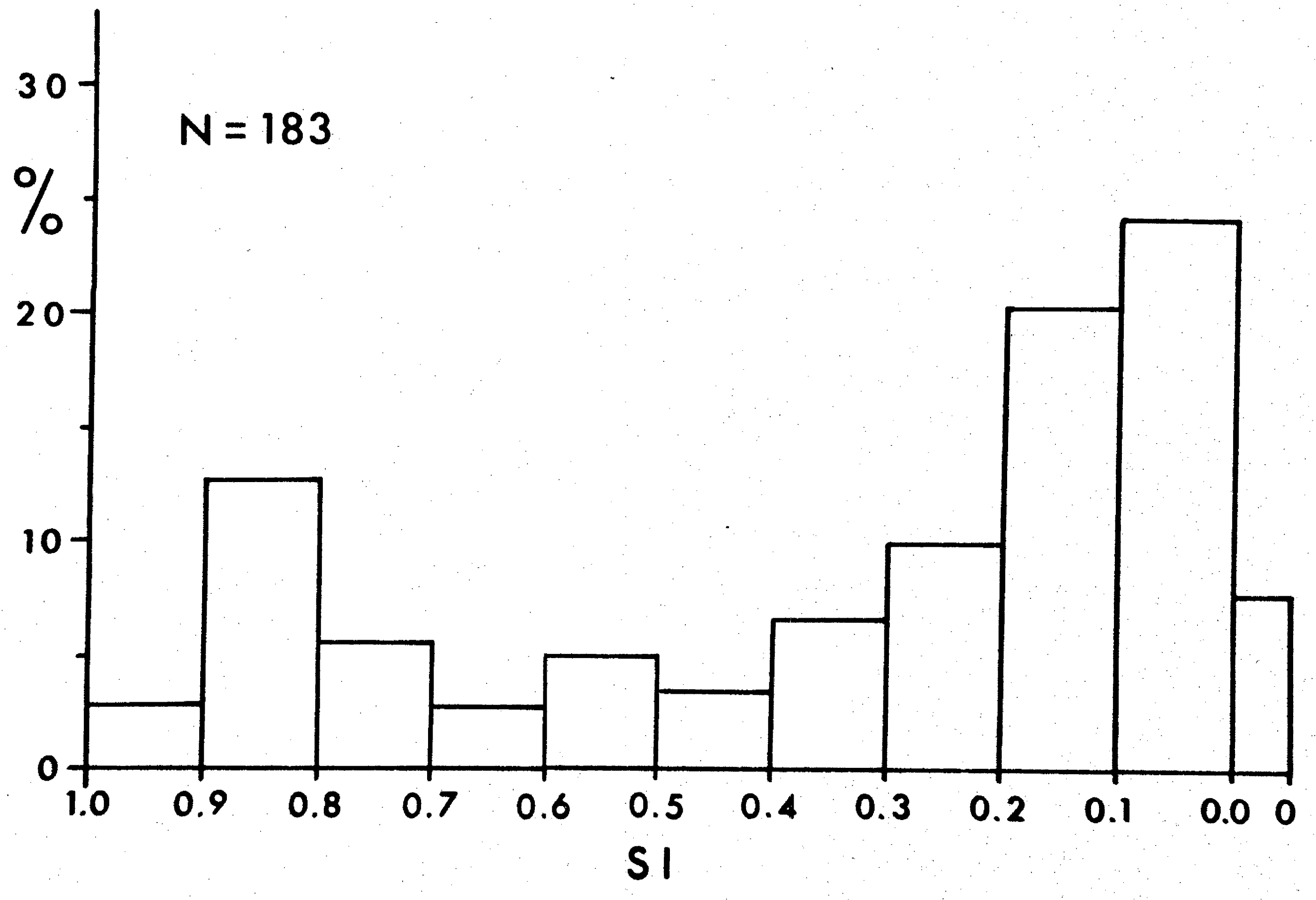


FIGURE 2.5 The stability spectrum of the Precambrian dykes from South Australia and Western Australia in terms of SI. N is the number of pilot specimens used in the analysis.

Rather, it is a reflection of the generally low level of stability found for the magnetic remanence of the Western Australian dykes. This is evident when the stability characteristics of the Western Australian and South Australian dykes are examined separately (described in Chapters 3 and 4 respectively). The difference in the stability spectrum of each collection is immediately obvious and the exercise illustrates a particular use of SI.

The index should also prove useful as a reliable indicator of relative stability in those studies concerned with the fundamental control of magnetic stability. It has been suggested (Dunlop *et al*, 1973) that the unstable components of remanence in a rock lie in the multidomain magnetic grains and the stable remanence resides in the single domain or pseudo-single domain grains. Therefore, the stability of a rock should be related to the ratio of its single domain (SD) type remanence to its multidomain (MD) type remanence. Hence it should be possible to demonstrate a direct relationship between SI and the ratio SD/MD, a possibility which is open to test using low temperature demagnetization techniques (Merrill, 1970) and ARM as an analogue of TRM (Dunlop *et al*, 1973).

# CHAPTER 3

# PRECAMBRIAN DYKES AND VOLCANICS FROM THE YILGARN BLOCK, WESTERN AUSTRALIA

## 3.1 INTRODUCTION

Previous palaeomagnetic investigations on rocks from the Yilgarn Block have been reported by Evans (1968) and Porath and Chamalaun (1968). Evans obtained a pole position from the 2420 My Widgiemooltha dyke swarm which outcrops south of Kalgoorlie (Fig. 3.1), while the study made by Porath and Chamalaun concerned a number of haematite ore bodies exposed in the Koolyanobbing Hills. They derived a single pole, but because of the lack of stratigraphic control on the age of ore formation, could only assign it a broad age of Precambrian. The present investigation forms an extension of these studies and reports results obtained from 54 Precambrian dykes and the 1400 My Morawa Lavas of the Billeranga Hills (Fig. 3.1).

Many swarms of Precambrian dykes intrude the Yilgarn Block. They are particularly well-developed along its western margin adjacent to the Darling Fault (Prider, 1965) and along its southern margin just north of the Albany-Frazer Province (Sofoulis, 1958). Apart from the Widgiemooltha dykes in the Kalgoorlie area, dykes are comparatively rare in the interior of the Block and are found only at isolated localities (Bridge, 1972 gives a compendium). Outcrop is poor inland because of peneplanation in the Late Tertiary (Jutson, 1934) and erosion under arid conditions in recent times. For the purpose of collection therefore, attention was confined to the marginal quartz-dolerite dyke swarms. The presence of laterite in many of the areas where these occur prompted the use of aerial

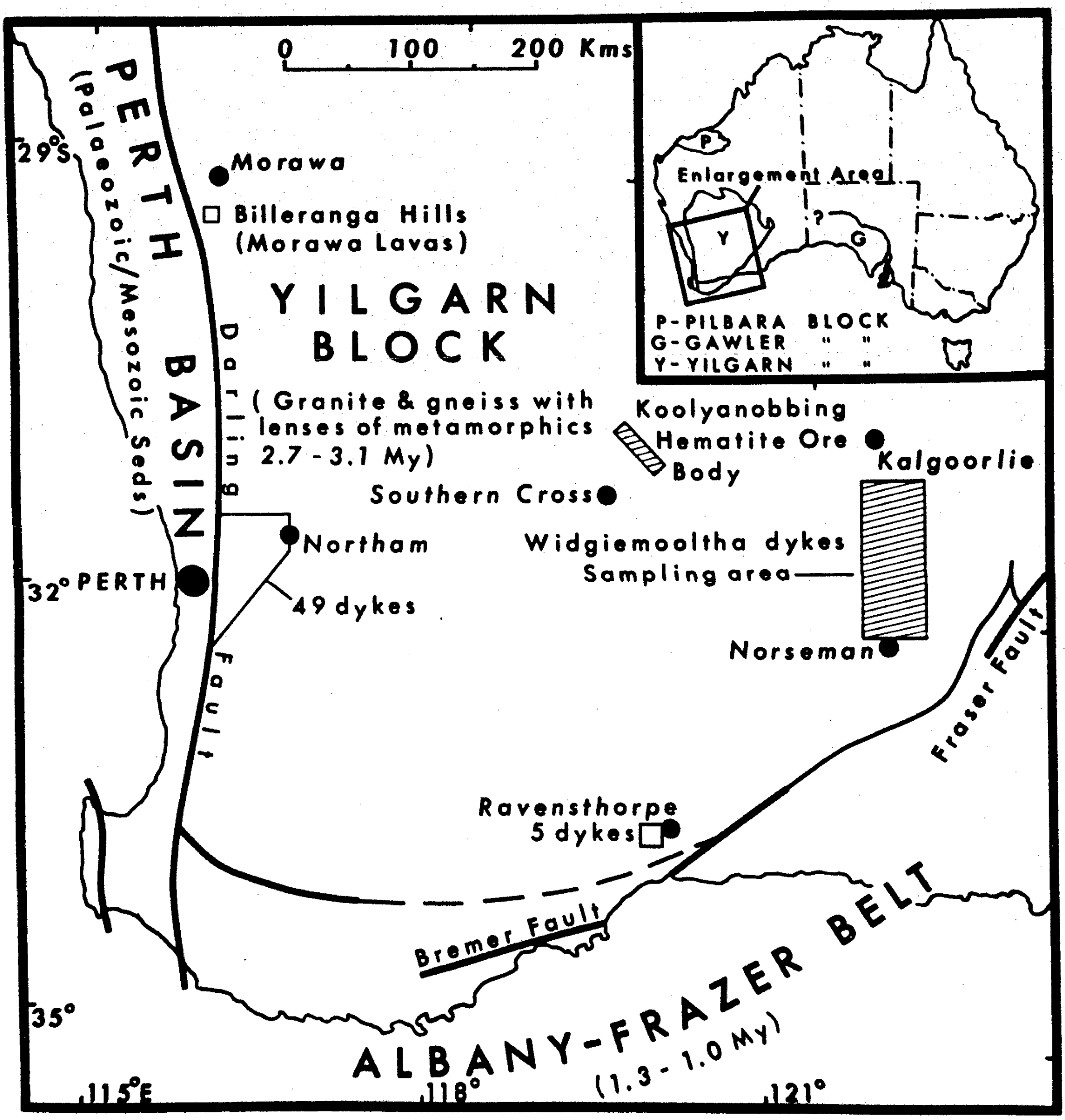


FIGURE 3.1 The southern Yilgarn Block showing the principal sampling areas of the dykes and lavas and the location of the Widgiemooltha dyke suite (studied by Evans, 1968) and the haematite ore bodies of the Koolyanobbing Hills (studied by Porath, 1967a).

photographs in determining suitable collecting localities. They suggested a series of quarries and rail-cuttings in the Perth region (Fig. 3.1) for dykes along the western margin, and the bed of Phillips River, near Ravensthorpe, for dykes along the southern margin.

There is no concrete evidence concerning the relationship of the dyke swarms with one another, only correlations based on trends (Sofoulis, 1958; Sofoulis and Bock, 1962). In this context though, palaeomagnetic studies are particularly useful in establishing whether igneous rocks from widely separated localities are of the same or different ages. This has been well demonstrated by studies of intrusives into the Canadian Shield (Fahrig *et al*, 1965; Larochelle, 1966; Fahrig *et al*, 1971) and the Precambrian shield of Rhodesia (McElhinny and Opdyke, 1964). The technique is based on the presumption that rocks of the same age will have similar directions of magnetic remanence, and those of different age, different directions.

Apart from providing further palaeomagnetic data for Yilgarn Block rocks, the investigation was expected to yield information concerning the age relationships of the dykes and, by dating of these using the Rb-Sr technique, provide narrower age constraints on the time of ore formation using the pole obtained by Porath and Chamalaun (1968).

## 3.2 GEOLOGY

### 3.2.1 Perth Region

The region (Fig. 3.2) consists essentially of a granite-gneiss complex (Prider, 1945) comprising older granite-gneisses intruded by younger massive granites. Along the northern and eastern margins of the complex, granites intrude two belts of highly-folded, medium- to high-grade metasediments and metavolcanics, the Jimperding Series of Prider (1934) and the Chittering Series of Miles (1938).

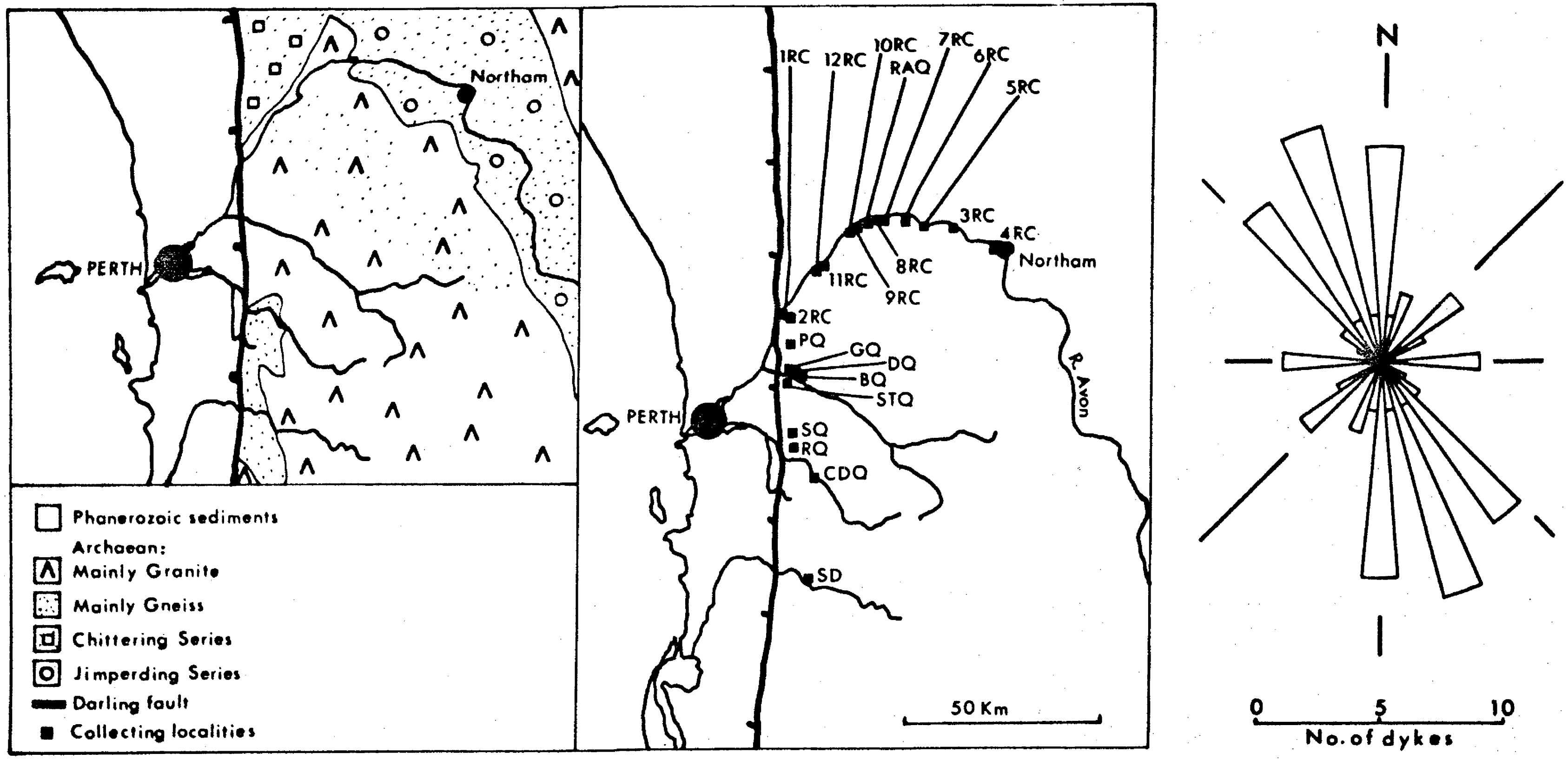


FIGURE 3.2 Geological sketch map of the Perth Region, with sampling localities and a compass rose diagram of the trends of the dykes collected.

The basic dykes invade all rocks of the area and have generally been classified as either quartz-dolerites or epidiorites. The term 'epidiorite' has been used in the literature to refer to those quartz-dolerites which have suffered varying degrees of uralitization (Miles, 1938). This alteration is considered to have resulted from deuteric processes rather than from a later regional metamorphism (Fletcher and Hobson, 1932; Cole and Gloe, 1940; Davis, 1942; Prider, 1944; Geary, 1952). The majority trend between a northwesterly and northeasterly direction (i.e. sub-parallel to the Darling Fault) and have been injected along zones of weakness such as bedding planes in the metasediments and joints in the granite (Miles, 1938; Cole and Gloe, 1940) or parallel to shear zones in the country rock (Prider, 1948a). The intrusive network is particularly dense in the vicinity of the Darling Fault, where crustal extension due to intrusion has been estimated at 10% (Prider, 1948b). Post-intrusive tectonic instability, possibly related to movements along the Darling Fault, is demonstrated at many localities by dykes with sheared margins or shear zones cutting and offsetting dykes (Clarke and Williams, 1926; Fletcher and Hobson, 1932; Miles, 1938; Cole and Gloe, 1940).

Field evidence indicating more than one age of dyke intrusion is rare (Prider, 1943; Thomson, 1943; Stephenson, 1970) while the relationship of the dykes in one part of the region to those in another is obscure since mapping has been done at disconnected localities. However, recent radiometric dating studies of updated biotites in the Mundaring Granite (2700 My) have suggested that more than one intrusive event is represented. This work (Compston and Arriens, 1968) combined with that of Compston and Pidgeon (1962) places the intrusive activity in the late Precambrian possibly earliest Cambrian within the time interval 750 My - 500 My.

### 3.2.2 Ravensthorpe District

Sofoulis (1958) has given the most recent account of the geology of the area. The Archaean basement (Fig. 3.3) consists of a remnant, arcuate structure of synclinally-folded metasediments and metavolcanics preserved in a sea of gneiss. A magmatic granite, emplaced within the core of this structure, has been intruded by a suite of north-northwest trending basic dykes. They have been converted to amphibolites of slightly schistose character and occur exclusively within the boundaries of the granite. They have been interpreted as end-stage differentiates of the consolidating magma, a pegmatite of which gives an age of 2700 My (Jeffery, 1956).

Along the southern margin of the area is a narrow belt of gently folded, sometimes overturned, stratified metasediments which outcrop in the Mt. Barren Ranges. A similar series finds topographic expression in the Stirling Ranges about 275 Kms to the west, north of Albany. Examination of the intervening country led Sofoulis to the conclusion that the metasediments in the Stirling Ranges are a westerly extension of those in the Mt. Barren Ranges. The two series are therefore equivalent. The Stirling Ranges metasediments have been radiometrically dated (Turek and Stephenson, 1966) and give a metamorphic age of 1150 My and a minimum depositional age of 1340 My.

The youngest known intrusives are a swarm of east to east-northeast trending quartz-dolerite dykes. They cut all rocks of the Archaean basement but do not penetrate the metasediments of the Mt. Barren Ranges. Accepting the conclusion of Sofoulis concerning the metasediments, the age of these dykes would lie in the range 2700 My - 1340 My.

### 3.2.3 The Billeranga Hills

The Billeranga Hills are situated about 300 Kms north of Perth just inland of the Darling Fault. They form part of the outcrop of the

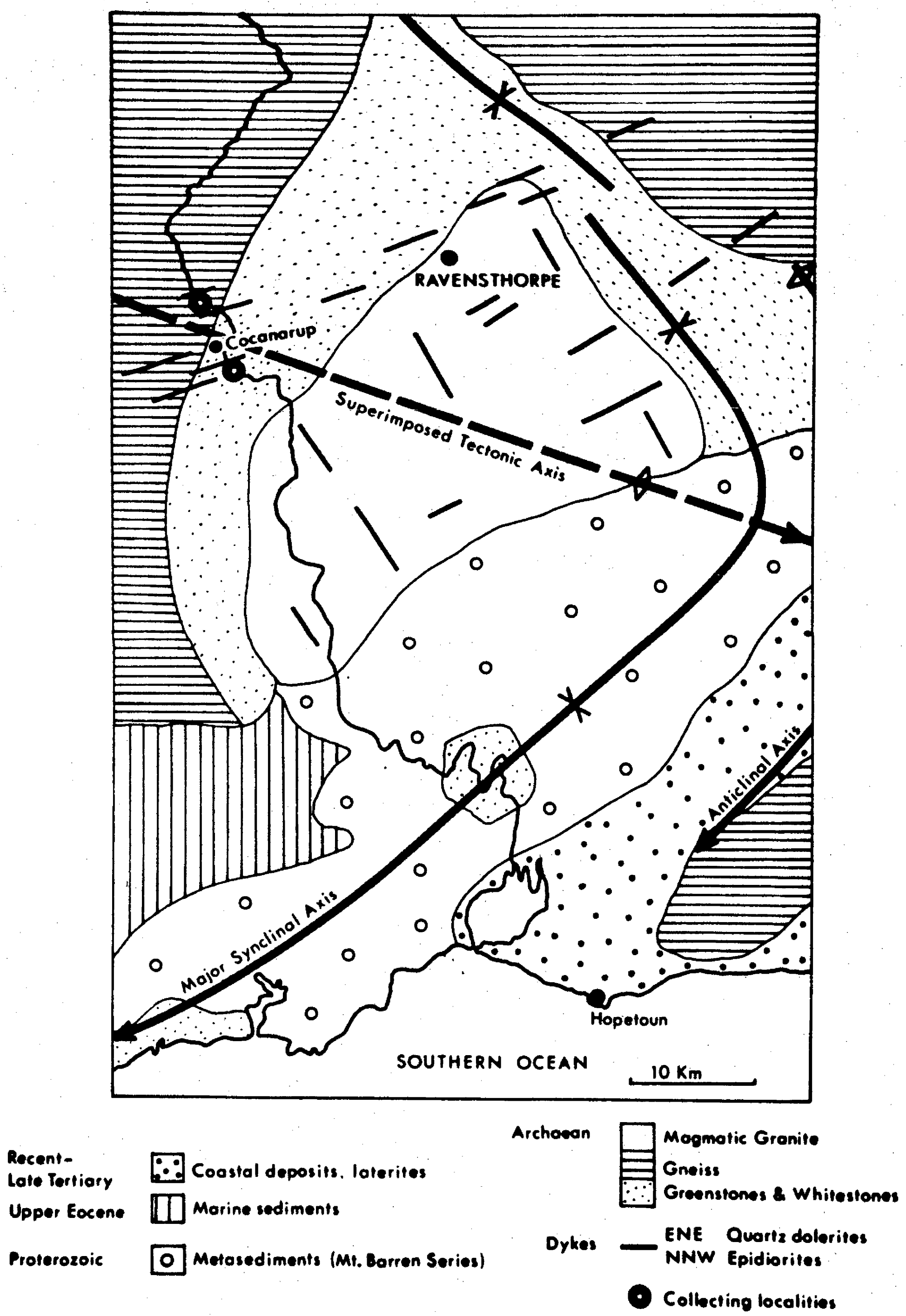


FIGURE 3.3 Geological sketch map of the Ravensthorpe District (after Sofoulis, 1958).

Billeranga Group (McWhae *et al*, 1958; Arriens and Lalor, 1959), a sedimentary and interbedded volcanic rock sequence which unconformably overlies the Archaean basement gneisses. The succession is gently tilted to the west and is intruded by dolerite dykes of at least two ages. The interbedded Morawa Lavas are of trachytic and andesitic composition and give (Compston and Arriens, 1968) an age of 1400 My using the Rb-Sr technique (1390 ± 150 My - P.A. Arriens, unpublished information).

## 3.3 LOCALITY AND SAMPLING DETAILS

The collecting localities and sampling scheme are summarized in Table 3.1. Five dykes were sampled from the Ravensthorpe district and belong to the younger suite of east to east-northeast trending dykes. They were collected from fresh exposures in the bed of Phillips River. Attempts to sample the baked contact zones of the country rock gneisses were unsuccessful.

Forty nine dykes were sampled from two geographically distinct areas of the Perth region. Nineteen dykes came from fresh exposures in a series of rail-cuttings along the Avon River valley to the northeast of Perth, as far inland as Northam (Fig. 3.2). The remaining thirty dykes were collected in the vicinity of the Darling Scarp to the east of Perth. The dykes were freshly exposed and all but two were sampled in quarries opened up in the area for the purpose of providing road metal. Pertinent points to note are that in Boya Quarry dyke 31 cut dyke 32, and in Swan Quarry dykes 49 and 50 were in contact - any cross-cutting relationship that might have been present here was obscured by recent quarrying operations.

Six samples of baked contact material were collected from the country rock adjacent to three dykes.

## TABLE 3.1

### Locality and Sampling Details of the Western Australian Dykes and Lavas

| Locality | No. of Dykes | Dyke Identification | Sample Identification | Map No.*:Map Ref. |
|---|---|---|---|---|
| RAVENSTHORPE DYKES | | | | |
| Phillips River | 5 | | | SI 50-8:287847 & 288843 |
| | | 1 | PR 1-5 | |
| | | 2 | PR 6,7 | |
| | | 3 | PR 8,9 | |
| | | 4 | PR 10,11 | |
| | | 5 | PR 14,15 | |
| PERTH REGION: AVON VALLEY DYKES | | | | |
| Rail Cuttings | 18 | | | |
| Rail cutting no.3 | | 8 | 3RC 1-5 | SH 50-14:453094 |
| | | 9 | 3RC 6-8 | |
| no.4 | | 10 | 4RC 1-5 | SH 50-14:468085 |
| | | 11 | 4RC 6-8 | |
| no.5 | | 12 | 5RC 1-3 | SH 50-14:445099 |
| | | 13 | 5RC 4-6 | |
| no.6 | | 14 | 6RC 1-5 | SH 50-14:437094 |
| no.7 | | 15 | 7RC 1-5 | SH 50-14:428095 |
| no.8 | | 16 | 8RC 1-3 | SH 50-14:427094 |
| | | 17 | 8RC 4-8 | |
| no.9 | | 18 | 9RC 1-3 | SH 50-14:425093 |
| | | 19 | 9RC 4-6 | |
| no.10 | | 20 | 10RC 1-3 | SH 50-14:425093 |
| | | 21 | 10RC 4-6 | |
| | | 22 | 10RC 7-9 | |
| no.11 | | 23 | 11RC 1-3 | SH 50-14:411081 |
| | | 24 | 11RC 4-6 | |
| no.12 | | 25 | 12RC 1-3 | SH 50-14:411080 |
| Quarry | 1 | 26 | RAQ 1-3 | SH 50-14:427094 |
| PERTH REGION: DARLING SCARP DYKES | | | | |
| Rail Cuttings | 2 | | | SH 50-14:405069 |
| Rail cutting no.1 | | 6 | 1RC 1-3 | |
| no.2 | | 7 | 2RC 1-3 | |
| Canning Dam Quarry | 1 | 27 | CDQ 1-3 | SI 50-2:412024 |
| Darlington Quarry | 3 | | | SH 50-14:405053 |
| | | 28 | DQ 1,2,8 | |
| | | 29 | DQ 3-5 | |
| | | 30 | DQ 6,7,9 | |

*1:250,000 Topographic Series, Australia: Edition 1, Series R502

Continued

TABLE 3.1

(Continued)

| Locality | No. of Dykes | Dyke Identification | Sample Identification | Map No.*:Map Ref. |
|---|---|---|---|---|
| PERTH REGION: DARLING SCARP DYKES (Continued) | | | | |
| Boya Quarry | 2 | | | SH 50-14:407053 |
| | | 31 | BQ 1-5 | |
| | | 32 | BQ 6-12 | |
| Greenmount Quarry | 2 | | | SH 50-14:404054 |
| | | 33 | GQ 1-5,10 | |
| | | 34 | GQ 8,9,11 | |
| Serpentine Dam | 2 | | | SI 50-2:410994 |
| | | 35 | SD 1-5 | |
| | | 36 | SD 6-8 | |
| Stathams Quarry | 2 | | | SH 50-14:404051 |
| | | 37 | STQ 1-5 | |
| | | 38 | STQ 6-8 | |
| Readymix Quarry | 5 | | | SI 50-2:402035 |
| | | 39 | RQ 1-5 | |
| | | 40 | RQ 6-8 | |
| | | 41 | RQ 9-11 | |
| | | 42 | RQ 12-14 | |
| | | 43 | RQ 15-17 | |
| Swan Quarry | 7 | | | SI 50-2:402038 |
| | | 44 | SQ 1-5 | |
| | | 45 | SQ 6-8 | |
| | | 46 | SQ 9-13 | |
| | | 47 | SQ 14,15 | |
| | | 48 | SQ 16,17 | |
| | | 49 | SQ 18-20,27,28 | |
| | | 50 | SQ 21-26 | |
| Pioneer Quarry | 4 | | | SH 50-14:405062 |
| | | 51 | PQ 1-3 | |
| | | 52 | PQ 4-8 | |
| | | 53 | PQ 9-11 | |
| | | 54 | PQ 12-14 | |
| MORAWA LAVAS | | | | |
| Billeranga Hills | — | — | BH 1-10 | SH 50-6:387368 |

*1:250,000 Topographic Series, Australia: Edition 1, Series R502

The compass rose diagrams of the dyke trends (Fig. 3.2) demonstrate that all trends recorded in the Perth region are represented by the collection. In general most dykes varied in width between 3 m and 30 m.

In the Billeranga Hills, ten samples were taken from a 30 m section of the Morawa Lavas. The number of flows represented by the collection was unknown.

Except for the samples from Phillips River which were field drilled, all were collected as blocks. Generally three to five samples were taken from each dyke distributed, wherever possible, across the width. A sun compass was used for orientation in most cases, checked with the aid of a magnetic compass. In the laboratory each sample or core provided three cylindrical specimens (28 mm x 28 mm). The 205 samples yielded 610 specimens.

## 3.4 PALAEOMAGNETIC RESULTS

### 3.4.1 The Dykes

Dyke-mean directions of NRM are given in Table 3.2 and plotted in Fig. 3.4a. Intensities of magnetization spanned a large spectrum covering four orders of magnitude (0.4 to 1356 $mAm^{-1}$). Of the 54 dykes sampled, dyke-mean directions for 32 were significant (statistical procedures are described in Chapter 1). For all three areas, their directions were scattered and were almost exclusively of negative polarity. Scattered distributions of initial remanence however, are a common feature of many palaeomagnetic investigations of Precambrian rocks (McElhinny and Opdyke, 1964; Larochelle, 1966; Park *et al*, 1973). Statistical randomness of the remaining 22 dykes resulted either from within-dyke streaking of sample-mean directions towards the present field direction or from genuine random distributions which, in three of the dykes, were considered to have resulted from lightning strikes, indicated

TABLE 3.2

Dyke-mean directions of remanence before magnetic cleaning

| Locality | Dyke No. | N* | R | D | I | Int |
|---|---|---|---|---|---|---|
| RAVENSTHORPE DYKES | | | | | | |
| Phillips River | 1 | 2 | 1.70 | — | — | 563 |
| | 2 | 2 | 1.78 | — | — | 1356 |
| | 3 | 2 | 1.99 | 36.3 | 33.2 | 1020 |
| | 4 | 2 | 1.96 | 203.1 | 39.7 | 994 |
| | 5 | 2 | 1.39 | — | — | 843 |
| PERTH REGION: AVON VALLEY DYKES | | | | | | |
| Rail cutting no.3 | 8 | 5 | 3.20 | — | — | 0.5 |
| | 9 | 3 | 2.91 | 359.4 | -26.7 | 18.3 |
| no.4 | 10 | 5 | 4.00 | 174.7 | -86.3 | 38.0 |
| | 11 | 3 | 2.93 | 20.6 | -49.5 | 11.4 |
| no.5 | 12 | 3 | 2.48 | — | — | 120 |
| | 13 | 3 | 2.72 | 345.8 | - 2.0 | 3.8 |
| no.6 | 14 | 5 | 3.01 | — | — | — |
| no.7 | 15 | 5 | 4.70 | 11.0 | 34.2 | 671 |
| no.8 | 16 | 3 | 2.77 | 156.0 | -63.8 | 346 |
| | 17 | 4 | 3.94 | 354.8 | -56.7 | 311 |
| no.9 | 18 | 2 | 1.99 | 191.1 | -26.3 | 66.5 |
| | 19 | 3 | 2.98 | 167.8 | -46.2 | 40.4 |
| no.10 | 20 | 2 | 1.92 | 169.7 | -71.2 | 52.9 |
| | 21 | 3 | 2.98 | 160.8 | -62.6 | 93.6 |
| | 22 | 3 | 2.67 | 248.0 | -62.9 | 249 |
| no.11 | 23 | 3 | 2.84 | 20.8 | -15.9 | 60.0 |
| | 24 | 3 | 2.13 | — | — | 42.3 |
| no.12 | 25 | 2 | 1.97 | 350.9 | 27.8 | 20.8 |
| Quarry | 26 | 3 | 2.88 | 139.9 | -73.9 | 62.3 |

*N = Number of samples

Continued

## TABLE 3.2

(Continued)

| Locality | Dyke No. | N* | R | D | I | Int |
|---|---|---|---|---|---|---|
| PERTH REGION: DARLING SCARP DYKES | | | | | | |
| Rail cutting no.1 | 6 | 3 | 2.78 | 110.6 | - 2.4 | 0.4 |
| no.2 | 7 | 3 | 1.45 | — | — | 88.3 |
| Canning Dam Quarry | 27 | 3 | 2.81 | 229.1 | -56.7 | 104 |
| Darlington Quarry | 28 | 3 | 2.21 | — | — | 99.4 |
| | 29 | 3 | 2.39 | — | — | 112 |
| | 30 | 2 | 1.97 | 193.9 | -66.8 | 45.6 |
| Boya Quarry | 31 | 5 | 2.43 | — | — | 54.1 |
| | 32 | 5 | 4.91 | 36.9 | -72.6 | 2.9 |
| Greenmount Quarry | 33 | 6 | 5.63 | 31.7 | 70.7 | 192 |
| | 34 | 2 | 1.81 | — | — | 8.3 |
| Serpentine Dam | 35 | 5 | 4.74 | 246.4 | -75.8 | 603 |
| | 36 | 3 | 2.81 | 247.7 | -43.6 | 430 |
| Stathams Quarry | 37 | 3 | 1.79 | — | — | 34.0 |
| | 38 | 2 | 1.95 | 35.4 | -54.7 | 1.1 |
| Readymix Quarry | 39 | 5 | 4.23 | 304.1 | -33.4 | 14.7 |
| | 40 | 3 | 2.28 | — | — | 85.5 |
| | 41 | 3 | 2.53 | — | — | 7.7 |
| | 42 | 3 | 1.81 | — | — | 71.8 |
| | 43 | 3 | 1.66 | — | — | 0.8 |
| Swan Quarry | 44 | 5 | 3.71 | 84.9 | -18.8 | 25.5 |
| | 45 | 2 | 1.90 | — | — | 0.8 |
| | 46 | 3 | 2.60 | — | — | 27.2 |
| | 47 | 2 | 1.75 | — | — | 2.0 |
| | 48 | 2 | 1.86 | — | — | 0.9 |
| | 49 | 4 | 3.54 | 351.7 | -30.1 | 7.6 |
| | 50 | 5 | 4.94 | 250.8 | 25.0 | 5.3 |
| Pioneer Quarry | 51 | 3 | 2.92 | 335.0 | -18.9 | 27.9 |
| | 52 | 5 | 4.53 | 357.8 | -51.5 | 97.9 |
| | 53 | 3 | 2.86 | 45.1 | -38.3 | 1.5 |
| | 54 | 2 | 1.85 | — | — | 42.0 |

*N = Number of samples

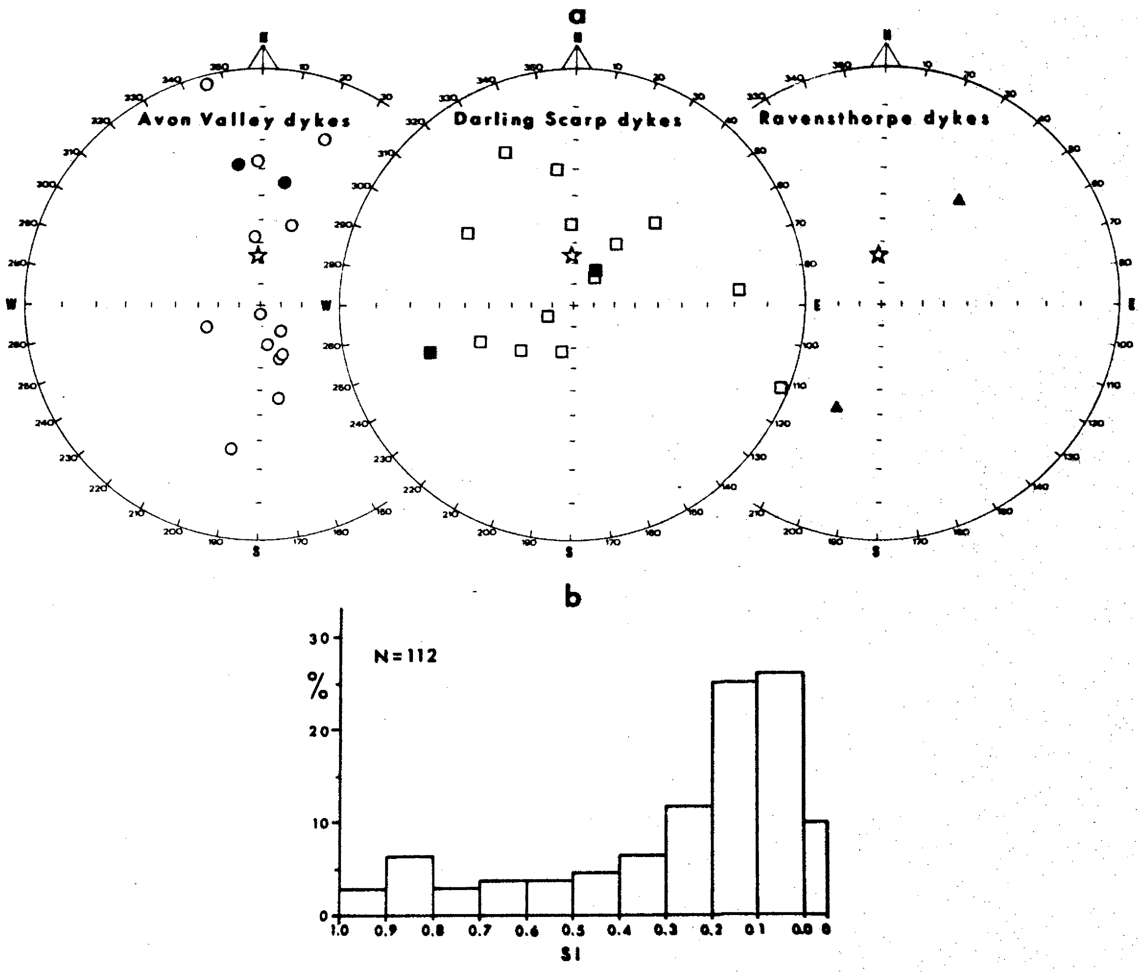


FIGURE 3.4 Western Australian dykes:
(a) Dyke-mean directions of uncleaned magnetic remanence.
(b) The stability spectrum of the dykes in terms of SI (see Chapter 2 for definition of the stability index SI). N is the number of pilot specimens used in the analysis.

by unusually large variations in sample intensities of magnetization of two to three orders of magnitude.

Repeat measurements of one specimen from each sample after an elapsed period of three months showed that two thirds of the collection had acquired temporary components of magnetization (Creer, 1957). Angular changes of 100° and intensity changes of 200% were observed in extreme cases.

The stability of remanence was tested by subjecting at least two pilot specimens from each dyke to stepwise alternating-field demagnetization. The stability characteristics of the collection are represented in terms of an histogram (Fig. 3.4b) of SI values determined for the 112 pilot specimens (a full description of the stability index, SI, is given in Chapter 2). The histogram shows that the stability of the collection is generally low, with about one third of the pilot specimens being partially stable or unstable. The reason for this low level of stability was the generally low values of the maximum coercivity of the stable component - it rarely exceeded 50 mT - and the ubiquitous presence of soft components of magnetization which were removed in fields of 5 mT to 10 mT. About one tenth of the pilot specimens have SI values greater than 0.8 indicating that their remanence is of definite single domain or pseudo-single domain origin. The stability characteristics of the collection are in sharp contrast to those of the South Australian dykes (Chapter 4).

One point which calculation of the SI values revealed was the variation of stability within certain dykes. Thus, for about half of the dykes in the collection, one pilot specimen belonged to the stable remanence classes A - C and the other to the partially stable and unstable classes D and E.

The presence of this variation prevented the application of a single, initial cleaning field to many of the dykes during bulk demagnetization.

Thus, an optimum cleaning field interval was established for each dyke using the optimum cleaning index of Briden (1972) and the initial cleaning field was the lower field of this interval. However, for those dykes with the stability variation, the field interval thus selected was often different for the two pilot specimens. Therefore, for remaining samples from such dykes, two initial cleaning fields often had to be applied merely to establish the optimum cleaning interval. After application of the initial cleaning field to all samples, the higher field of the optimum cleaning field interval was then applied to establish repeatability of the cleaned directions. In most cases cleaning fields were within the range 5 mT to 32.5 mT.

Resulting from the repeatability exercise it was sometimes found that specimens required higher cleaning fields to minimise within-dyke scatter of directions. The cleaned, stable directions for each dyke were ultimately selected by examination of the data at the specimen, rather than the sample, level. Specimens further than a semi-angle of 40° away from the group-mean direction were discarded. In accordance with this practice, to avoid giving samples with only one useful specimen direction too much weight, dyke-mean directions of cleaned remanence have been calculated by assigning unit weight to specimens. Specimens from 48 of the dykes responded satisfactorily to magnetic cleaning. Within-dyke reversals of magnetization were present in three cases.

The cleaned dyke-mean directions of magnetization are listed in Table 3.3. The directions for the three collecting areas fall into one or more groups. These are shown in Fig. 3.5. Samples from each of these groups were submitted to Drs Compston and Crawford for Rb-Sr dating. Their work suggested that six, or possibly seven, of the ten groups belonged to different ages. The following points arose:

## TABLE 3.3

Dyke-mean directions of remanence after magnetic cleaning

| Locality | Dyke No. | N(Sa)[1] | R | D | I | Group |
|---|---|---|---|---|---|---|
| RAVENSTHORPE DYKES | | | | | | |
| Phillips River | 1 | 16(5) | 15.69 | 91.3 | 77.6 | RD |
| | 2 | 6(2) | 5.88 | 129.1 | 73.2 | RD |
| | 3 | 6(2) | 5.98 | 10.0 | 81.4 | RD |
| | 4 | 6(2) | 5.98 | 188.0 | 80.7 | RD |
| | 5[2] | 3(1) | 2.94 | 285.9 | -51.3 | — |
| PERTH REGION: AVON VALLEY DYKES | | | | | | |
| Rail cutting no.3 | 8 | 7(3) | 6.05 | 347.3 | 49.6 | YF |
| | 9 | ........... Unstable ........... | | | | |
| no.4 | 10 | 10(4) | 9.12 | 230.2 | -82.5 | YA |
| | 11 | 9(3) | 8.90 | 338.5 | -38.2 | YC |
| no.5 | 12 | 6(2) | 5.44 | 10.3 | 48.6 | YF |
| | 13 | 7(3) | 6.73 | 333.3 | 49.0 | YF |
| no.6 | 14 | 14(5) | 13.62 | 5.6 | 45.5 | YF |
| no.7 | 15 | 15(5) | 14.90 | 16.9 | 51.3 | YB |
| no.8 | 16 | ........... Unstable ........... | | | | |
| | 17 | 9(4) | 8.32 | 357.4 | 43.0 | YF |
| no.9 | 18 | 6(2) | 5.94 | 223.6 | 18.4 | YE |
| | 19 | 7(3) | 6.96 | 170.1 | -40.9 | YF |
| no.10 | 20 | 3(2) | 2.92 | 167.0 | -44.7 | YF |
| | 21 | 7(3) | 6.65 | 168.5 | -39.3 | YB |
| | 22 | 6(2) | 5.93 | 224.6 | -11.5 | YE |
| no.11 | 23 | 9(3) | 8.78 | 17.3 | -45.3 | YC |
| | 24 | 6(2) | 5.73 | 113.6 | -53.1 | YF |
| no.12 | 25[2] | 3(1) | 2.83 | 353.4 | 45.9 | YF |
| Quarry | 26 | 9(3) | 8.92 | 135.3 | -56.5 | YB |

[1] N(Sa) = Number of specimens (samples)

[2] Mean based on specimens from only one sample. The result from this dyke was omitted from the palaeomagnetic pole calculations.

Continued

## TABLE 3.3

(Continued)

| Locality | Dyke No. | N(Sa)[1] | R | D | I | Group |
|---|---|---|---|---|---|---|
| PERTH REGION: DARLING SCARP DYKES | | | | | | |
| Rail cutting no.1 | 6 | 7(3) | 6.28 | 255.0 | 52.7 | YD |
| no.2 | 7 | 6(2) | 5.79 | 246.7 | 39.4 | YD |
| Canning Dam Quarry | 27 | 5(2) | 4.93 | 188.7 | -56.8 | YF |
| Darlington Quarry | 28 | 9(3) | 8.83 | 91.1 | 78.9 | YA |
| | 29 | 8(3) | 7.65 | 37.0 | 75.4 | YA |
| | 30 | 6(2) | 5.87 | 122.1 | -51.4 | YF |
| Boya Quarry | 31 | 11(4) | 10.32 | 328.5 | 64.2 | YB |
| | 32 | 15(5) | 14.68 | 345.1 | -74.2 | YC |
| Greenmount Quarry | 33 | 18(6) | 17.90 | 50.5 | 82.9 | YA |
| | 34 | 9(3) | 8.50 | 291.4 | 80.9 | YA |
| Serpentine Dam | 35 | 12(4) | 11.42 | 263.8 | -62.9 | YA |
| | 36 | 9(3) | 7.71 | 250.4 | -30.5 | YE |
| Stathams Quarry | 37 | 7(4) | 6.75 | 272.2 | 64.2 | YD |
| | 38 | 6(2) | 5.81 | 23.7 | -62.2 | YC |
| Readymix Quarry | 39 | 10(4) | 9.27 | 281.6 | 47.2 | YD |
| | 40 | 6(2) | 5.84 | 243.8 | 30.7 | YD |
| | 41 | .... Partially Remagnetized .... | | | | |
| | 42 | 6(2) | 5.95 | 273.2 | 43.4 | YD |
| | 43 | 8(3) | 7.24 | 266.5 | 63.9 | YD |
| Swan Quarry | 44 | 12(5) | 11.35 | 173.3 | 63.6 | YC |
| | 45 | 6(2) | 5.57 | 320.2 | -50.8 | YC |
| | 46 | 4(2) | 3.84 | 352.0 | -35.8 | YC |
| | 47 | 6(2) | 5.60 | 254.6 | 42.4 | YD |
| | 48 | .... Partially Remagnetized .... | | | | |
| | 49 | 11(4) | 9.92 | 2.3 | -43.8 | YC |
| | 50 | 18(6) | 17.87 | 257.8 | 28.1 | YD |
| Pioneer Quarry | 51 | 9(3) | 8.76 | 324.5 | -35.2 | YC |
| | 52 | 11(5) | 9.73 | 4.5 | -59.9 | YC |
| | 53 | 4(2) | 3.97 | 60.5 | -36.2 | YD |
| | 54 | 8(3) | 7.60 | 318.3 | -53.0 | YC |

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[1] N(Sa) = Number of specimens (samples)

[2] Mean based on specimens from only one sample. The result from this dyke was omitted from the palaeomagnetic pole calculations.

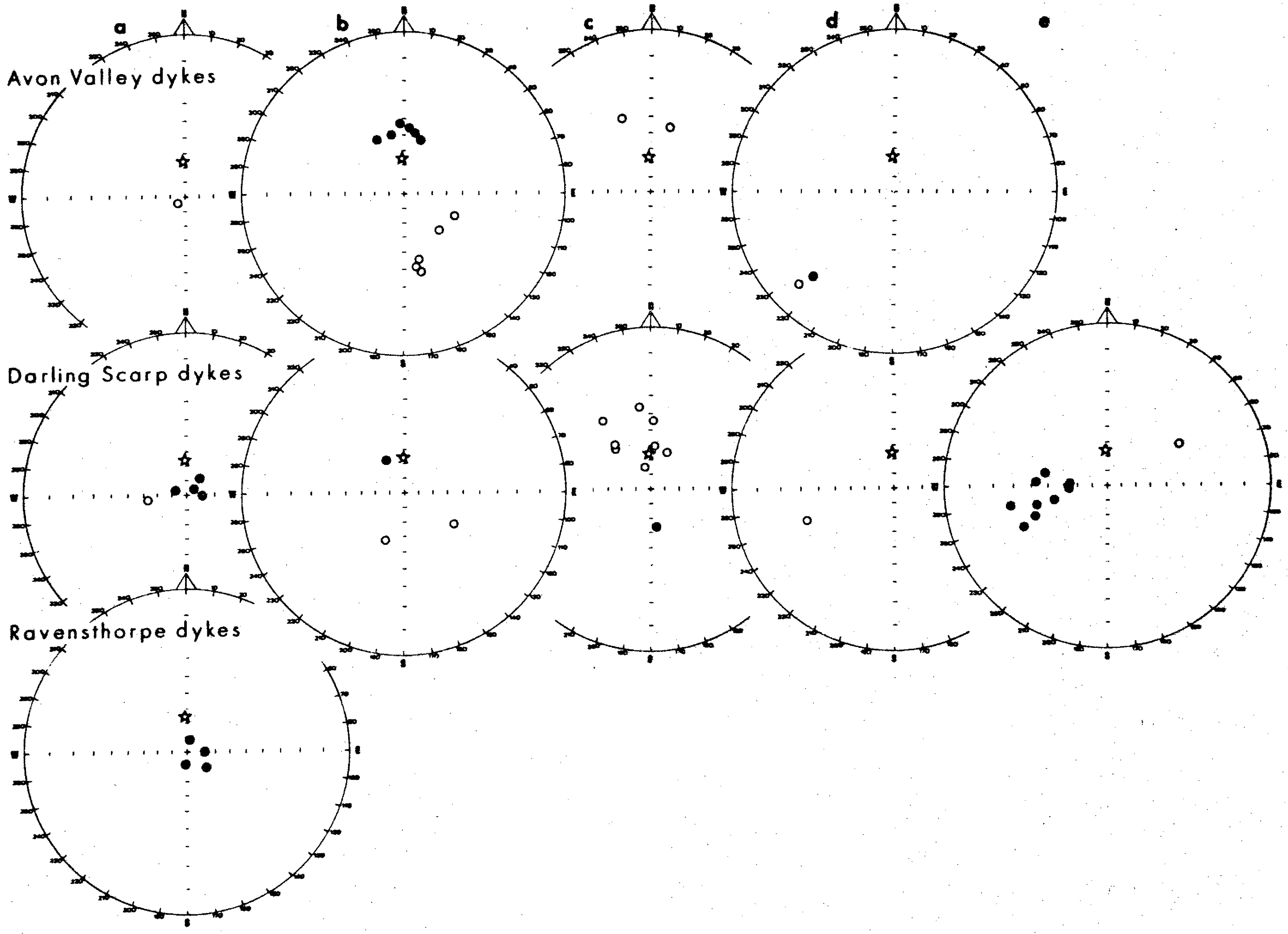

FIGURE 3.5 Western Australian dykes: Dyke-mean directions of cleaned magnetic remanence grouped according to directional similarity and collecting area.

(i) The Ravensthorpe group (Fig. 3.5a) may be older than similar directions obtained from dykes of the Avon Valley and Darling Scarp areas of the Perth region

(ii) Directions shown in Fig. 3.5a, yielded by Avon Valley and Darling Scarp dykes, are similar in age.

(iii) The Avon Valley directions of Fig. 3.5b belong to dykes of two different ages. Both ages are also represented by dykes from the Darling Scarp which give directions (Fig. 3.5b) similar to those of the Avon Valley dykes.

(iv) The age of the Avon Valley directions in Fig. 3.5c is no different to that of similar Darling Scarp directions.

Combining the groups of directions with this information in mind yielded the seven independent groups plotted in Fig. 3.6 (assuming that the Darling Scarp and Avon Valley directions of Fig. 3.5d belong to dykes of similar age). The age and trends of the dykes belonging to each group are also shown. It is evident that for dykes in the Perth region, there is no correlation between a particular group and a particular strike direction. Group-mean directions of magnetization are listed in Table 3.5.

### 3.4.2 Baked Contact Studies

Baked contact studies proved useful as a field test for establishing the time-stability of the remanence (McElhinny, 1973) and for establishing, on palaeomagnetic evidence alone, the relative ages of some of the groups of directions.

The initial remanence of the six samples of baked granite-gneiss country rock was rather weak (0.1 - 0.3 $mAm^{-1}$) and the specimens too inhomogeneously magnetized for any significance to be attached to the directions obtained. Further work with them was therefore not pursued.

In many quarries, dykes of more than one group were present. Three examples of one dyke partially baking another were found and are illustrated in Fig. 3.7 and Fig. 3.8. Fig. 3.7a illustrates the

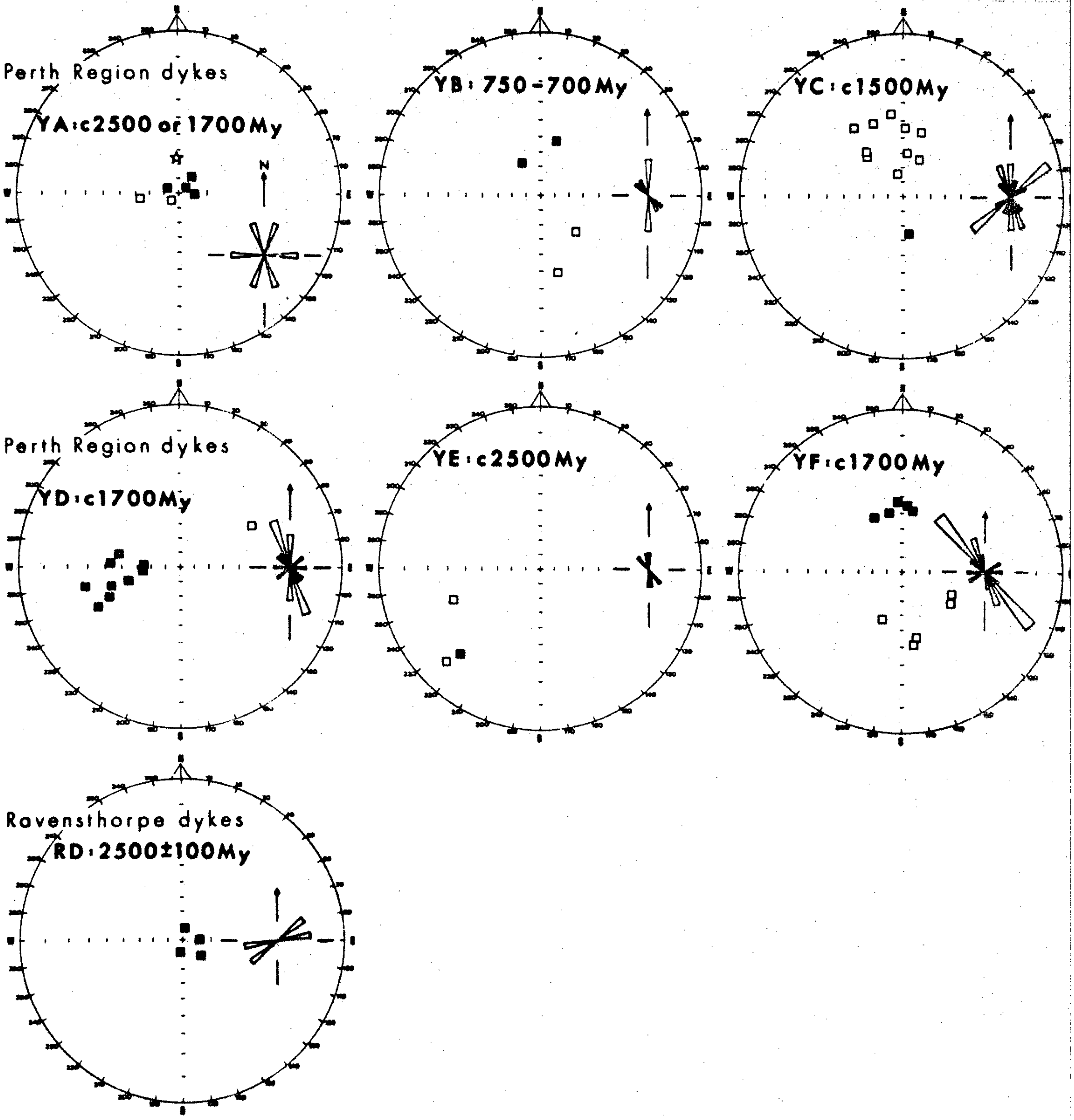

FIGURE 3.6 Western Australian dykes: Dyke-mean directions of cleaned magnetic remanence grouped according to directional similarity and isotopic age information. The compass rose diagrams depict the trends of the dykes within each group.

Fig 3.7a-Swan Quarry

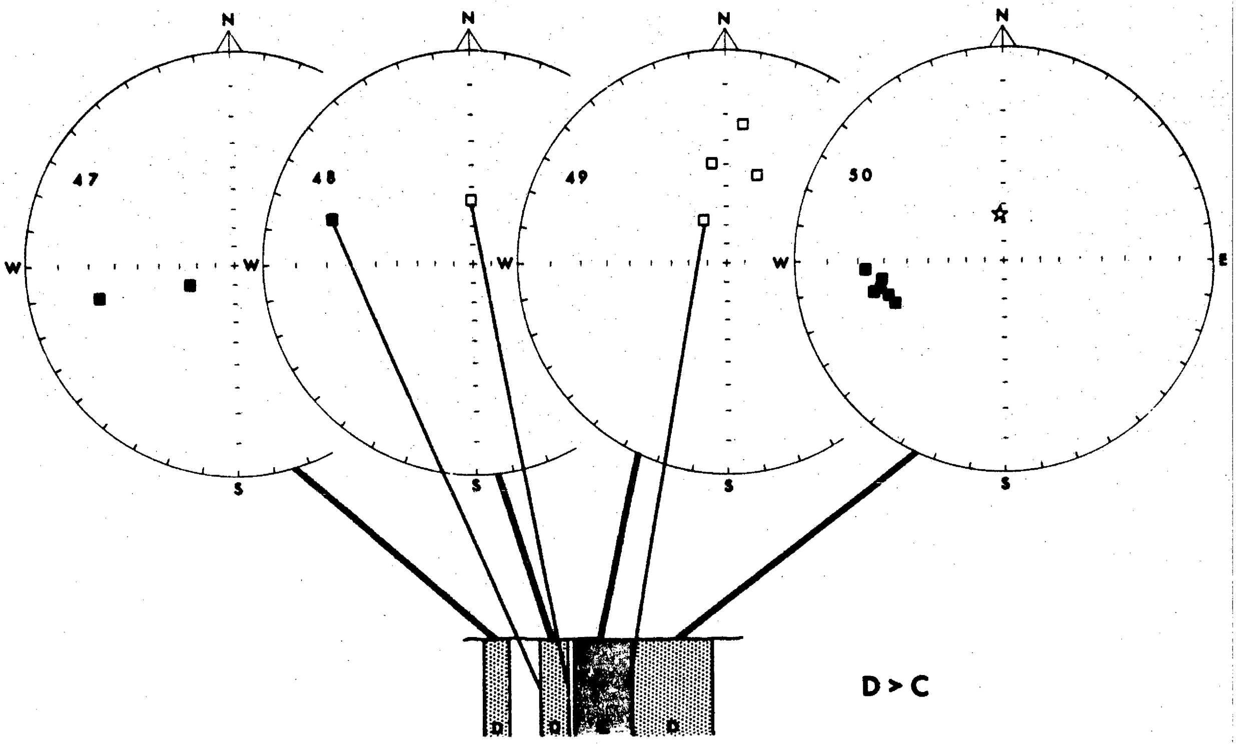

Fig 3.7b-Boya Quarry

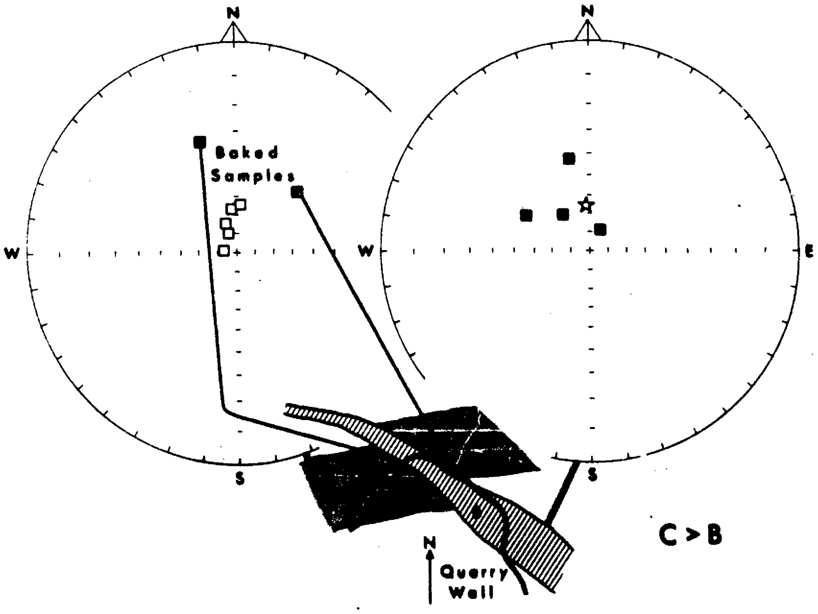

FIGURE 3.7 Baked contact relationships observed in dykes from the Swan and Boya Quarries, Perth Region.

relationship of dykes 47 - 50, sampled in Swan Quarry. A sample taken from the extreme margin of a YC group dyke (no. 49) at its interface with a YD group dyke (no. 50), records a YC group direction. This demonstrates that the YC group dyke is younger than the YD group dyke. A second YD group dyke (no. 48) has been partially remagnetized by this YC group dyke and records both YC group and YD group directions.

In Boya Quarry (Fig. 3.7b), a YC group dyke was cut by a YB group dyke. Samples from the margin of the YC group dyke, where in contact with the YB group dyke, record YB group directions, demonstrating that this margin was thermally remagnetized when the YB group dyke was intruded.

Finally the situation depicted in Fig. 3.8, found for dyke 41 in the Readymix Quarry, enables age relationships to be inferred. Traversing the width of the dyke (right to left in Fig. 3.8), directions typical of the YA group pass, via intermediate directions, to those typical of the YC group. The YC pilot specimen direction approaches the direction of the YA pilot specimen at 40 mT which is taken to indicate that this dyke was originally a YA group dyke which has subsequently suffered partial reheating from an adjacent dyke inferred to belong to the YC group (not all dykes exposed in the quarries were sampled). The ratio of the component of magnetization added during reheating to the original component varies across the width of the dyke and accounts for the streaking observed between the YA group and YC group directions. The component acquired in reheating is considered to be viscous PTRM (Chamalaun, 1964).

From these studies it is evident that in age YA and YD > YC > YB. This magnetic evidence for relative age is corroborated by the Rb-Sr dating studies (Table 3.5). No other magnetic evidence was present in the collection regarding the relative ages of other groups in the Perth region.

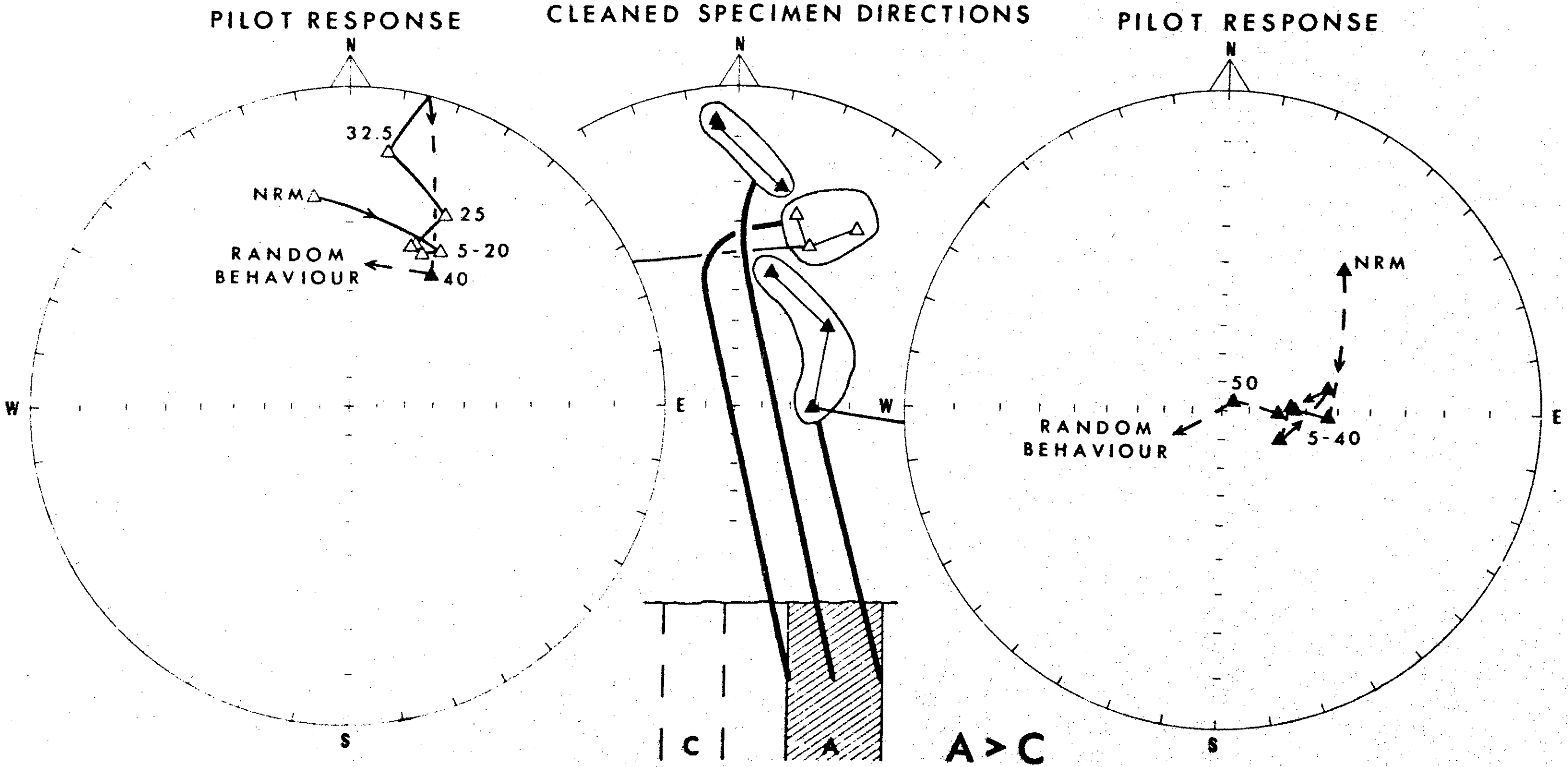

FIGURE 3.8 Pilot specimen behaviour and directions of cleaned magnetic remanence observed in specimens from a partially remagnetized dyke from the Readymix Quarry, Perth Region. The numbers in the pilot response diagrams refer to the demagnetizing fields (in mT) used in stepwise alternating field demagnetization.

### 3.4.3 The Morawa Lavas

Sample-mean directions of NRM (Table 3.4) were reasonably well grouped (Fig. 3.9a). Intensities lay in the range 5.4 to 83,924 $mAm^{-1}$.

The stability of remanence was tested by subjecting six specimens to stepwise alternating field demagnetization and two specimens to partial thermal demagnetization up to maximum temperature of 640°C. The pilot specimen directions either remained stable up to the applied maximum temperature (Fig. 3.9c) or peak field of 210 mT (Fig. 3.9b) or came to stable endpoints after an initial angular change which was accompanied by a large drop in intensity (Fig. 3.9d).

The remaining specimens were magnetically cleaned in a field of 20 mT. The cleaned sample-mean directions of remanence are listed in Table 3.4 and plotted in Fig. 3.9a. Cleaning did little to bring the directions of samples 9 and 10 into better agreement with the main group. The directions of these two samples have therefore not been included in the calculation of the formation-mean direction (Table 3.5). Cleaning did produce a decrease in dispersion for the remaining samples however.

## 3.5 INTERPRETATION OF RESULTS

The initial directions of remanent magnetization within and between dykes were scattered due to the presence of soft viscous components of magnetization acquired in the present field. These were responsible for the streaked distributions observed and their effects demonstrated as temporary components of magnetization acquired in the laboratory. Cleaning of the collection in alternating field values of 5 - 32.5 mT, values typically required for the removal of such components, revealed consistently directed, stable components of magnetization within 48 of the dykes. These components of magnetic remanence are regarded as primary for the following reasons:

## TABLE 3.4

### Morawa Lavas: Sample-mean directions of magnetization before and after magnetic cleaning

| Sample | Before cleaning | | | | | After cleaning | | | |
|---|---|---|---|---|---|---|---|---|---|
| | N[1] | R | D | I | Int | N | R | D | I |
| BH 1 | 3 | 2.999 | 306.1 | -41.7 | 46.9 | 3 | 2.999 | 304.9 | -38.3 |
| BH 2 | 3 | 2.997 | 288.9 | -38.7 | 20.8 | 3 | 2.997 | 300.6 | -39.0 |
| BH 3 | 2 | 1.999 | 294.9 | -48.8 | 14.6 | 2 | 1.998 | 288.7 | -42.5 |
| BH 4 | 3 | 2.999 | 295.2 | -32.0 | 18.2 | 3 | 2.999 | 299.1 | -35.2 |
| BH 5 | 3 | 2.988 | 220.6 | -54.6 | 5.4 | 3 | 2.903 | 340.4 | -21.4 |
| BH 6 | 3 | 2.988 | 338.5 | -24.3 | 83924 | 3 | 2.990 | 338.0 | -23.5 |
| BH 7 | 3 | 2.999 | 285.2 | - 9.7 | 3527 | 3 | 2.991 | 282.2 | -39.1 |
| BH 8 | 3 | 2.999 | 25.4 | -28.2 | 277 | 3 | 2.999 | 307.4 | -51.2 |
| BH 9[2] | 3 | 2.991 | 6.6 | -27.7 | 15.7 | 3 | 2.822 | 78.0 | -71.5 |
| BH 10[2] | 3 | 2.994 | 199.6 | 0.1 | 830 | 3 | 2.989 | 195.9 | - 1.2 |

[1] N = Number of specimens

[2] Sample-mean direction not used in calculation of formation-mean direction.

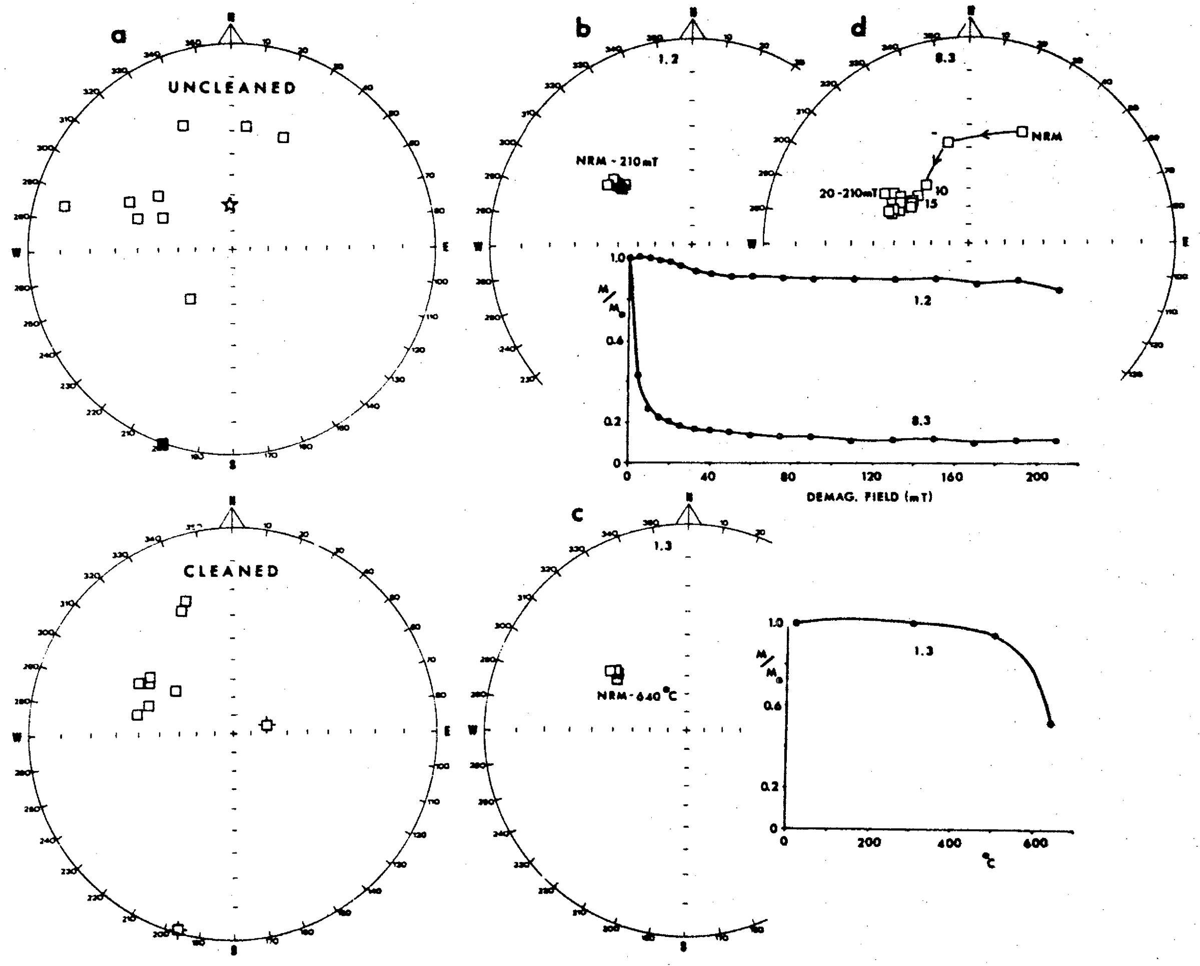

FIGURE 3.9 Morawa Lavas:

(a) Sample-mean directions of magnetization before and after magnetic cleaning. Crossed symbols represent sample-mean directions of magnetization not used in the calculation of the formation-mean direction of magnetization.

(b) & (d) Directional behaviour and normalized intensity decay curves ($M/M_O$) of two pilot specimens during alternating field demagnetization.

(c) Behaviour of a pilot specimen in response to thermal demagnetization.

TABLE 3.5

Group-mean directions of magnetization and pole positions for the Precambrian dykes and lavas from Western Australia

| | Group | Age (My) | N[1] | R | D | I | a | Pole Position Lat.° | Pole Position Long.° | A |
|---|---|---|---|---|---|---|---|---|---|---|
| Ravensthorpe Dykes | RD | 2500 ± 100 | 4 | 3.94 | 114.3 | 82.9 | 13.2 | 38.3S | 136.2E | 25.5 |
| Perth Region Dykes | YA | c2500 or c1700[2] | 6 | 5.89 | 61.1 | 80.6 | 10.0 | 21.7S | 133.7E | 17.9 |
| | YB | 750 - 700 | 4 | 3.84 | 164.4 | -55.0 | 21.7 | 19.9S | 282.0E | 28.1 |
| | YC | c1500[3] | 11 | 10.47 | 347.7 | -53.0 | 10.8 | 79.7N | 2.7E | 13.0 |
| | YD | c1700[4] | 10 | 9.66 | 257.6 | 45.5 | 9.5 | 23.5S | 46.1E | 9.9 |
| | YE | c2500 | 3 | 2.76 | 232.1 | - 8.1 | 46.1 | 28.3S | 0.4E | 31.0 |
| | YF | c1700 | 10 | 9.59 | 344.9 | 50.8 | 10.5 | 24.7N | 101.8E | 14.0 |
| Morawa Lavas | ML | 1390 ± 140 | 8 | 7.58 | 309.0 | -38.1 | 14.0 | 42.8N | 22.4E | 14.7 |

[1] N = Number of dykes or, in the case of the Lavas, number of samples.

[2] The Rb-Sr isotopic data are consistent with either of these ages.

[3] These dykes are certainly not older than 1500 My but may be somewhat younger.

[4] This is the minimum age. The dykes may be somewhat older.

(i) Baked contact studies.

(ii) Consistent directions from geographically widely separated collecting localities.

(iii) Presence of directions belonging to more than one group at single localities, precluding widespread remagnetization.

(iv) Laboratory stability tests.

It follows that the reversals of magnetization observed in the groups are probably records of reversals of the ambient geomagnetic field during intrusion of the dykes. However, records of within-dyke reversals of magnetization in three cases cannot be interpreted in such terms. The dykes are about 10 m - 20 m wide and use of the cooling equation of Jaeger (1957) to calculate the travel time of the magnetite Curie point isotherm from edge to centre of such dykes yields a result of about one year, three orders of magnitude less than the time required for a polarity reversal of the Earth's magnetic field (Larson *et al*, 1971; McElhinny, 1973). Such a mechanism can produce reversals within larger igneous bodies (Beck, 1972). These dykes are small and since there was no field evidence to indicate that they were multiple intrusions, the reversals probably result from the operation of some self-reversal mechanism (Nagata, 1961). A similar phenomenon has been encountered by Strangway (1961).

The combined palaeomagnetic-dating investigation has demonstrated that the dykes collected belong to swarms of six or seven different ages. The palaeomagnetic technique of separating igneous activity into discrete events of differing age was particularly useful in those cases where directions of remanence were different. However, the investigation has highlighted the point that when the time-scale of such activity is long, as in the present case where it covers approximately 1800 My, it is not necessarily valid to assume the converse, that similar ages can be assumed on the basis of similar directions of remanence. This is not surprising since over such a long time span, the observed rate of apparent polar-wandering of 0.2° - 0.3° per My throughout geological time (McElhinny, 1973) would enable the path of the pole to cross itself several times. This situation has arisen, for example, in the Precambrian apparent polar-wander path for Africa (Piper, 1972). In such cases therefore, additional information is necessary for establishing similarity of age.

Although the present investigation has revealed the presence of six ages of dyke intrusion in the Perth region, extending in age into the Archaean, the dating work of Compston and Pidgeon (1962) and Compston and Arriens (1968) suggests that at least one or more late Precambrian swarms, not represented by the collection, are also present. A very complex intrusive history is therefore indicated for the Perth region, and by implication, for the whole western margin of the Yilgarn Block. It might be the igneous activity is related to distinct periods of tectonic activity along the Darling Fault. It has been argued (Wilson, 1958) that the Fault is an early Precambrian feature.

The consistently directed component of magnetization revealed in eight samples of the Morawa Lavas, is considered to be primary. Stability was tested by alternating field and thermal demagnetization techniques. The pole position (Table 3.5) is different to poles so far determined for younger rocks (McElhinny, 1973). The thermal demagnetization results suggest that in two samples at least, haematite is the source of stable remanence. Both magnetite and haematite are present in the lavas (Arriens and Lalor, 1959). The haematite is considered to have originated during sub-aqueous extrusion. Although the magnetization of a further two samples exhibited very high resistance to AF cleaning their directions remained oblique to the main population. They may represent real oblique (intermediate?) directions or more likely, samples of material not properly *in situ*.

The pole positions calculated for the dykes and volcanics are given in Table 3.5. For the dyke group YE, palaeosecular variation effects are not considered to have been averaged out. Its pole therefore, is regarded as a VGP (Cox and Doell, 1960) and in the interpretation of the data in Chapter 6 is used as a guideline only in constructing a Precambrian apparent polar-wander path for Australia.

# CHAPTER 4

# PRECAMBRIAN DYKES FROM THE GAWLER BLOCK, SOUTH AUSTRALIA

## 4.1 INTRODUCTION

Detailed mapping and dating (Compston *et al*, 1966; Thomson, 1969a, 1972) of rocks from the southeastern corner of the Gawler Block (Fig. 4.1) where the basement is well exposed, have shown the area to have suffered numerous phases of intrusive and extrusive igneous activity during the Precambrian, particularly in the period immediately following stabilization of the basement at 1780 My (Compston and Arriens, 1968). Because the geological history of the area is reasonably well understood and igneous material is often very suitable for palaeomagnetic work, a collection was made of a swarm of basic dykes which outcrop there. This chapter presents the results of the palaeomagnetic investigation of these dykes.

Previous palaeomagnetic work on rocks from the Gawler Block consists of two studies. Briden and Ward (1966), reported results obtained from measuring the magnetic inclinations of some late Precambrian sediments obtained from two borecores, one located just to the north of Port Augusta and the other near Woomera, which is about 170 Kms to the northwest of Port Augusta. Although such measurements do not allow calculation of pole positions, their results have proved useful in providing support for the Precambrian apparent polar-wander path proposed for Australia in Chapter 6. The other study was that made by Chamalaun and Porath (1968) who investigated the magnetic remanence of some haematite ore bodies that are exposed in the Middleback Ranges of northeastern Eyre Peninsula (Fig. 4.1). Absence of stratigraphic control on the age of the ore bodies however, only enabled them to assign a

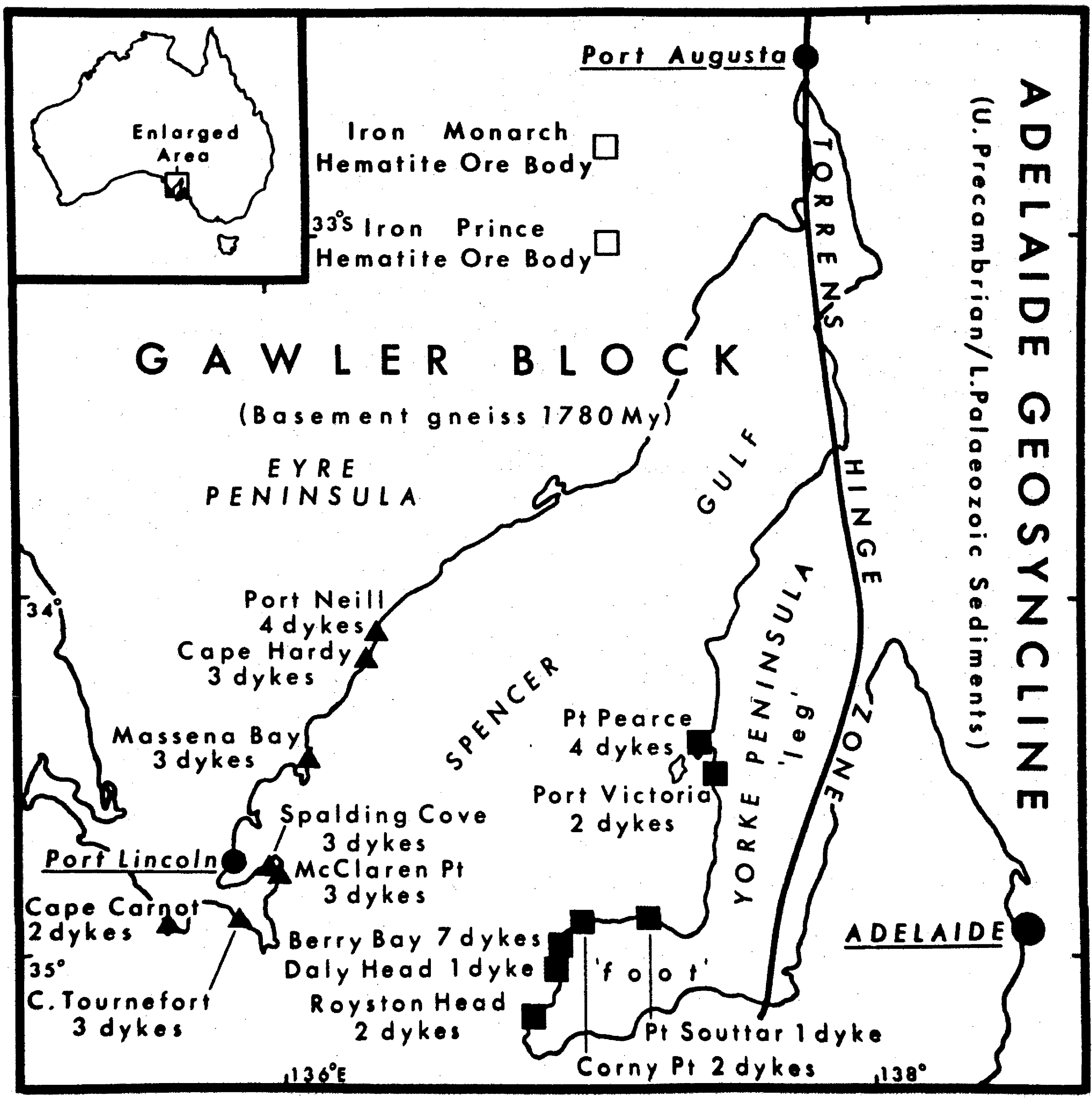

FIGURE 4.1 The southeastern corner of the Gawler Block, showing the sampling localities of the dykes and the location of the haematite ore bodies of the Middleback Ranges (studied by Porath, 1967a). The Torrens Hinge Zone is a complex fault structure forming the boundary between the Gawler Block and the younger Adelaide Geosyncline.

broad age of Precambrian, but less than about 1780 My, to the three poles obtained. The aim of the present investigation was therefore twofold, to provide further palaeomagnetic data for the Precambrian and to enable a tighter age control to be put on the time of ore formation.

## 4.2 GEOLOGY

The dykes outcrop along the Spencer Gulf coastlines of the Southern Eyre Peninsula and Yorke Peninsula. Both are part of the Gawler Block; the Gulf is just a geologically young graben structure which originated from tectonism initiated in the Late Tertiary-Early Quaternary (Firman, 1969). Current seismicity in the area (Stewart and Mount, 1972) suggests that tectonism is still active. The eastern margin of the Gawler Block, delineated by the Torrens Hinge Zone (Thomson, 1969a), coincides with the eastern coastline of Yorke Peninsula.

### 4.2.1 Southern Eyre Peninsula

The foundation of this part of the Eyre Peninsula (Fig. 4.2) is a broad band of Proterozoic metasediments (Johns, 1961). These have been tightly folded, with dips of 75° to 85°, into a series of synclines and anticlines whose axes trend sinuously northward roughly paralleling the coastline. The sequence has been divided into an older gneissose part, the Flinders Group, granulites of which have been dated at 1780 ± 120 My (Compston and Arriens, 1968), and a younger schistose part, the Hutchison Group. Near the base of the Hutchison Group an haematite quartzite — the Greenpatch Metajaspilite — is developed which, with little doubt, is considered equivalent (Whitten, 1966) to the haematite quartzites of the Middleback Group (Miles, 1955). These outcrop further to the north in the Middleback Ranges and are host to the commercially exploited, haematite ore bodies referred to in the Introduction (4.1).

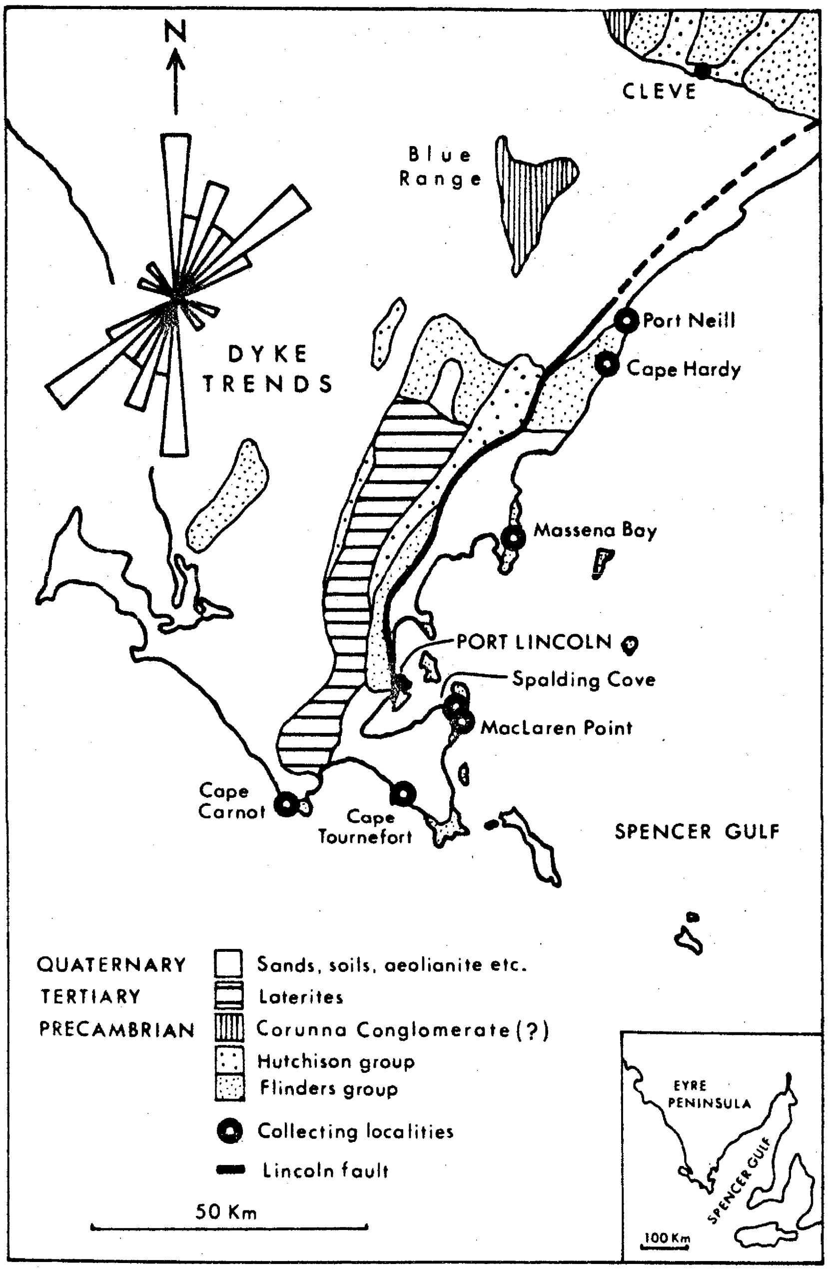

FIGURE 4.2 Geological sketch map of Eyre Peninsula and compass rose diagram of measured dyke trends.

The basic dykes occur in the gneisses of the Flinders Group south of Tumby Bay and are generally concordant with the basement foliation. As a result the dykes strike mainly north to northeast. Their field occurrence is either that of elongated, lenticular, dark bands often penetrated by veinlets of country rock, or as intrusive, massive bodies with chilled contacts and without visible country rock contamination. Tilley (1921) made an extensive study of the dykes and divided them into metadolerites (granulite grade rocks) and various types of amphibolites. Johns (1961) has also recorded some dykes with primary doleritic textures. From field relationships and petrographic studies therefore, the suggestion is that the dykes belong to more than one age of intrusion.

Apart from vertical block uplift along faults in the region associated with formation of the Spencer Gulf graben in the Late Tertiary (Miles, 1952), Johns (1961) finds evidence of only one other period of deformation since folding and granitization of the basement metasediments. This he believes produced the gentle westerly tilt now observed for a conglomerate which outcrops in the Blue Range and west of Cleve. This is correlated with the Corunna Conglomerate found further north (Thomson, 1969a) and which is dated at 1535 My (Compston *et al,* 1966). However, Johns concluded that whatever the cause of the deformation it did not apparently affect the central and southern parts of the Southern Eyre Peninsula, the area from which the dykes were collected.

### 4.2.2 Yorke Peninsula

The basement of this Peninsula (Fig. 4.3), like that of Southern Eyre Peninsula, consists of a highly folded sequence of gneissic metasediments, with dips varying from 70° to vertical (Crawford, 1965). The relationship between the metasediments of the two Peninsulas however, is obscure. Dating of granites along the west coast of the 'foot' of the Peninsula (Thomson, 1972) and of the intrusive Moonta Porphyry in the northern

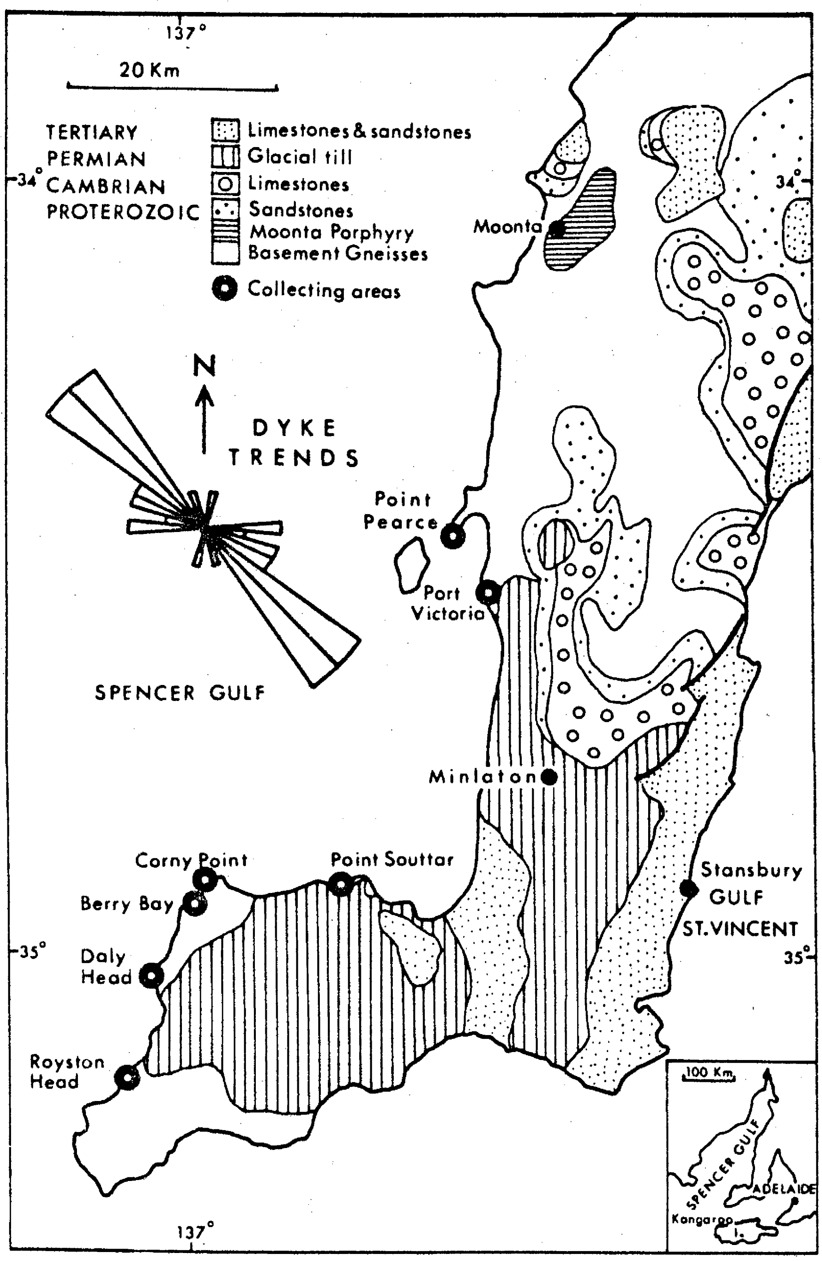

FIGURE 4.3 Geological sketch map of Yorke Peninsula and compass rose diagram of dyke trends.

part of the 'leg' (Compston *et al*, 1966) indicate that the metasediments have a minimum age of about 1450 My.

The dykes have been converted to amphibolite and are generally concordant with the basement gneisses, although Crawford (1965) observes that '...a few discordant dyke-like bodies also occur...'. Strikes are generally north to northwest. There is no evidence as to whether the dykes are of one age or several.

Following peneplanation of the basement, the Peninsula saw accumulations of Proterozoic, Cambrian, Permian, Tertiary and Quaternary material. The developments are essentially thin, except for a thick Cambrian sequence in the subsided Dalrymple Basin near Stansbury. From these overlying sediments two observations can be made. Firstly, since the dykes are nowhere seen to cut the Proterozoic shelf sediments (Crawford, 1965), the age of the dykes is established to be Precambrian. Secondly, they enable determination of whether any significant regional tilting of the area has occurred since their deposition. This is particularly important in view of the proximity of the Torrens Hinge Zone which has been the locus of intermittent, tectonic activity since the late Precambrian (Stuart and von Sanden, 1972). Sprigg (1961) reported that a 800 m bore in the Minlaton area penetrated only flat-lying Cambrian sediments, while to the south, on Kangaroo Island north of the Cygnet Fault, Cambrian sediments are again flat-lying. Crawford (1965) observed that both the Cambrian and Proterozoic sediments of the northern part of the Peninsula are flat-lying, but in the centre part found they tend to be gently tilted to the west as a result of movement along a series of north trending normal faults present there. It is evident though that this is not on a scale which is regionally significant. It is therefore concluded that no significant regional tilting of the basement has occurred since deposition of the oldest overlying sediments despite the occurrence of an orogeny in the adjacent Adelaide Geosyncline in the Late Cambrian-Early Ordovician (Wopfner, 1969).

## 4.3 LOCALITY AND SAMPLING DETAILS

Sampling localities of all dykes were coastal, outcrop being confined to the intertidal zone. The samples collected thus came from the freshest exposures available. Some dykes were observed whose margins were ill-defined and there was evidence of assimilation with the host rock. Where these relationships were clearly evident, such dykes were avoided. At most localities visited more than one dyke outcropped, but in no case was there any cross-cutting of dykes. Dykes sampled averaged 3 m - 10 m width and at multiple dyke localities were generally separated by about 30 m. Table 4.1 gives specific information regarding collecting localities and sampling scheme.

One hundred and thirty one samples were collected from 40 dykes. Two separate collections were made, one comprising 35 dykes and the other, five dykes. The distinction is made because the second collection of five dykes was sampled and investigated by Dr B.J.J. Embleton. Except for the single dyke which was field-drilled, all dykes were hand-sampled and in all but eight cases, hand samples were oriented using both sun compass and magnetic compass. In general three or five samples were collected from each dyke, distributed across the width. In the laboratory three or four cylindrical specimens (28 mm x 28 mm) were cored from each sample, providing 401 specimens.

## 4.4 DESCRIPTION OF PALAEOMAGNETIC RESULTS

Intensities of NRM spanned a wide range of values from 0.9 to 3489 $mAm^{-1}$. The mean directions of initial remanence of 20 dykes were non-random. These are plotted in Fig. 4.4a and listed in Table 4.2. Broadly speaking, they fall into two scattered groups with opposite

## TABLE 4.1

Locality and Sampling Details of the South Australian Dykes

| Locality | No. of Dykes | Dyke Identification | Sample Identification | Map No.*:Map Ref. |
|---|---|---|---|---|
| EYRE PENINSULA | | | | |
| Port Neill | 4 | | | SI 53-11:435783 |
| | | 1 | EP 1-3 | |
| | | 2 | EP 4-6 | |
| | | 3 | EP 7-9 | |
| | | 4 | EP 10-12 | |
| Cape Hardy | 3 | | | |
| | | 5 | EP 13-15 | SI 53-11:431776 |
| | | 6 | EP 16-18 | |
| | | 7 | EP 19-21 | |
| Massena Bay | 3 | | | SI 53-11:412741 |
| | | 8 | EP 22-24 | |
| | | 9 | EP 25-27 | |
| | | 10 | EP 28-30 | |
| Spalding Core | 3 | | | SI 53-11:399706 |
| | | 11 | EP 31-33 | |
| | | 12 | EP 34-36 | |
| | | 13 | EP 37-39 | |
| McClaren Point | 3 | | | |
| | | 14 | EP 40-42 | SI 53-11:401703 |
| | | 15 | EP 43-45 | |
| | | 16 | EP 46-49 | |
| Cape Tournefort | 3 | | | SI 53-11:387688 |
| | | 17 | EP 50-52 | |
| | | 18 | EP 53-55 | |
| | | 19 | EP 56-58 | |
| Cape Carnot | 2 | | | SI 53-11:363685 |
| | | 20 | EP 59-61 | |
| | | 21 | EP 62-64 | |

*1:250,000 Topographic Series, Australia: Edition 1, Series R502

Continued

TABLE 4.1

(Continued)

| Locality | No. of Dykes | Dyke Identification | Sample Identification | Map No.*:Map Ref. |
|---|---|---|---|---|
| YORKE PENINSULA | | | | |
| Souttar Point | 1 | | | SI 53-12:526691 |
| | | 22 | YP 1-4; YPH 1 | |
| Corny Point | 2 | | | SI 53-12:502691 |
| | | 23 | YP 5-7; YPH 2,3 | |
| | | 24 | YPH 4-6 | |
| Berry Bay | 7 | | | SI 53-12:497685 to 501688 |
| | | 25 | YP 8-10 | |
| | | 26 | YP 11-13 | |
| | | 27 | YP 14,15 | |
| | | 28 | YP 16-18 | |
| | | 29 | YP 19-21 | |
| | | 30 | YP 22-24 | |
| | | 31 | YP 25-27 | |
| Daly Head | 1 | | | SI 53-16:493675 |
| | | 32 | YP 28-32 | |
| Royston Head | 2 | | | SI 53-16:654655 |
| | | 33 | YP 33-35 | |
| | | 34 | YP 36-38 | |
| Port Victoria | 2 | | | SI 53-12:548736 |
| | | 35 | YP 39-42 | |
| | | 36 | PO 1-4 | |
| Point Pearce | 4 | | | SI 53-12:544742 |
| | | 37 | PO 5-7 | |
| | | 38 | PO 8-11 | |
| | | 39 | PO 12-15 | |
| | | 40 | PO 16-19 | |

*1:250,000 Topographic Series, Australia: Edition 1, Series R502

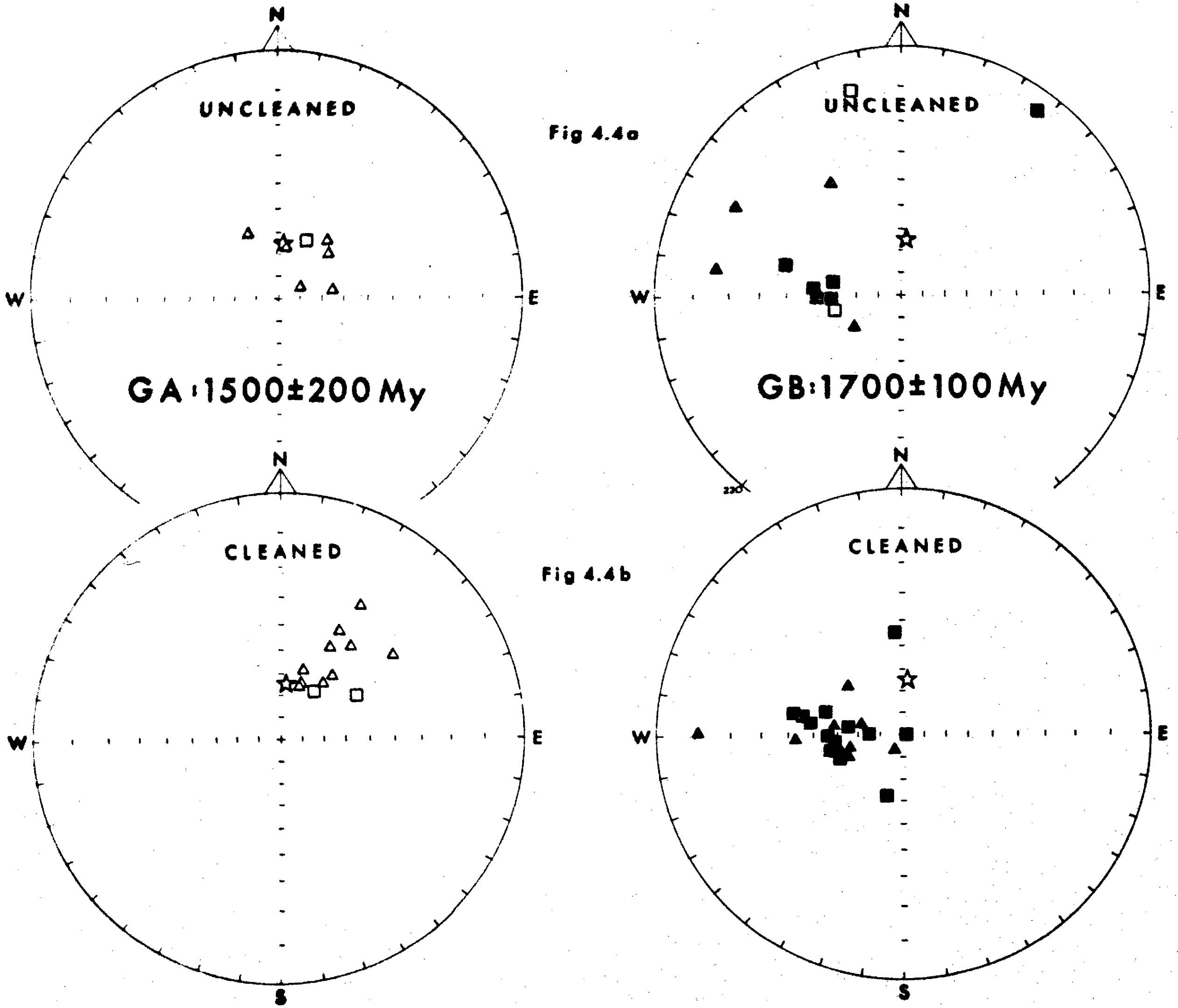

FIGURE 4.4 South Australian dykes: Dyke-mean directions of magnetization before and after magnetic cleaning.

TABLE 4.2

Dyke-mean directions of remanence before magnetic cleaning

| Locality | Dyke No. | N* | R | D | I | Int. |
|---|---|---|---|---|---|---|
| EYRE PENINSULA | | | | | | |
| Port Neill | 1 | 3 | 2.98 | 7.5 | -66.2 | 23.7 |
| | 2 | 3 | 1.72 | — | — | 18.2 |
| | 3 | 2 | 1.90 | — | — | 215 |
| | 4 | 1 | — | — | — | — |
| Cape Hardy | 5 | 3 | 2.84 | 62.2 | -78.2 | 4.5 |
| | 6 | 3 | 2.24 | — | — | 1.5 |
| | 7 | 3 | 1.79 | — | — | 2.5 |
| Massena Bay | 8 | 3 | 2.79 | 298.0 | 15.6 | 1304 |
| | 9 | 3 | 1.19 | — | — | 14.4 |
| | 10 | 1 | — | — | — | — |
| Spalding Cove | 11 | 3 | 2.97 | 237.6 | 65.2 | 532 |
| | 12 | 2 | 1.00 | — | — | 21.6 |
| | 13 | 3 | 2.40 | — | — | 1253 |
| McClaren Point | 14 | 3 | 2.95 | 327.7 | 33.6 | 0.9 |
| | 15 | 1 | — | — | — | — |
| | 16 | 1 | — | — | — | — |
| Cape Tournefort | 17 | 3 | 2.99 | 49.4 | -59.2 | 293 |
| | 18 | 3 | 2.94 | 39.9 | -55.6 | 30.2 |
| | 19 | 3 | 2.83 | 81.1 | -65.2 | 173 |
| Cape Carnot | 20 | 3 | 2.81 | 335.4 | -57.5 | 222 |
| | 21 | 3 | 2.96 | 278.9 | 16.3 | 3489 |

*N = Number of samples per dyke

Continued

TABLE 4.2

(Continued)

| Locality | Dyke No. | N* | R | D | I | Int. |
|---|---|---|---|---|---|---|
| YORKE PENINSULA | | | | | | |
| Souttar Point | 22 | 5 | 4.16 | 37.3 | 4.6 | 4.1 |
| Corny Point | 23 | 3 | 1.75 | — | — | 4.3 |
| | 24 | 3 | 2.995 | 6.3 | 20.0 | 258 |
| Berry Bay | 25 | 3 | 2.43 | — | — | 835 |
| | 26 | 3 | 1.80 | — | — | 30.1 |
| | 27 | 2 | 1.82 | — | — | 2.5 |
| | 28 | 1 | — | — | — | — |
| | 29 | 3 | 2.997 | 267.8 | 53.0 | 2087 |
| | 30 | 3 | 2.994 | 267.7 | 58.5 | 1387 |
| | 31 | 2 | 1.60 | — | — | 1.7 |
| Daly Head | 32 | 2 | 1.98 | 345.7 | -10.5 | 73.2 |
| Royston Head | 33 | 3 | 2.997 | 282.2 | 59.1 | 102 |
| | 34 | 3 | 2.99 | 285.3 | 37.7 | 317 |
| Port Victoria | 35 | 4 | 3.64 | 26.5 | -60.6 | 506 |
| | 36 | 4 | 2.24 | — | — | 328 |
| Point Pearce | 37 | 2 | 1.996 | 258.5 | -59.7 | 4.8 |
| | 38 | 4 | 2.24 | — | — | 224 |
| | 39 | 3 | 2.83 | 273.7 | 51.2 | 84.9 |
| | 40 | 4 | 1.69 | — | — | 37.3 |

*N = Number of samples per dyke

polarities, though not antiparallel. Statistical randomness of the directions in the remaining 20 dykes was either due to streaking of sample or specimen directions towards the present field axis, or to an apparent lack of any preferred orientation.

The stability of NRM was tested by subjecting 71 pilot specimens from the 35 dykes of the first collection to stepwise alternating field demagnetization. The stability characteristics are summarized in terms of the stability index, SI, defined in Chapter 2. Values of SI obtained for the collection are shown in histogram form in Fig. 4.5. It is evident that a complete spectrum of magnetic stability is represented, although stability characteristics tend to be concentrated at the extreme ends of the spectrum. The peak at SI values less than 0.1 corresponds to partially and completely unstable magnetic remanence, and the other, at SI values greater than 0.8, reflects extremely stable remanence which is of single domain or pseudo-single origin. However, any pilot specimen with a value of SI greater than 0.11 (75% of the pilot specimen collection) reaches a well-defined endpoint. A general observation from the histogram therefore, is that the majority of pilot specimens possess a stable component of magnetic remanence, but the maximum coercivity of this component varies considerably from one pilot specimen to the next.

The procedure adopted for bulk magnetic cleaning of this collection was the same as that used for the Western Australian dykes (Chapter 3, Section 3.4.1). The remanence of the second collection of five dykes (investigated by Dr B.J.J. Embleton) was analyzed in a different manner, but for all 40 dykes cleaning fields generally fell within the range 5 mT to 32.5 mT. A marked within-dyke variation of magnetic stability was found in 10 dykes, therefore, as in the case of the Western Australian dykes (Chapter 3, Section 3.4.1), unit weight has been assigned to specimens in calculating dyke-mean directions of cleaned remanence.

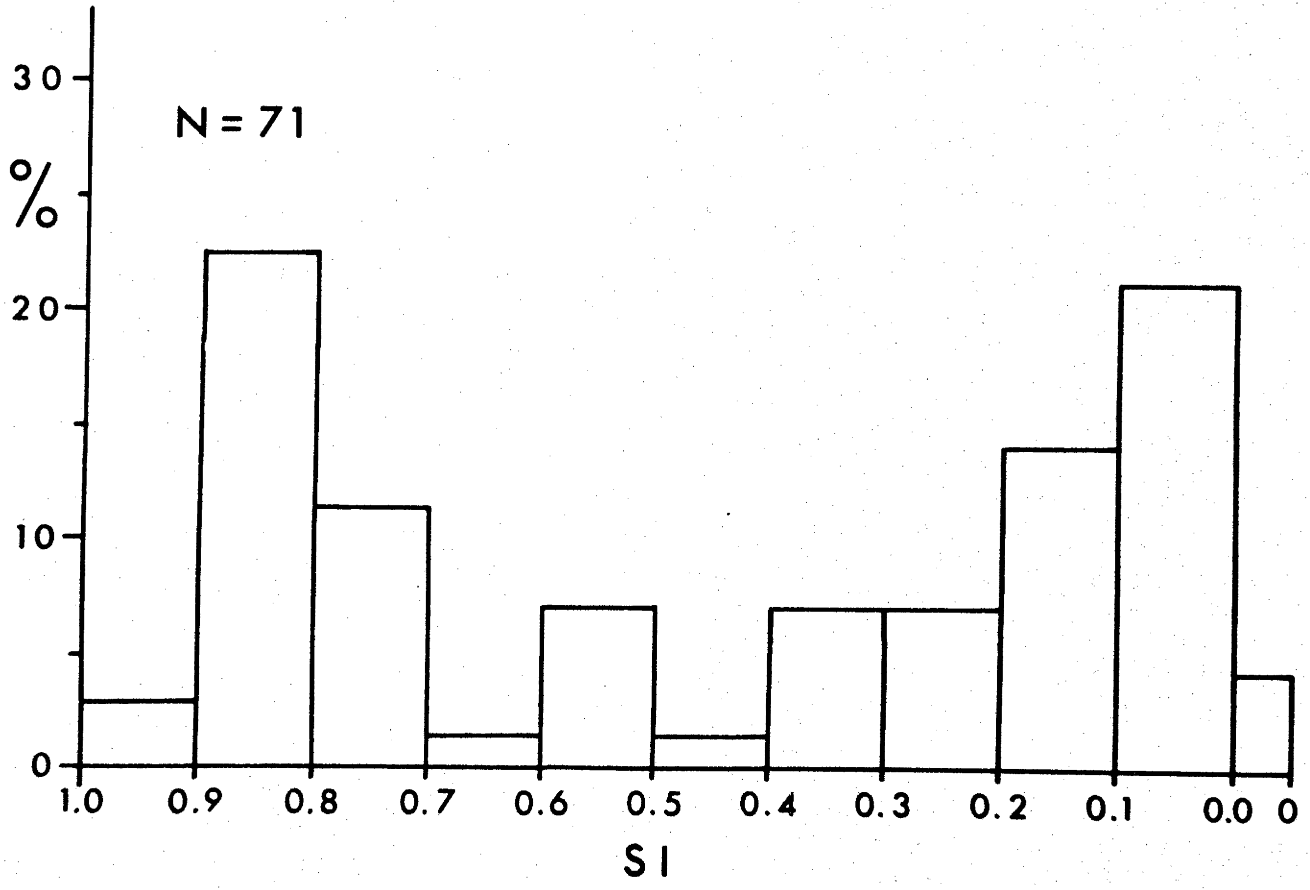

FIGURE 4.5 The stability spectrum of the South Australian dykes in terms of SI (see Chapter 2 for definition of the stability index SI). N is the number of pilot specimens used in the analysis.

Specimens from 34 dykes responded satisfactorily to magnetic cleaning. The dyke-mean directions of cleaned remanence are listed in Table 4.3 and plotted in Fig. 4.4b. They fall into two distinct groups. Also shown are the ages of the two groups obtained from Rb-Sr dating work carried out by Drs Compston and Crawford of this Department on representative samples from each group.

## 4.5 INTERPRETATION OF RESULTS

Soft viscous components of magnetization acquired in the present field were responsible for the observed scatter and streaking of the NRM directions. Removal of these components in low cleaning fields revealed that the stable remanence of the dykes belonged to two well-defined groups.

One of the groups, GA, is magnetized near the present field direction and might therefore be thought to reflect a recently imposed direction of Late Tertiary or younger age (Wellman *et al*, 1969). Several lines of evidence discount this possibility. In several localities, dykes constituting both groups are present and occur in close proximity to one another. This observation and the fact that the pilot specimens of each group exhibit a complete range of magnetic stability, rule out the possibility of a subsequent regional thermal event affecting the magnetization. Furthermore, there is no evidence from Rb-Sr work to indicate the presence of a very young event.

Selective remagnetization by low temperature (chemical) processes is also discounted in view of results obtained by Johnson and Merrill (1974). They found that single domain magnetite grains may oxidize at low temperatures yet still record their initial directions of remanent magnetization irrespective of the magnetic field direction imposed during the process. Specimens from *both* groups yielded SI values greater

## TABLE 4.3

Dyke-mean directions of remanence after magnetic cleaning

| Locality | Dyke No. | N(Sa)[1] | R | D | I | Group |
|---|---|---|---|---|---|---|
| EYRE PENINSULA | | | | | | |
| Port Neill | 1 | 9(3) | 8.96 | 17.5 | -63.6 | GA |
| | 2 | 3(2) | 2.97 | 37.0 | -39.4 | GA |
| | 3 | 9(3) | 8.58 | 31.1 | -25.6 | GA |
| | 4 | 7(3) | 6.60 | 283.6 | 70.2 | GB |
| Cape Hardy | 5 | 9(3) | 8.31 | 20.3 | -62.9 | GA |
| | 6 | 8(3) | 7.75 | 28.6 | -36.4 | GA |
| | 7[2] | — | — | — | — | — |
| Massena Bay | 8 | 9(3) | 8.991 | 257.9 | 58.7 | GB |
| | 9 | 8(3) | 7.59 | 267.1 | 43.4 | GB |
| | 10 | 6(2) | 5.97 | 210.0 | 81.9 | GB |
| Spalding Cove | 11 | 9(3) | 8.96 | 248.5 | 62.8 | GB |
| | 12 | 7(3) | 6.56 | 255.3 | 65.2 | GB |
| | 13 | 9(3) | 8.57 | 277.2 | 58.3 | GB |
| McClaren Point | 14 | 9(3) | 7.85 | 312.0 | 56.7 | GB |
| | 15[2] | — | — | — | — | — |
| | 16 | 8(3) | 7.13 | 18.1 | -57.3 | GA |
| Cape Tournefort | 17 | 9(3) | 8.94 | 36.6 | -58.2 | GA |
| | 18 | 9(3) | 8.93 | 27.4 | -44.0 | GA |
| | 19 | 9(3) | 8.43 | 38.8 | -53.3 | GA |
| Cape Carnot | 20 | 5(2) | 4.59 | 53.6 | -30.4 | GA |
| | 21 | 9(3) | 8.30 | 271.2 | 11.7 | GB |

[1] N(Sa) = Number of specimens (samples)

[2] No specimens from these three dykes contained magnetic remanence with stable end-point behaviour. SI values were less than 0.1.

Continued

TABLE 4.3

(Continued)

| Locality | Dyke No. | N(Sa)[1] | R | D | I | Group |
|---|---|---|---|---|---|---|
| YORKE PENINSULA | | | | | | |
| Souttar Point | 22 | 15(5) | 12.77 | 356.5 | 45.2 | GB |
| Corny Point | 23[3] | 2(1) | 1.96 | 265.0 | 45.7 | GB |
| | 24[2] | — | — | — | — | — |
| Berry Bay | 25 | 9(3) | 8.996 | 257.3 | 57.2 | GB |
| | 26[3] | 3(1) | 2.97 | 285.9 | 68.5 | GB |
| | 27 | 6(2) | 5.81 | 59.8 | -51.2 | GA |
| | 28 | 7(3) | 6.21 | 194.7 | 60.9 | GB |
| | 29 | 9(3) | 8.990 | 268.8 | 56.5 | GB |
| | 30 | 9(3) | 8.991 | 265.6 | 58.8 | GB |
| | 31 | 5(2) | 4.79 | 269.7 | 75.1 | GB |
| Daly Head | 32[3] | 3(1) | 2.81 | 171.7 | 77.6 | GB |
| Royston Head | 33 | 9(3) | 8.98 | 277.6 | 65.3 | GB |
| | 34 | 9(3) | 8.992 | 281.3 | 42.6 | GB |
| Port Victoria | 35 | 11(4) | 10.39 | 35.4 | -63.3 | GA |
| | 36 | 6(2) | 5.59 | 103.9 | 88.7 | GB |
| Point Pearce | 37 | 9(3) | 8.72 | 285.6 | 54.3 | GB |
| | 38 | 9(3) | 8.66 | 249.4 | 59.7 | GB |
| | 39 | 12(4) | 11.35 | 277.6 | 49.0 | GB |
| | 40 | 12(4) | 11.73 | 280.8 | 45.6 | GB |

[1] N(Sa) = Number of specimens (samples)

[2] No specimens from these three dykes contained magnetic remanence with stable end-point behaviour. SI values were less than 0.1.

[3] Specimens from only one sample yielded SI values greater than 0.1. Results from these three dykes were omitted from the palaeomagnetic pole calculations.

# TABLE 4.4

Group-mean directions of remanence and palaeomagnetic poles

| Group | Age | N* | R | Mean Direction |  |  | Pole Position |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  | D | I | a | Lat.° | Long.° | A |
| GA | 1500 ± 200 My | 12 | 11.59 | 34.7 | -49.5 | 8.5 | 61.4N | 230.8E | 8.6 |
| GB | 1700 ± 100 My | 22 | 20.51 | 272.5 | 61.1 | 8.5 | 22.8S | 86.4E | 11.3 |

*N = Number of dykes

than 0.8, thus implying the single domain nature of their magnetic grains.

Foliation is often imparted to a rock fabric as a result of metamorphism. The dykes have suffered varying degrees of medium-grade metamorphism and although a macroscopic foliation is absent, foliation on a smaller scale might be present. The possibility however, that such a foliation could have produced a systematic deflection of the directions of remanence of the dykes is considered remote in view of the results of Irving and Park (1973) on visibly foliated rocks. They found that '...deflections [of the directions of stable remanence] show no systematic relationship to the foliation...'. The effect of foliation was merely to introduce a randomly directed component.

It is concluded therefore that the groups of directions, GA and GB, refer to the primary components of magnetization of the dykes acquired during separate periods of intrusion. Pole positions calculated for the two groups are given in Table 4.4.

The close similarity in the pole positions of the dykes with those obtained by Chamalaun and Porath (1968) from the haematite ore bodies of Iron Monarch and Iron Prince in the Middleback Ranges, now makes it possible to propose constraints for the time of ore formation. In addition, the palaeomagnetic results have an important bearing on a recently proposed model for the structural history of the region (Crawford and Campbell, 1973a). A fuller consideration of these aspects of the palaeomagnetic study however, is deferred until Chapter 6.

# CHAPTER 5

# LATE PRECAMBRIAN-CAMBRIAN SEDIMENTS FROM THE ADELAIDE GEOSYNCLINE, SOUTH AUSTRALIA

## 5.1 INTRODUCTION

Previous palaeomagnetic work undertaken on sedimentary rocks of late Precambrian-Cambrian age from the Adelaide Geosyncline (Fig. 5.1a) has been reported by Briden (1964, 1967a). The results obtained however, were disappointing. The rock samples were either too weak to measure accurately with instruments then available, or possessed magnetic remanence which remained scattered after partial thermal demagnetization and Briden's general conclusion was that the formations had been extensively remagnetized in the Early Tertiary. Results from a late Precambrian sequence at Hallett Cove and the Middle Cambrian Billy Creek Formation indicated that a primary remanence might have been present, but here again directions remained too scattered.

Despite this extensive investigation therefore, no useable palaeomagnetic results were forthcoming. A feature of this investigation was that partial thermal demagnetization was rarely taken above temperatures of 400°C. However, a number of studies have shown that primary magnetization is sometimes only revealed at demagnetizing temperatures much higher than 400°C (Chamalaun and Creer, 1964; Irving and Opdyke, 1965; Storetvedt *et al*, 1968). In view of this and the more sensitive magnetometers now available, a new palaeomagnetic investigation of late Precambrian-Cambrian sediments from the Geosyncline was undertaken.

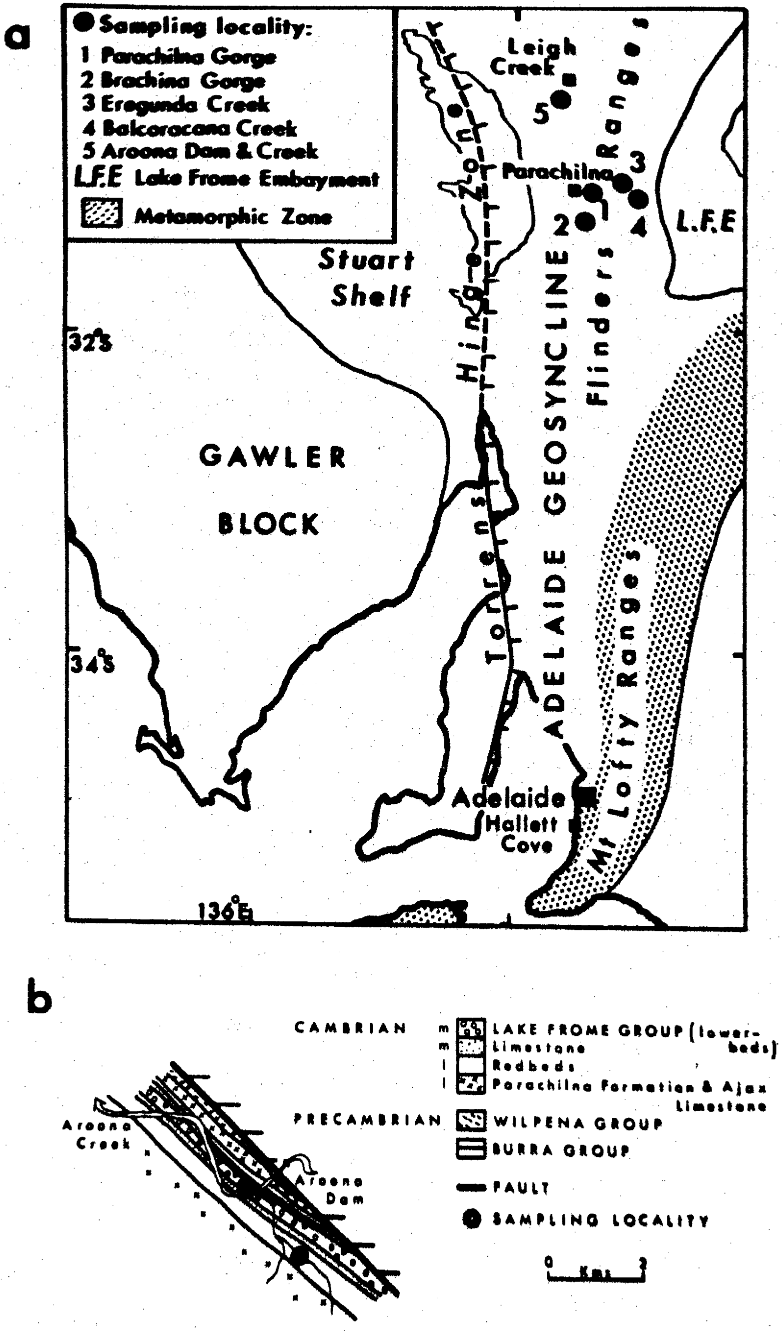

FIGURE 5.1 (a) The sampling localities of the late Precambrian and Cambrian sediments shown in relation to the principal structural elements of the Adelaide Geosyncline. 1, 2, 3 = Pound Quartzite; 2, 5 = Middle Cambrian (lower beds of the Lake Frome Group); 5 = Lower Cambrian; 4 = Upper Cambrian-?Lower Ordovician (upper beds of the Lake Frome Gooup).

(b) Geological sketch map of the Aroona Creek and Dam area — sampling localities of the Lower and some Middle Cambrian sediments.

## 5.2 GEOLOGY

The Adelaide Geosyncline (Thomson, 1969b) contains a sequence of essentially shallow marine and continental sediments deposited during the Upper Precambrian (Adelaidean) to Early Ordovician. The Gawler Block which flanks the western margin of the Geosyncline (Fig. 5.1a) has been the major source of clastics during its depositional history, with sedimentation sporadically overlapping onto the eastern margin of the Block (the Stuart Shelf). The developments here are generally thin and little disturbed, but in the geosynclinal zone are folded and reach a thickness in excess of 15 Km. The geological histories of the Gawler Block and the Adelaide Geosyncline have thus been intimately related throughout the evolution of the Geosyncline.

The sedimentary sequence was folded in the Delamerian Orogeny during the Late Cambrian-Early Ordovician. Radiometric ages within the range 490 - 460 My have been obtained from granites associated with the tectonic activity and metamorphosed shales and volcanics (Compston *et al*, 1966; White *et al*, 1967; Cooper and Compston, 1971; Dasch *et al*, 1971). Regional metamorphism was confined mainly to the southern and eastern parts of the Orogen (Offler and Fleming, 1968). Intensity of folding and metamorphism decrease in a general northwesterly direction from these areas, so that in the Flinders Ranges of the northern part of the Adelaide Geosyncline, the sedimentary sequence is unmetamorphosed and preserved in large, open, north-trending synclinal structures.

The present rugged relief of the Flinders Ranges owes its origin to uplift in the Late Tertiary. As a result of a more humid erosional cycle in the Pleistocene, numerous rivers flowing transversely to the fold axes have cut deep gorges through many fold profiles, thus providing good outcrop exposure of most members of the geosynclinal sequence (Campana, 1958).

An account of the stratigraphy of the sequence is given by Thomson (1969b) and Wopfner (1969). The Precambrian (Adelaidean) part of the sequence has been divided into four major rock groups of which the Wilpena Group is the youngest. The overlying Cambrian comprises two rock groups: the Hawker Group of Early Cambrian age represented by drab coloured sandstones and carbonates, and the Lake Frome Group of Middle and Late Cambrian, possibly Early Ordovician age (Daily *et al*, 1973), which consists of 3,000 m of red-beds. The two Groups are separated by a red-bed formation and an overlying limestone which contains *Redlichia* fauna of late Early Cambrian age (Daily, 1957). Samples for palaeomagnetic work were collected from red-beds at four stratigraphic levels. Collections were made in the northern Flinders Ranges because of the excellent exposure and to avoid the effects of regional metamorphism dominant in the southern parts of the Orogen. The sequences collected were:

(i) Late Cambrian, possibly Early Ordovician red-beds from the uppermost part of the Lake Frome Group.

(ii) Middle Cambrian red-beds from the lowest part of the Lake Frome Group.

(iii) Lower Cambrian red-beds (Billy Creek Formation equivalents).

(iv) Late Precambrian Pound Quartzite.

The Pound Quartzite is the uppermost member of the Wilpena Group and comprises two units (Forbes, 1971): the lower Bonney Sandstone which is a red sandstone and siltstone, and the upper Rawnsley Quartzite, a white, resistant quartzite responsible for the rugged ridges throughout the Flinders Ranges. The Pound Quartzite was for long considered the basal unit of the Cambrian (Campana, 1958) until the discovery in its upper unit of fossils (*Ediacara* fauna) of late Precambrian age

(Glaessner, 1959; Wade, 1970). It is thus the youngest late Precambrian unit in the Adelaide Geosyncline and is overlain by thick sequences of limestones with *Archaeocyatha* fauna belonging to the Lower Cambrian Hawker Group. The contact is generally disconformable, but could be conformable in the Lake Frome Embayment (Freeman, 1966).

## 5.3 LOCALITY AND SAMPLING DETAILS

The sampling areas are shown in Fig. 5.1b and Fig. 5.2. Sampling details have been summarized in Table 5.1. In all cases samples were collected as blocks and oriented with a sun compass and magnetic compass. In general, three cylindrical specimens (28 mm x 28 mm) were cored from each sample in the laboratory.

## 5.4 DESCRIPTION OF PALAEOMAGNETIC RESULTS

### 5.4.1 Pound Quartzite

Intensities of the NRM of the samples were weak, ranging from 0.6 to 6.9 $mAm^{-1}$. NRM sample-mean directions (Table 5.2) which were significant (see Chapter 1) are plotted in Fig. 5.3a prior to correction for bedding tilt. They cluster near the present geomagnetic field direction in the area and are streaked in a general northwesterly direction. Application of Graham's fold test (Graham, 1949) to these directions (Table 5.3) increased their dispersion significantly (McElhinny, 1964) after tectonic correction.

The stability of remanent magnetization was tested by subjecting nine pilot specimens to stepwise thermal demagnetization up to a maximum temperature of 670°C. Their susceptibilities were monitored to check for the occurrence of any chemical changes that might have taken place during heating. Three types of directional behaviour were observed in these pilot specimen studies:

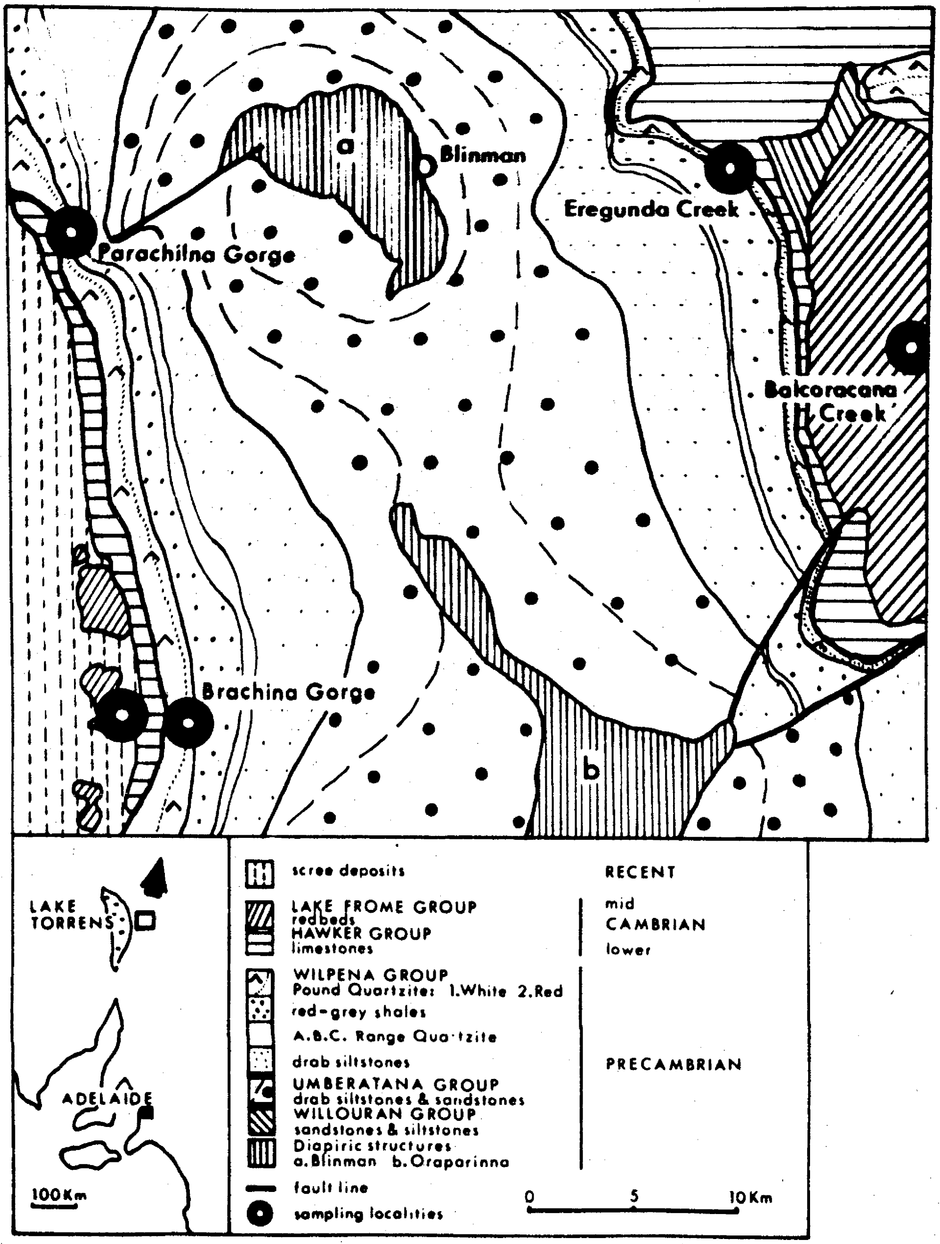

FIGURE 5.2 Geological sketch map of the sampling localities of the late Precambrian Pound Quartzite and the Late and some Middle Cambrian sediments (taken from the South Australian Geological Survey Sheet H 54-13 'Parachilna').

TABLE 5.1

Locality and sampling details of the Late Precambrian to Cambrian sediments

| Locality | Sample Identification | Map Reference* | Remarks |
|---|---|---|---|
| Late Precambrian Pound Quartzite | | | |
| Brachina Gorge | SPQ 1-23 | H 54-13:146120 | Samples collected at five points over a distance of about 1 Km. Collection spans from the base (SPQ 1-9) to the top (SPQ 21-23) of the formation. Beds dip at 40° to the WNW. |
| Parachilna Gorge | SPQ 24-32 | H 54-13:140145 | Collection stratigraphically near the middle of the formation. Beds dip at 70° to the SW. |
| Eregunda Creek | SPQ 33-39 | H 54-13:174150 | At the top of the formation. Beds dip at 35° to the NNE. |

*South Australian geological atlas series — 1:250,000

Continued

TABLE 5.1

(Continued)

| Locality | Sample Identification | Map Reference* | Remarks |
|---|---|---|---|
| Cambrian Sediments | | | |
| (a) Early Cambrian | | | |
| Aroona Dam | F 30-47 | SH 54-9:647209 | 70 m section exposed in a creek just below the dam. Beds dip at 45° to the NE. |
| (b) Middle Cambrian | | | |
| Brachina Gorge | F 1-16 | H 54-13:142120 | Collected from a 200 m section. Beds dip at 80° to the W. |
| Aroona Creek | F 17-29 | SH 54-9:647211 | Represent about 100 m of section. Beds dip at 40° to the NE. |
| (c) Late Cambrian | | | |
| Balcoracana Creek | F 48-58 | H 54-13:184142 | Near the top of the Lake Frome Group. Collected from a 150 m long section in beds dipping at 70° to the E. |

*South Australian geological atlas series — 1:250,000

TABLE 5.2

Late Precambrian Pound Quartzite: Sample-mean directions of magnetization before and after thermal cleaning

| Sample[1] | Before Cleaning | | | | | | | After Cleaning | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Uncorrected[3] | | Corrected | | | | | Uncorrected | | Corrected | |
| | N[2] | R | D | I | D | I | Int | N | R | D | I | D | I |
| SPQ 1 | 3 | 2.50 | — | — | — | — | — | 3 | 1.96 | — | — | — | — |
| 2 | 3 | 2.90 | 331.5 | -64.7 | 91.1 | -58.7 | 2.7 | 2 | 1.92 | 197.5 | - 3.3 | 198.7 | 6.0 |
| 3 | 3 | 2.79 | 325.8 | -58.7 | 45.6 | -65.3 | 3.3 | 3 | 1.96 | — | — | — | — |
| 4 | 3 | 2.96 | 318.8 | -40.7 | 6.4 | -66.7 | 2.2 | 3 | 2.32 | — | — | — | — |
| 5 | 3 | 2.41 | — | — | — | — | — | 3 | 2.02 | — | — | — | — |
| 6 | 3 | 2.98 | 311.1 | -41.4 | 5.1 | -69.2 | 3.2 | 3 | 2.64 | 330.0 | -15.8 | 349.5 | -39.9 |
| 7 | 3 | 2.89 | 302.0 | -19.9 | 302.0 | -70.9 | 1.6 | 3 | 2.70 | 230.7 | 54.7 | 266.0 | 21.7 |
| 8 | 3 | 2.81 | 319.9 | -41.5 | 27.5 | -76.2 | 1.6 | 3 | 2.27 | — | — | — | — |
| 9 | 3 | 1.10 | — | — | — | — | — | 2 | 1.98 | 191.2 | 16.3 | 209.8 | 25.8 |
| 10 | 3 | 2.19 | — | — | — | — | — | 3 | 0.58 | — | — | — | — |
| 11 | 3 | 2.83 | 309.4 | -47.1 | 18.7 | -75.7 | 1.1 | 3 | 2.35 | — | — | — | — |
| 12 | 3 | 2.96 | 253.3 | - 8.0 | 240.8 | -39.7 | 0.8 | 3 | 2.07 | — | — | — | — |
| 13 | 3 | 2.82 | 300.6 | -13.6 | 306.2 | -51.8 | 1.6 | 3 | 2.54 | — | — | — | — |
| 14 | 3 | 2.89 | 278.9 | -28.4 | 264.3 | -65.6 | 1.3 | 3 | 2.31 | — | — | — | — |
| 15 | 3 | 2.86 | 273.0 | -31.1 | 224.1 | -68.6 | 1.7 | 3 | 2.50 | — | — | — | — |
| 16 | 3 | 2.65 | 261.6 | - 8.2 | 250.4 | -43.4 | 1.0 | 3 | 1.17 | — | — | — | — |
| 17 | 3 | 2.85 | 353.0 | -23.8 | 16.2 | -34.3 | 0.7 | 2 | 1.98 | 198.0 | 1.0 | 198.2 | 1.5 |
| 18 | 3 | 2.60 | — | — | — | — | — | 2 | 1.99 | 154.2 | 1.0 | 162.0 | 27.0 |
| 19 | 3 | 2.27 | — | — | — | — | — | 3 | 2.67 | 231.9 | 46.0 | 251.2 | 17.0 |

[1] Each sample represents a different stratigraphic horizon.

[2] N = Number of specimens.

[3] Refers to bedding correction.

Continued

TABLE 5.2

(Continued)

| Sample[1] | Before Cleaning | | | | | | | After Cleaning | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Uncorrected[3] | | Corrected | | | | | Uncorrected | | Corrected | |
| | N[2] | R | D | I | D | I | Int | N | R | D | I | D | I |
| SPQ 21 | 3 | 2.83 | 330.9 | -35.9 | 55.6 | -70.4 | 2.1 | 2 | 1.96 | 333.7 | 26.2 | 333.5 | -26.5 |
| 22 | 3 | 2.72 | 318.6 | -22.3 | 174.9 | -80.2 | 1.3 | 3 | 2.35 | — | — | — | — |
| 23 | 3 | 2.99 | 15.8 | -65.1 | 101.6 | -39.3 | 2.8 | 3 | 2.00 | — | — | — | — |
| 24 | 3 | 2.69 | 2.7 | -61.3 | 38.3 | - 3.5 | 1.9 | 3 | 1.43 | — | — | — | — |
| 25 | 3 | 2.96 | 355.6 | -77.0 | 49.8 | -15.4 | 2.6 | 3 | 2.07 | — | — | — | — |
| 26 | 3 | 1.84 | — | — | — | — | — | 3 | 2.63 | 199.3 | 50.2 | 215.9 | - 9.4 |
| 27 | 3 | 2.70 | 60.5 | -59.0 | 61.3 | 13.0 | 2.3 | 3 | 1.66 | — | — | — | — |
| 28 | 3 | 2.76 | 133.2 | -56.8 | 93.4 | - 5.2 | 0.9 | 3 | 2.75 | 190.2 | 36.2 | 200.5 | -16.9 |
| 29 | 3 | 2.76 | 9.3 | -75.5 | 50.4 | - 8.9 | 2.2 | 3 | 0.85 | — | — | — | — |
| 30 | 3 | 2.06 | — | — | | | — | 3 | 0.40 | — | — | — | — |
| 31 | 3 | 2.99 | 31.4 | -81.5 | 53.3 | -16.3 | 4.3 | 3 | 1.33 | — | — | — | — |
| 32 | 3 | 2.98 | 333.2 | -63.7 | 29.9 | -24.9 | 6.9 | 3 | 1.67 | — | — | — | — |
| 33 | 3 | 2.97 | 341.9 | -61.8 | 266.0 | -64.0 | 2.4 | 3 | 1.75 | — | — | — | — |
| 34 | 3 | 2.99 | 356.1 | -75.1 | 232.3 | -65.8 | 4.1 | 3 | 1.76 | — | — | — | — |
| 35 | 3 | 2.80 | 351.5 | -51.8 | 269.5 | -63.3 | 1.9 | 3 | 1.02 | — | — | — | — |
| 36 | 3 | 2.95 | 336.7 | -54.3 | 275.9 | -65.5 | 2.4 | 3 | 1.44 | — | — | — | — |
| 37 | 3 | 2.83 | 5.0 | -74.8 | 212.0 | -70.3 | 0.6 | 3 | 0.73 | — | — | — | — |
| 38 | 3 | 2.88 | 259.6 | -53.8 | 235.0 | -28.8 | 1.5 | 3 | 1.81 | — | — | — | — |
| 39 | 3 | 2.99 | 304.6 | -60.7 | 248.4 | -51.4 | 0.9 | 3 | 2.19 | — | — | — | — |

[1] Each sample represents a different stratigraphic horizon.

[2] N = Number of specimens.

[3] Refers to bedding correction.

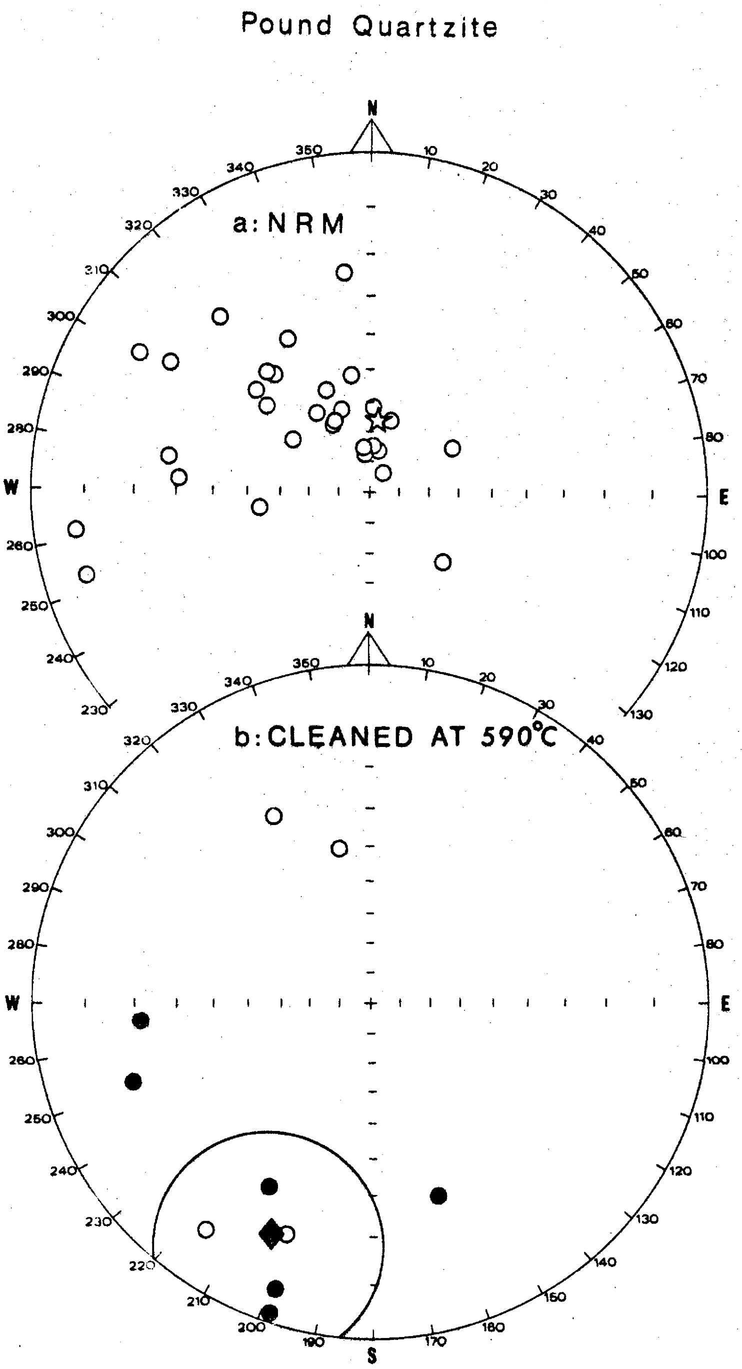

FIGURE 5.3 Pound Quartzite: Sample-mean directions of magnetization before and after thermal cleaning. The directions in (a) are plotted with respect to the present horizontal; those in (b) have been corrected for bedding. The circle represents the cone of confidence at the 95% probability level associated with the mean direction (indicated by a diamond).

## TABLE 5.3

Fold Test data

| Unit | N* | | k | |
|---|---|---|---|---|
| | | | Uncorrected | Corrected |
| Pound Quartzite | NRM | 30 | 6.0 | 3.2 |
| | cleaned | 10 | 4.7 | 4.7 |
| Lake Frome Group (Єm) | NRM | 24 | 4.3 | 1.4 |
| (lower beds) | cleaned | 15 | 1.9 | 5.9 |

*N = Number of samples

(i) Specimen directions initially far from the present field axis remained unchanged up to the applied maximum temperature of 670°C (Fig. 5.4a). The remanence was of the thermally discrete type (Irving and Opdyke, 1965) residing in grains with blocking temperatures near to the Curie point of haematite.

(ii) Specimen directions initially close to the present field direction underwent substantial angular changes at low temperatures and realized stable endpoints in the temperature range 440°C - 630°C (Fig. 5.4b). Intensities of magnetization became very weak (0.3 - 0.7 $mAm^{-1}$) and probably caused the dispersion in the endpoint groupings as illustrated by the pilot specimen of Fig. 5.4b. Remanence was of the thermally distributed type (Irving and Opdyke, 1965) being carried by grains covering a blocking temperature spectrum whose maximum was at 630°C.

(iii) Directions initially close to the present field remained unchanged up to the onset of unstable behaviour (Fig. 5.4c). Remanence was thermally distributed with highest blocking temperatures in the region of 630°C - 650°C.

The intensity decay curves for the three types of behaviour showed the presence of a rather soft component of magnetization removed in temperatures of 150°C - 250°C. In most cases intensities dropped to 20% or less of their initial values by 670°C.

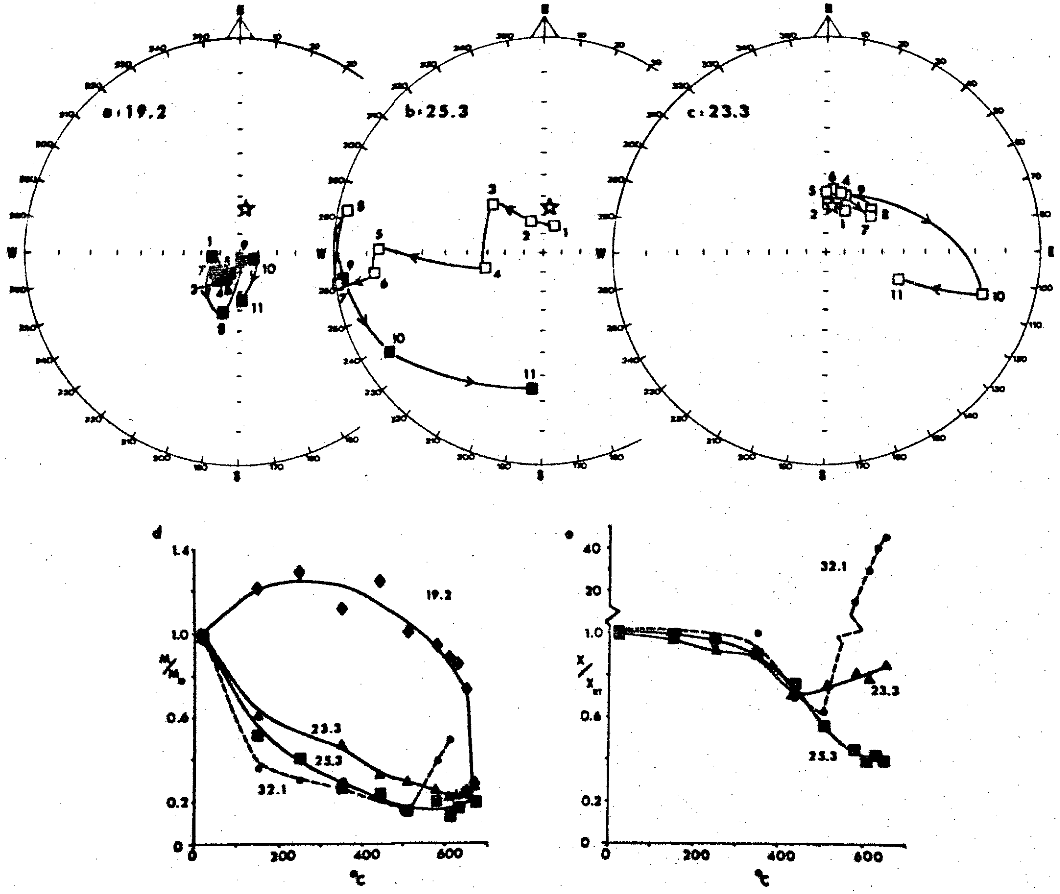

FIGURE 5.4 Pound Quartzite: Directional, intensity ($M/M_o$ curves — $M_o$ referring to the intensity of NRM) and susceptibility ($\chi/\chi_{RT}$ curves — RT referring to room temperature) behaviour of some pilot specimens during thermal demagnetization. The numbers 1-11 refer to the following demagnetization temperatures (in °C) respectively: NRM, 150, 250, 350, 440, 510, 570, 610, 630, 650, 670. Note the correlation between the large increase in susceptibility of pilot specimen 32.1 and the increase in its remanent intensity. Directional behaviour (not shown) of this pilot specimen became correspondingly unstable. It was not possible to monitor susceptibility for pilot specimen 19.2 during demagnetization.

With one exception, the susceptibilities of the pilot specimens decayed with increasing temperature. Above 610°C they remained essentially unchanged. The exception showed a 30 fold increase in susceptibility above 510°C. This increase was paralleled by an increase in intensity and the onset of directionally unstable behaviour. But for this instance, there was no correlation between directional behaviour during demagnetization and susceptibility change.

The net result of the pilot demagnetization studies was that they demonstrated the existence of a stable component of magnetization which could be isolated in the temperature range 440°C - 630°C. All remaining specimens were therefore thermally cleaned at 590°C. After bulk cleaning, the sample-mean directions of magnetization of 33 of the samples could be considered random. However, examination of these samples at the *specimen* level revealed that whilst some specimens had remained magnetized near to the present field direction, the directions in others had undergone systematic angular changes in excess of 90°. For five of these 33 samples it was possible to eliminate an aberrant specimen, leaving two specimens which had cleaned satisfactorily.

The 10 cleaned sample-mean directions are plotted in Fig. 5.3b after correction for bedding tilt and are listed in Table 5.2. Two samples are magnetized in the opposite sense to the main group. Comparison of directions before and after cleaning, but prior to tectonic correction, showed that they had undergone an average systematic rotation of 80° away from the present field direction along an approximate north-south trend. The precision of the cleaned formation mean (Table 5.3) was unchanged as a result of correction for bedding tilt. (It is necessary to point out that the fold test, prior to cleaning, relied heavily on samples from the Eregunda Creek and Parachilna Gorge collecting localities, all but two of which were rejected after cleaning.) The cleaned formation mean is given in Table 5.5.

### 5.4.2 Cambrian Sediments

The NRM sample-mean directions of magnetization for the Early, Middle and Late Cambrian sediments are plotted with respect to the present horizontal in Fig. 5.5a-c respectively and listed in Table 5.4. Intensities of remanence lay in the range 0.5 to 33.0 $mAm^{-1}$. Sample-mean directions for the Middle Cambrian sediments prior to tectonic correction (Fig. 5.5b) were clustered around the present field direction and were significantly more dispersed (McElhinny, 1964) after correction for bedding tilt (Table 5.3). The sample-mean directions for the Early (Fig. 5.5a) and Late Cambrian sediments (Fig. 5.5c) were streaked towards the present field along a northeast-southwest trending axis.

Seven pilot specimens were selected from the three formations to test the stability of remanence. A detailed description of the results is omitted because their behaviour was essentially the same as that found for the Pound Quartzite pilot specimens. Thus specimens magnetized near the present field direction prior to tectonic correction either remained directionally stable there until the onset of unstable behaviour, or underwent angular changes of 30° - 60° at low temperatures and came to stable endpoints. Remanences were thermally distributed and showed sharp intensity drops of 30% - 50% of initial values by 250°C. One pilot magnetized far from the present field had thermally discrete remanence and remained essentially directionally stable up to 650°C. Susceptibility values for five pilot specimens increased after treatment at 510°C, but only in two of these was there a correlation between susceptibility change and directional behaviour.

The thermal demagnetization studies indicated that stable components of magnetization could be isolated by treatment at 500°C for the Early Cambrian sediments and Middle Cambrian sediments from the Aroona Creek collecting locality and 590°C for the Late Cambrian sediments and Middle Cambrian sediments collected at Brachina Gorge.

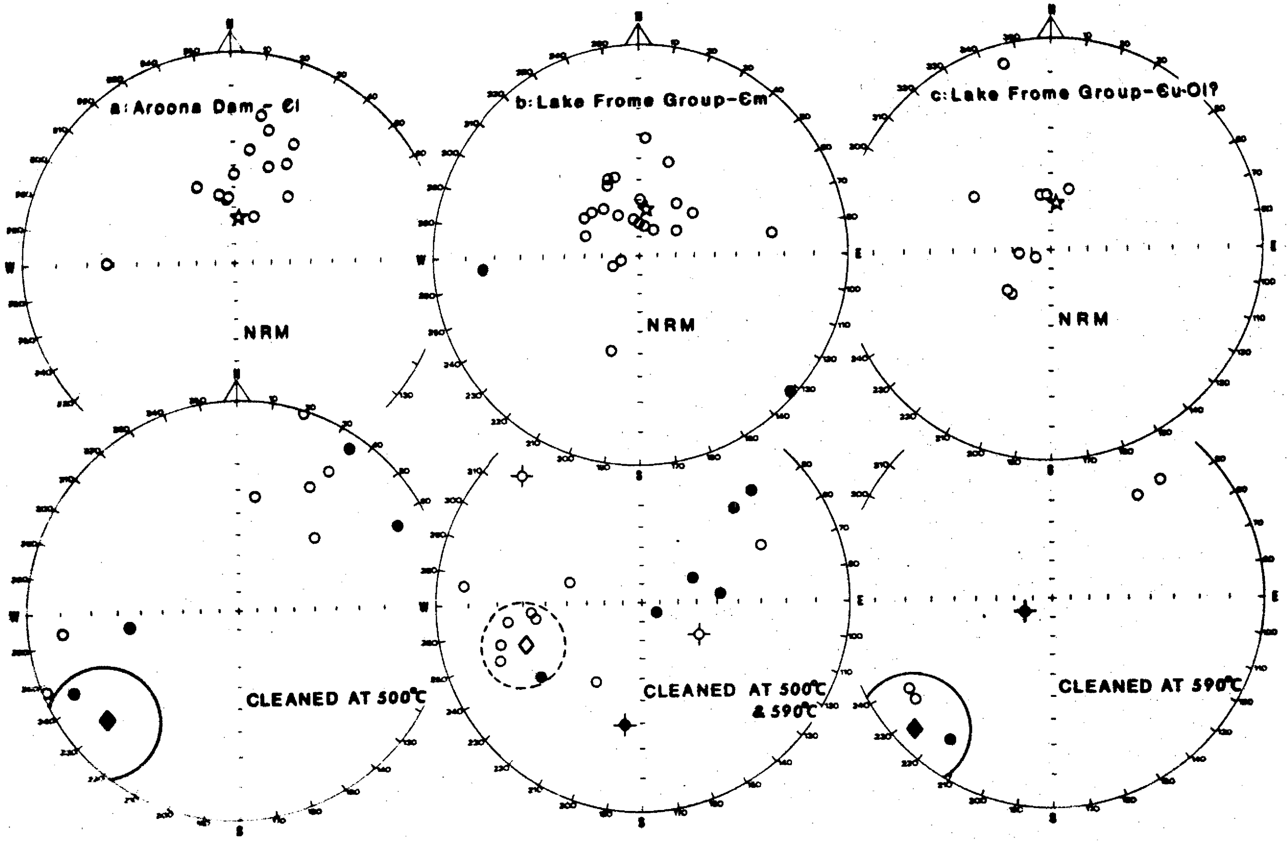

FIGURE 5.5 Cambrian sediments: Sample-mean directions of magnetization before and after thermal cleaning. The NRM directions are plotted with respect to the present horizontal; the cleaned directions have been corrected for bedding. The circles represent cones of confidence at the 95% probability level associated with each mean direction (indicated by a diamond). Crossed symbols represent sample-mean directions sufficiently oblique to the mean axes of magnetization that they may record intermediate field directions.

TABLE 5.4

Cambrian Sediments: Sample-mean directions of magnetization before and after thermal cleaning

| Sample | Before Cleaning | | | | | | | After Cleaning | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Uncorrected | | Corrected | | | | | Uncorrected | | Corrected | |
| | N | R | D | I | D | I | Int | N | R | D | I | D | I |
| Early Cambrian | | | | | | | | | | | | | |
| F 30 | 3 | 2.96 | 335.2 | -46.0 | 283.9 | -49.6 | 5.6 | 3 | 2.51 | — | — | — | — |
| 33 | 2 | 1.99 | 23.7 | -34.8 | 354.5 | -75.1 | 5.8 | 2 | 1.94 | 13.6 | 40.6 | 19.1 | 0.3 |
| 34 | 3 | 2.99 | 28.7 | -33.5 | 12.3 | -75.5 | 4.5 | 3 | 2.96 | 12.8 | 6.8 | 8.5 | -32.5 |
| 35 | 3 | 2.96 | 352.9 | -56.3 | 270.0 | -62.5 | 3.8 | 3 | 2.98 | 252.1 | 2.0 | 262.2 | 34.9 |
| 36 | 3 | 2.97 | 270.7 | -27.5 | 262.6 | 0.5 | 2.6 | 3 | 2.98 | 247.8 | -29.1 | 243.9 | 8.1 |
| 37 | 2 | 1.99 | 27.6 | -24.8 | 1.6 | -72.8 | 4.8 | 2 | 1.95 | 31.6 | 54.4 | 34.7 | 3.6 |
| 38 | 3 | 2.95 | 349.0 | -52.8 | 263.6 | -54.6 | 4.1 | 3 | 2.71 | 262.1 | -42.9 | 247.5 | - 0.6 |
| 39 | 2 | 1.52 | — | — | — | — | — | 2 | 1.95 | 278.2 | -35.1 | 263.5 | - 9.7 |
| 40 | 3 | 2.96 | 1.0 | -44.2 | 302.0 | -65.3 | 4.3 | 3 | 2.87 | 28.8 | -37.2 | 6.2 | -77.9[1] |
| 42 | 3 | 2.99 | 8.3 | -32.6 | 336.6 | -66.4 | 4.1 | 2 | 1.99 | 358.9 | -30.1 | 327.1 | -59.3[1] |
| 43 | 2 | 1.99 | 18.6 | -27.0 | 352.0 | -31.5 | 4.3 | 2 | 1.96 | 30.5 | 18.8 | 30.4 | -22.0 |
| 44 | 3 | 2.99 | 353.3 | -57.6 | 271.7 | -63.1 | 3.2 | 2 | 1.98 | 68.7 | - 5.2 | 79.0 | -38.5 |
| 45 | 2 | 1.99 | 22.7 | -63.2 | 240.6 | -73.8 | 4.7 | 2 | 1.97 | 48.9 | -57.6 | 182.3 | -78.9[1] |
| 46 | 2 | 1.98 | 11.0 | -19.2 | 352.7 | -53.6 | 3.5 | 2 | 1.95 | 33.4 | 27.3 | 33.7 | -13.6 |
| 47 | 2 | 1.99 | 39.7 | -45.5 | 82.6 | -86.4 | 2.9 | 2 | 1.97 | 74.7 | 45.1 | 62.5 | 9.1 |

[1] Sample mean direction of magnetization not used in calculation of formation mean (see text).

[2] One specimen became too weak for accurate measurement.

Continued

TABLE 5.4

(Continued)

| Sample | Before Cleaning | | | | | | | After Cleaning | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Uncorrected | | Corrected | | | | | Uncorrected | | Corrected | |
| | N | R | D | I | D | I | Int | N | R | D | I | D | I |
| Middle Cambrian | | | | | | | | | | | | | |
| F 1 | 4 | 3.93 | 348.3 | -69.4 | 82.6 | -13.8 | 4.0 | 4 | 3.58 | 159.2 | 40.3 | 235.1 | 29.6 |
| 2 | 3 | 2.99 | 290.3 | -58.5 | 96.6 | -37.1 | 2.6 | 3 | 2.99 | 270.5 | -39.2 | 117.7 | -55.2[1] |
| 3 | 3 | 2.91 | 356.1 | -72.0 | 84.4 | -10.6 | 3.7 | 2 | 1.98 | 83.3 | -17.7 | 64.6 | 59.9[2] |
| 4 | 3 | 2.99 | 4.2 | -73.8 | 87.7 | -18.2 | 3.3 | 3 | 2.35 | — | — | — | — |
| 5 | 2 | 1.93 | 304.3 | -53.6 | 86.5 | -49.3 | 1.8 | 2 | 0.87 | — | — | — | — |
| 6 | 2 | 1.99 | 34.8 | -56.3 | 72.7 | 2.8 | 3.0 | 2 | 1.94 | 37.3 | -25.6 | 44.5 | 16.0 |
| 7 | 3 | 2.32 | — | — | — | — | — | 3 | 0.52 | — | — | — | — |
| 8 | 3 | 2.94 | 54.9 | -67.4 | 92.4 | - 3.7 | 3.2 | 3 | 2.35 | — | — | — | — |
| 9 | 3 | 2.97 | 334.6 | -48.9 | 74.1 | -33.0 | 4.8 | 3 | 2.89 | 350.0 | -44.4 | 64.6 | -25.0 |
| 10 | 3 | 2.96 | 359.8 | -59.6 | 74.4 | - 8.0 | 2.2 | 3 | 2.78 | 43.6 | -26.4 | 44.2 | 25.7 |
| 11 | 3 | 2.91 | 29.8 | -73.9 | 84.9 | 1.5 | 3.1 | 3 | 1.31 | — | — | — | — |
| 12 | 3 | 1.92 | — | — | — | — | — | 3 | 2.99 | 105.5 | - 6.7 | 126.0 | 80.4 |
| 13 | 3 | 2.51 | — | — | — | — | — | 3 | 2.74 | 235.4 | 13.3 | 210.7 | -42.7 |
| 14 | 3 | 2.99 | 52.8 | -54.5 | 73.2 | 18.8 | 3.0 | 3 | 2.61 | — | — | — | — |
| 15 | 2 | 1.78 | — | — | — | — | — | 2 | 1.89 | — | — | — | — |
| 16 | 3 | 2.85 | 80.6 | -24.4 | 62.6 | 55.4 | 2.7 | 3 | 1.24 | — | — | — | — |
| 17 | 3 | 2.97 | 197.1 | -39.6 | 205.2 | -11.9 | 5.5 | 3 | 2.41 | — | — | — | — |
| 18 | 3 | 2.99 | 262.1 | -81.5 | 238.7 | -50.5 | 2.7 | 2 | 1.99 | 255.3 | -47.8 | 248.2 | -17.6[2] |
| 19 | 3 | 2.94 | 132.5 | 1.5 | 133.2 | - 3.7 | 33.0 | 3 | 2.67 | 263.6 | -47.6 | 253.9 | -18.7 |
| 20 | 2 | 1.99 | 341.0 | -48.0 | 286.2 | -48.1 | 5.5 | 2 | 1.99 | 343.5 | -49.0 | 285.6 | -50.0 |
| 21 | 3 | 2.97 | 311.6 | -55.3 | 268.7 | -31.4 | 3.4 | 3 | 1.47 | — | — | — | — |
| 22 | 3 | 2.89 | 17.3 | -40.2 | 314.1 | -67.7 | 2.5 | 3 | 2.84 | 312.7 | -58.4 | 265.8 | -33.5 |

Footnotes as on previous page

Continued

TABLE 5.4

(Continued)

| Sample | Before Cleaning | | | | | | | After Cleaning | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Uncorrected | | Corrected | | | | | Uncorrected | | Corrected | |
| | N | R | D | I | D | I | Int | N | R | D | I | D | I |
| Middle Cambrian (Continued) | | | | | | | | | | | | | |
| F 23 | 3 | 2.53 | — | — | — | — | — | 2 | 1.93 | 145.5 | 63.9 | 83.4 | 48.5[2] |
| 24 | 3 | 2.97 | 336.9 | -47.5 | 284.0 | -46.6 | 3.1 | 3 | 2.93 | 291.8 | -31.3 | 276.2 | - 9.4 |
| 25 | 3 | 2.94 | 2.9 | -30.8 | 328.2 | -51.1 | 3.1 | 3 | 2.87 | 324.0 | - 8.4 | 317.0 | - 9.6[1] |
| 26 | 3 | 2.92 | 250.1 | -74.6 | 238.6 | -24.1 | 1.7 | 3 | 1.17 | — | — | — | — |
| 27 | 3 | 2.76 | 266.1 | 14.8 | 292.3 | 52.8 | 2.0 | 3 | 2.63 | 194.5 | - 9.7 | 188.2 | 28.9[1] |
| 28 | 3 | 2.99 | 330.9 | -65.1 | 260.1 | -37.1 | 14.4 | 3 | 2.97 | 327.6 | -62.6 | 262.9 | -35.3 |
| 29 | 3 | 2.98 | 322.2 | -58.1 | 263.7 | -40.1 | 11.5 | 3 | 2.99 | 296.2 | -51.2 | 262.4 | -23.7 |
| Late Cambrian | | | | | | | | | | | | | |
| F 48 | 3 | 2.86 | 227.6 | -58.6 | 244.7 | 8.4 | 1.8 | 3 | 0.97 | — | — | — | — |
| 49 | 3 | 2.29 | — | — | — | — | — | 2 | 1.68 | — | — | — | — |
| 50 | 3 | 2.84 | 354.5 | -61.0 | 292.4 | -16.9 | 1.5 | 3 | 2.08 | — | — | — | — |
| 51 | 3 | 2.45 | — | — | — | — | — | 3 | 2.74 | 41.8 | 23.6 | 40.8 | -26.2 |
| 52 | 3 | 2.86 | 345.2 | - 7.7 | 342.0 | 2.5 | 1.7 | 2 | 1.99 | 36.2 | 32.6 | 43.1 | -16.1 |
| 53 | 3 | 2.95 | 348.6 | -60.6 | 294.3 | -19.5 | 4.6 | 3 | 2.56 | — | — | — | — |
| 54 | 3 | 2.84 | 15.8 | -57.2 | 299.5 | -33.0 | 3.6 | 3 | 2.71 | 257.2 | 9.1 | 243.0 | 73.2[1] |
| 55 | 2 | 1.99 | 305.2 | -41.6 | 292.5 | 8.9 | 3.0 | 2 | 1.83 | — | — | — | — |
| 56 | 3 | 2.98 | 242.1 | -80.3 | 254.5 | - 7.6 | 9.1 | 3 | 2.96 | 179.7 | -71.5 | 238.5 | -12.1 |
| 57 | 3 | 2.99 | 222.2 | -57.8 | 245.1 | -10.4 | 12.8 | 3 | 2.99 | 206.9 | -51.2 | 234.0 | -11.5 |
| 58 | 3 | 2.99 | 263.7 | -72.0 | 261.8 | - 6.0 | 3.5 | 3 | 2.92 | 203.6 | -34.9 | 216.5 | 9.8 |

Footnotes as on previous page

The results of bulk cleaning for each of the Cambrian formations are considered separately:

(i) Of the 15 Early Cambrian samples, four were rejected. The sample-mean direction of one was considered random, while three remained magnetized near the present field direction. The directions of the remaining 11 samples however, rotated away from the present field direction by about 70° along an approximate northeast-southwest axis. Their directions are listed in Table 5.4 and plotted in Fig. 5.5a after correction for tectonic tilt. They fall into two groups of opposite polarity. The formation-mean direction is given in Table 5.5.

(ii) Eighteen Middle Cambrian samples responded to cleaning by moving away from the present field direction along a general northeast-southwest axis with angular changes varying from a few degrees to 130°. The sample-means are plotted in Fig. 5.5b and listed in Table 5.4. Directions fall into two groups of opposite polarity. In calculating the formation-mean direction (Table 5.5) three samples have been omitted. Their mean directions lay between 60° and 90° from the formation-mean. Application of the fold test (Table 5.3) to the 15 cleaned sample-means reduced their dispersion significantly.

(iii) Only six Late Cambrian samples responded successfully to thermal treatment (Table 5.4). They underwent systematic rotation away from the present field direction along a northeast-southwest axis and fell

## TABLE 5.5

Summary of palaeomagnetic results

| Rock Unit | Age[1] | N[2] | R | Mean Direction D | Mean Direction I | a | Pole Position Lat.° | Pole Position Long.° | A |
|---|---|---|---|---|---|---|---|---|---|
| Pound Quartzite | Latest Pr | 10 | 8.09 | 202.8 | 16.6 | 24.9 | 59.9S | 6.3E | 23.6 |
| Aroona Dam Sediments (Billy Creek equivalents?) | Є1 | 11 | 9.57 | 231.1 | 12.5 | 18.6 | 36.3S | 33.0E | 16.6 |
| Lake Frome Group (lower beds) | Єm | 15 | 12.64 | 250.5 | -29.2 | 17.1 | 5.5S | 23.0E | 14.7 |
| Lake Frome Group (upper beds) | Єu (?01) | 5 | 4.78 | 226.6 | 5.7 | 18.6 | 37.9S | 25.5E | 12.1 |
| Lake Frome Group (combined) | Єm-u (?01) | 20 | 16.51 | 243.4 | -20.1 | 15.4 | 14.2S | 23.5E | 12.6 |

[1] Age symbols: Pr = Precambrian; Є = Cambrian; O = Ordovician. Lower, Middle and Upper divisions denoted by 1, m and u respectively.

[2] N = Number of samples

into two groups (Fig. 5.5c) of opposite polarity. One of the samples however, cleaned to a very steep inclination. Its direction has been omitted from calculation of the formation-mean (Table 5.5).

## 5.5 INTERPRETATION OF RESULTS

Application of Graham's fold test to the uncleaned directions of magnetization in the Pound Quartzite and Middle Cambrian sediments demonstrated that their remanence was dominated by secondary magnetization acquired after folding. Their tectonically uncorrected directions, either scattered around or streaked towards the present field, indicate that the secondary magnetization was acquired in recent times. The presence of the same dominating secondary magnetization in the Early and Late Cambrian sediments is suggested by the similarity of their uncorrected NRM directions with those of the late Precambrian and Middle Cambrian formations.

Large, systematic, angular rotations of the remanent vectors away from the present field in the direction of streaking can be attributed to successful elimination of the secondary magnetization. The isolated components of magnetic remanence are interpreted to be the primary components of magnetization of these formations. In support of this interpretation, the following points are listed:

(i) The presence of opposing polarities of magnetization.

(ii) The cleaned directions are different from any that have so far been measured in Australian rocks of younger age (McElhinny, 1973).

(iii) For the Middle Cambrian sediments there is a positive fold test indicating the remanence to have been acquired prior to folding in the Late Cambrian-Early Ordovician.

(iv) Tropical palaeolatitudes are indicated by the formation-mean directions, in agreement with palaeoclimatic data (Briden and Irving, 1964; Thomson, 1969b; Wopfner, 1969) viz. the occurrence throughout the latest Precambrian and Cambrian in the Adelaide Geosyncline of thick sequences of dolomites and limestones and the occurrence of *Archaeocyatha* fauna.

The secondary magnetization could successfully be removed from some samples to reveal a primary magnetization because the maximum blocking temperature of the secondary magnetization (≤ 450°C) was less than the maximum blocking temperature of the primary component of magnetization (630°C - 650°C). Where the blocking temperature spectrum of the secondary components was of the same order as the spectrum of the primary component, they masked or replaced any primary remanence that might have been present. In many samples the secondary magnetization was inhomogeneously distributed. Directions measured in those samples were statistically random since some specimens remained magnetized near the present field while others had incompletely moved towards the primary direction. For the Pound Quartzite however, it was possible to eliminate an obviously completely remagnetized specimen in each of five samples leaving a minimum of two specimens per sample which retained primary remanent magnetization.

Thermal demagnetization suggests that the secondary remanence was composite, comprising two components. The softer component was eliminated in temperatures up to 250°C, as indicated by the pilot specimen intensity decay curves, and is considered to be a VRM acquired under the influence of the present field. Wilson and Smith (1968) found that such components are removed in temperatures of about 300°C or less. The harder component, requiring temperatures of 450°C to a maximum of 630°C - 650°C for removal, is interpreted to be a chemical remanence of recent origin. Only this type of remanence, in the absence of any post-depositional thermal metamorphism, can have such thermal stability (Nagata, 1961). A possible mechanism which could account for its acquisition is solution and redeposition, by permeating water, of the red, iron-oxide, pigment cement (Van Houten, 1973) which coats the quartz and other grains. A chemical nucleation process (Haigh, 1958) is therefore envisaged in which new magnetic particles grow through their critical blocking volumes with their moments biassed in the recent field direction. One may expect the porosity of the beds to be inhomogeneous and therefore the effects of remagnetization to be inhomogeneous. This would account for what is observed palaeomagnetically, i.e. that some samples and even specimens within samples retain a primary magnetization, yet adjacent samples and specimens are partially or completely remagnetized.

The demagnetization-intensity decay curves demonstrate that the main carrier of stable remanence is haematite, as found in other red-beds (Collinson, 1965). The susceptibility changes with temperature can be understood in terms of the physico-chemical production of new magnetic phases in response to heating. The effects of such changes however, were only apparent after stable endpoint behaviour had been initiated. The cleaned directions of remanence are therefore free of any effects due to this source.

The pole positions calculated from the primary directions of magnetization of each formation are given in Table 5.5. Since the number of samples of the Upper Lake Frome Group which responded successfully to demagnetization was only five, its pole was considered to be inadequately defined. Its directions were therefore combined with those of the Lower Lake Frome Group to define a single pole for the Lake

Frome Group. Bearing in mind the thicknesses of the sections represented and that they contain directions recording multiple reversals of the ancient geomagnetic field, it is considered that the poles represent sufficient time-averages to be free of the effects of palaeosecular variation.

The scatter of directions is sometimes high as in the case of the Pound Quartzite but no higher than that found in other late Precambrian-Lower Palaeozoic sedimentary formations (Embleton, 1972; Thompson, 1973). Thompson has suggested a possible cause in terms of the reduced intensity of the geomagnetic field at this time, but another possibility in the present case, in view of the recording of multiple reversals, is the likelihood that odd, intermediate directions of the field during its reversal, are present. Such directions have been recorded previously in sediments (McElhinny, 1970) and four samples in the present study (three Middle Cambrian, one Late Cambrian) were rejected on the basis of this possibility.

## 5.6 DISCUSSION

An observation arising out of the palaeomagnetic study is that the degree of remagnetization of a sedimentary sequence can be inhomogeneously distributed within individual beds and even, as in the case of the Pound Quartzite, within a single sample. Similar situations have been encountered by Luck (1972) during his study of Lower Palaeozoic sediments from northern Australia, and Farrell and May (1969) who, in a study of Permian red-beds from the Colorado Plateau, rejected 90% of their Monument Valley collection. The implication is that information relating to the primary magnetization of partially remagnetized sediments might be retrievable if results are scrutinized at the specimen, rather than sample, level. Application of this principle to the earlier work of Briden

(1964, 1967a) on rocks of late Precambrian-Cambrian age from the southern part of the Adelaide Geosyncline, has enabled a different interpretation to be put on his data, one which is more consistent with the geological knowledge of the area as it is now known. The analysis of this data is considered in the next chapter.

# CHAPTER 6

# PRECAMBRIAN TO EARLY PALAEOZOIC APPARENT POLAR WANDER PATH FOR AUSTRALIA

## 6.1 THE APPARENT POLAR WANDER PATH

### 6.1.1 Introduction

Since the early work of Irving and Green (1958) on the Palaeozoic of northern Australia and southeastern Australia, subsequent palaeomagnetic investigations in those regions (Green, 1961; Irving and Parry, 1963; Irving, 1966; Briden, 1966; McElhinny and Luck, 1970b; Luck, 1972) and in central Australia (Embleton, 1972a,b) have led to a fuller appreciation of their spatial relationships to one another during that time. McElhinny and Embleton (1974) have shown that the common polar wander path identified from central and northern Australia does not coincide with the curve for southeastern Australia. They observe that the two paths converge during the Devonian. This is consistent with the plate tectonic model describing the geological evolution of the Tasman Orogenic zone (Oversby, 1971; Solomon and Griffiths, 1972). The model (although probably oversimplified) describes the tectonic history in terms of successive episodes of accretion and suturing throughout the Palaeozoic.

### 6.1.2 Latest Precambrian to Early Palaeozoic

The arm of the Early Palaeozoic polar wander path which is relevant to discussion of Precambrian to Early Palaeozoic apparent polar wander for Australia is the common path identified for northern and central Australia. This is illustrated in Fig. 6.1. Also shown are the poles derived from the palaeomagnetic investigation of the late Precambrian and Early Palaeozoic sediments of the Adelaide Geosyncline

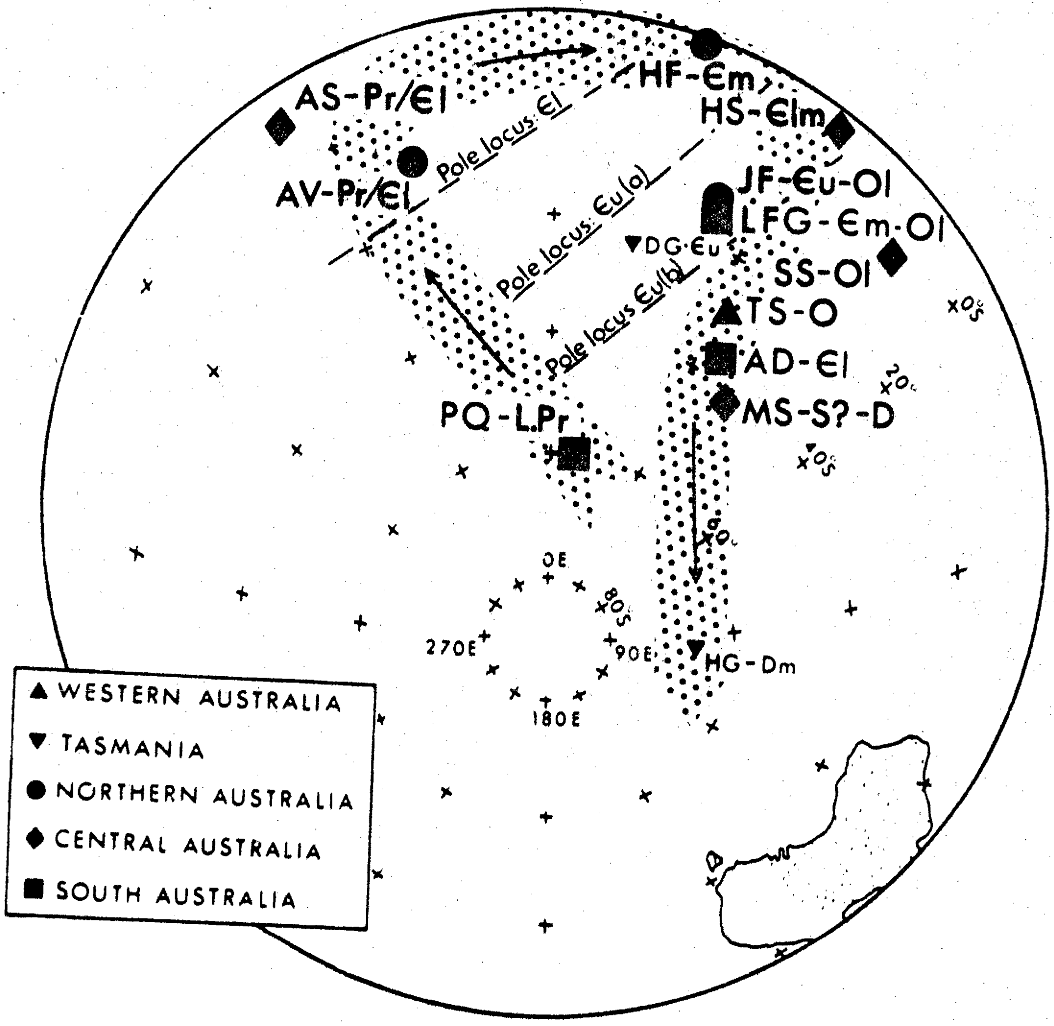

FIGURE 6.1 The late Precambrian-Early Palaeozoic apparent polar wander curve for the main Australian platform. The poles are listed in Table 6.1 and the sampling localities of the formations from which they were derived shown in Figure 6.2a, corresponding symbols being used. Large symbols refer to key poles (see Section 6.1.3). The Late Cambrian pole (DG) obtained from the Dundas Group of Tasmania is seen to lie on the curve in such a position that it is not necessary to invoke local rotation of that region relative to the main Australian platform (Section 6.3). The dashed lines represent the loci of the poles obtained by Briden (1964, 1967a) from studies of borecore material from Yorke Peninsula (Early Cambrian) and the Georgina Basin (Late Cambrian — a and b).

(Chapter 5), an Ordovician pole from the Tumblagooda Sandstone of the Carnarvon Basin, Western Australia (Embleton and Giddings, 1974) and a Late Cambrian pole from the Dundas Group, Tasmania based on a reassessment (Section 6.3) of the earlier data of Briden (1964, 1967b). The poles and their identification symbols are listed in Table 6.1 and the sampling localities of the formations from which they were derived shown in Fig. 6.2a.

It is evident from Fig. 6.1 that the similar aged poles for the Lake Frome Group (LFG), Dundas Group (DG) and Tumblagooda Sandstone (TS) are in excellent agreement not only with one another but with similar aged poles from northern and central Australia viz. the Jinduckin Formation (JF) and Stairway Sandstone (SS) respectively.

The apparent polar wander path is now known in sufficient detail to provide a suitable framework for the interpretation of results obtained by Briden and Ward (1966) from measurements of magnetic inclinations of Cambrian sediments penetrated by a number of borecores (sites shown in Fig. 6.2a). From the mean inclination of magnetization, the colatitude of the sampling site with respect to the palaeomagnetic pole can be calculated. Since declination is indeterminate, the calculation defines the arc of a circle on which the palaeomagnetic pole must lie. Arcs of three small circles relating to two borecores penetrating Upper Cambrian sediments in the Georgina Basin, northern Australia and a borecore penetrating Lower Cambrian sediments on Yorke Peninsula, South Australia are drawn in Fig. 6.1. These data are consistent with the Early Palaeozoic results.

The South Australian Early Cambrian pole (AD in Fig. 6.1) lies in the correct chronological sequence with respect to the Pound Quartzite pole and the Arumbera Sandstone pole (Embleton, 1972a). An Early Cambrian fossil (Wade, 1970) found in the uppermost beds of the Arumbera Sandstone (central Australia) is also apparently found in the

TABLE 6.1

Late Precambrian to Lower Palaeozoic palaeomagnetic poles used to define the polar wander curve with respect to the main Australian platform

| Rock Unit | Symbol | Age[1] | Pole Position[2] |  | A | Reference |
|---|---|---|---|---|---|---|
|  |  |  | Lat.° | Long.° |  |  |
| NORTHERN AUSTRALIA |  |  |  |  |  |  |
| ANTRIM PLATEAU VOLCANICS | AV | Pr/Є1 | 9S | 340E | 17 | McElhinny and Luck (1970b) |
| HUDSON FORMATION | HF | Єm | 18N | 19E | 13 | Luck (1972) |
| JINDUCKIN FORMATION | JF | Єu - O1 | 13S | 25E | 11 | Luck (1972) |
| CENTRAL AUSTRALIA |  |  |  |  |  |  |
| ARUMBERA SANDSTONE | AS | Pr/Є1 | 8N | 325E | 25 | Embleton (1972a) |
| HUGH RIVER SHALE | HS | Є1 - m | 11N | 37E | 8 | Embleton (1972a) |
| STAIRWAY SANDSTONE | SS | O1 | 2S | 50E | 8 | Embleton (1972b) |
| MEREENIE SANDSTONE | MS | S? - D | 41S | 40E | 10 | Embleton (1972b) |
| SOUTH AUSTRALIA |  |  |  |  |  |  |
| POUND QUARTZITE | PQ | Latest Pr | 60S | 6E | 24 | This thesis (Chapter 5) |
| AROONA DAM SEDIMENTS | AD | Є1 | 36S | 33E | 17 | This thesis (Chapter 5) |
| LAKE FROME GROUP | LFG | Єm-u (?O1) | 14S | 24E | 13 | This thesis (Chapter 5) |

[1] Age Symbols: Pr = Precambrian; Є = Cambrian; O = Ordovician; S = Silurian; D = Devonian. Lower, Middle and Upper divisions denoted by l, m and u respectively.

[2] Key poles (see Section 6.1.3) are shown in upper case type

Continued

TABLE 6.1

(Continued)

| Rock Unit | Symbol | Age[1] | Pole Position[2] |  | A | Reference |
|---|---|---|---|---|---|---|
|  |  |  | Lat.° | Long.° |  |  |
| WESTERN AUSTRALIA |  |  |  |  |  |  |
| TUMBLAGOODA SANDSTONE | TS | O? (Єm - Sl) | 30S | 31E | 9 | Embleton and Giddings (1974) |
| TASMANIA[3] |  |  |  |  |  |  |
| Dundas Group | DG | Єu | 23S | 13E | 12 | See Chapter 6, Section 6.3.3. |
| Housetop Granite plus aureole | HG | Dm | 67S | 94E | 27 | See McElhinny and Embleton (1974) |

[1] Age Symbols: Pr = Precambrian; Є = Cambrian; O = Ordovician; S = Silurian; D = Devonian. Lower, Middle and Upper divisions denoted by l, m and u respectively.

[2] Key poles (see Section 6.1.3) are shown in upper case type

[3] Briden (1964, 1967b) suggested that both Tasmanian formations had been remagnetized in the Tertiary. Such an interpretation may be premature at this stage and both may retain a primary magnetization to which the poles quoted refer (see Section 6.3.3 regarding the Dundas Group and McElhinny and Embleton (1974) regarding the Housetop Granite).

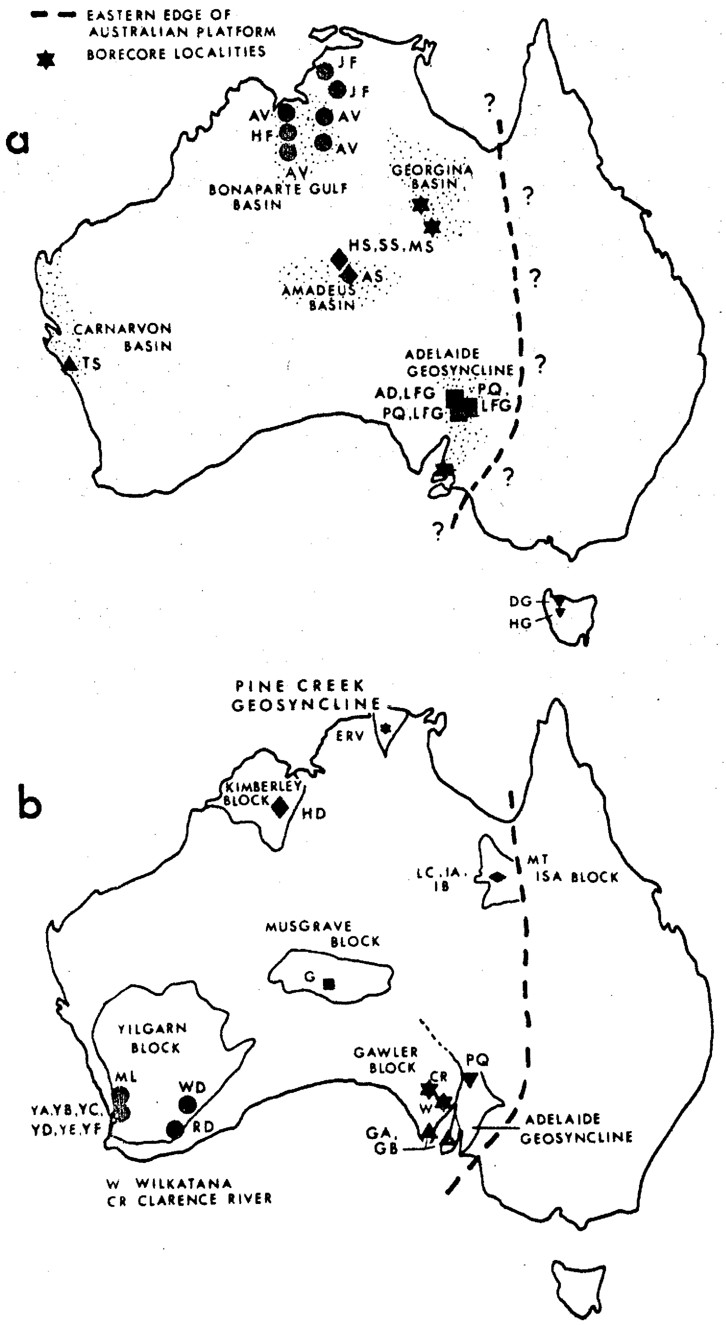

FIGURE 6.2 Sampling localities of formations yielding palaeomagnetic data used in the definition of a path of apparent polar wandering with respect to the main Australian platform during:
(a) the late Precambrian-Early Palaeozoic
(b) the interval c2500 My - c600 My.
Corresponding symbols are used in Figures 6.1, 6.3 and 6.4 to show the positions of the palaeomagnetic poles derived from the main sampling localities. Large symbols denote localities yielding key poles.

Parachilna Formation (South Australia). The Parachilna Formation disconformably overlies the Pound Quartzite (Thomson, 1969b) and is stratigraphically separated from the younger Lower Cambrian red-beds (pole AD) by several hundreds of metres of *Archaeocyathid* limestones of the Lower Cambrian Hawker Group. However, the pole lies in an anomalous position when compared with the pole of the Hudson Formation (HF). The AD pole was derived from sediments collected just below a thin *Redlichia* bearing limestone, while the Hudson Formation was sampled above the main *Redlichia* horizon in the Negri Group, Northern Territory (Luck, 1972). Elucidation of this anomaly will have to await further palaeomagnetic data from other localities.

The results from the Pound Quartzite allow extension of the Early Palaeozoic apparent polar wander path into the latest Precambrian. The next youngest group of poles belong to the Arumbera Sandstone (Embleton, 1972a) and the Antrim Plateau Volcanics (McElhinny and Luck, 1970b). Deposition of the Arumbera Sandstone was initiated during the final stages of the Petermann Ranges Orogeny, which affected the southern margin of the Amadeus Basin (Fig. 6.2a), and continued when orogenic activity ceased (Wells *et al*, 1970). Daily *et al* (1973) regard the principal phase of that Orogeny as post-*Ediacaran* i.e. the fauna preserved in the upper member of the Pound Quartzite (Chapter 5). The Pound Quartzite is thus older than the Arumbera Sandstone and that it could be substantially so, as suggested by the 50° or so of apparent polar wandering between the two poles, is consistent with the geological evidence favouring this (i) the presence of an orogeny between the ages of the two poles and (ii) the Pound Quartzite pole was derived from the pre-*Ediacaran* lower member.

During the period latest Precambrian to Early Palaeozoic, the apparent polar wander curve describes a loop of approximately 180° arc length. In Chapter 7 (Section 7.1) it is shown, in the context of

Gondwanaland, that this loop is supported by palaeomagnetic data from other Gondwanic continents.

### 6.1.3 Precambrian

The key poles used to define the apparent polar wander path for the Precambrian are those that satisfy the following criteria:

(a) Poles must be based on directions of remanent magnetization whose stability has been demonstrated in the laboratory using standard demagnetization techniques.

(b) Where good stratigraphic control is absent, a pole must have an associated radiometric age.

(c) Investigations must be based on an adequate rock collection so that palaeosecular variation is considered to be averaged out (e.g. see McElhinny, 1973, p. 105).

When linking adjacent poles in chronological order, it has been assumed, in the absence of compelling evidence to the contrary, that the minimum amount of apparent polar wandering has occurred in the time interval separating the poles. This is a principle which has guided other workers (McElhinny *et al*, 1968; Spall, 1971) in setting up Precambrian apparent polar wander paths for other continents.

Precambrian poles satisfying (a), (b) and (c) are listed in Table 6.2. The localities from which they were derived are shown in Fig. 6.2b. The list includes two poles previously reported. The Widgiemooltha Dyke suite, dated by the Rb-Sr method at 2420 ± 30 My (Turek, 1966) outcrops south of Kalgoorlie in the Yilgarn Block. A well-defined pole for the suite has been reported by Evans (1968). A pole from the Hart Dolerite, dated at 1800 ± 25 My by Rb-Sr (Bofinger, 1967) is given in McElhinny and Evans (1974). The Dolerite outcrops along the eastern edge of the Kimberley Block adjacent to the Halls Creek Mobile Zone in northern Western Australia (Dow and Gemuts, 1969).

Precambrian poles which do not satisfy (a), (b) and (c) or which are of questionable reliability are listed in Table 6.3 and their

## TABLE 6.2

Key poles for the Precambrian of Australia

| Rock Unit | Symbol | Age (My) | Pole Position[1]<br>Lat.° | <br>Long.° | A |
|---|---|---|---|---|---|
| YILGARN BLOCK[2] | | | | | |
| RAVENSTHORPE DYKES | RD | 2500 ± 100 | 38N | 316E | 26 |
| WIDGIEMOOLTHA DYKES | WD | 2420 ± 30 | 9N | 337E | 8 |
| DYKES, GROUP YF | YF | c1700 | 25N | 102E | 14 |
| DYKES, GROUP YD | YD | c1700 | 24S | 46E | 10 |
| DYKES, GROUP YC | YC | c1500 | 80S | 183E | 13 |
| MORAWA LAVAS | ML | 1390 ± 140 | 43S | 202E | 15 |
| DYKES, GROUP YB | YB | 750 - 700 | 20S | 282E | 28 |
| KIMBERLEY BLOCK | | | | | |
| HART DOLERITE | HD | 1800 ± 25 | 29N | 46E | 24 |
| GAWLER BLOCK | | | | | |
| DYKES, GROUP GB | GB | 1700 ± 100 | 23S | 86E | 11 |
| DYKES, GROUP GA | GA | 1500 ± 200 | 61S | 51E | 9 |
| ADELAIDE GEOSYNCLINE | | | | | |
| POUND QUARTZITE | PQ | Latest Pr | 60S | 6E | 24 |

[1] See text for reference.

[2] A diagram of the main structural elements of Australia is given in Chapter 1, Section 1.2.

TABLE 6.3

Precambrian poles for Australia not satisfying key pole status

| Rock Unit | Symbol | Age | Pole Position[1] Lat.° | Long.° | A or dp,dm |
|---|---|---|---|---|---|
| PINE CREEK GEOSYNCLINE[2] | | | | | |
| Edith River Volcanics | ERV | 1760 My | 6N | 346E | 15,24 |
| MT. ISA BLOCK | | | | | |
| Lunch Creek Loppolith | LC | ?<1450 My | 58S | 205E | 15 |
| Dykes, Group IA | IA | <LC | 12S | 124E | 11 |
| Dykes, Group IB | IB | <LC | 53S | 102E | 11 |
| MUSGRAVE-MANN BLOCK | | | | | |
| Giles Complex | G | 1250 - 1140 | 68S | 163E | 23,29 |
| YILGARN BLOCK | | | | | |
| Dykes, Group YE[3] | YE | c2500 | 28S | 0E | 31 |
| Dykes, Group YA | YA | c2500 or c1700 | 22S | 134E | 18 |

[1] See text for reference.

[2] A diagram of the main structural elements of Australia is given in Chapter 1, Section 1.2.

[3] The pole quoted is regarded as VGP (see Chapter 3).

sampling localities shown in Fig. 6.2b. Irving and Green (1958) reported the first Precambrian palaeomagnetic poles for Australia. All three poles were based on uncleaned remanence. The formations studied were the Edith River Volcanics (dated at 1760 My by P.J. Leggo — in Walpole *et al*, 1968) and the Upper Precambrian (Adelaidean) Buldiva Quartzite, both sampled from the Pine Creek Geosyncline, Northern Territory (Walpole *et al*, 1968) and a sequence of Lavas from the Pilbara region of Western Australia. The only evidence of stability of the magnetic remanence of the Lavas and the Quartzite (Irving, 1964) is that the directions were well-grouped far from the ambient field direction. This does not preclude the possibility of systematically directed components of secondary remanence. Therefore, because no estimate could be made of the reliability of their remanence, their poles are neither considered further nor listed in Table 6.3. In the case of the Edith River Volcanics there was a positive fold test (Irving, 1964) to demonstrate stability. However, there is a possibility that some of the sites collected were not in the Edith River Volcanics but in the ?Early Cambrian Antrim Plateau Volcanics, which are also extensively developed in the same area. The pole for the Edith River Volcanics (Table 6.3) is very similar to that yielded by the Antrim Plateau Volcanics (McElhinny and Luck, 1970b — Table 6.1) so that until a new collection is made, the reliability of the Edith River Volcanics pole must be considered low.

Facer (1971) recently reported a pole from a series of mafic and ultramafic bodies in the Musgrave Block, central Australia, collectively referred to as the Giles Complex. Attempts at direct Rb-Sr dating of the Complex (Gray, 1971) were unsuccessful although evidence is adduced that emplacement occurred within the range 1250 My - 1140 My. Uncertainty has been expressed in the literature concerning the mode of emplacement of this Complex. It is generally regarded as intrusive into the Musgrave Block, but whether the event was comagmatic or extended over a distinct time span is contentious. However, in a recent interpretation of the tectonic history of the area, Davidson (1973) regards the Giles Complex as representing a slab of layers 2 and 3 of oceanic lithosphere sheared-off during plate subduction, suggesting a cold emplacement origin. Duff and Langworthy (1974) dispute this interpretation. Unfortunately, the cleaned directions of remanence from the discrete bodies of the Complex are of little help in deciding the issue of emplacement. Their poles (Table 5 of Facer, 1971) are scattered and could be consistent with either the cold emplacement origin or intrusion over an extended time span. The pole quoted by Facer is based on meaning the cleaned directions of magnetization from the different bodies and assigning unit weight to specimens. Because of the large scatter in the directions of magnetization and the discussion surrounding the mode of emplacement, the reliability of the pole is regarded as questionable until further, more detailed, work can be carried out.

The pole for the YA group of dykes from the Perth region of the Yilgarn Block (Chapter 3) is placed in the less reliable category listed in Table 6.3, because of the ambiguity in its age. The dykes have been altered by younger events so that data points for defining an isochron are scattered. Depending on the criterion adopted in the interpretation of this data, the age of the dykes could either be of the order of 2500 My or 1700 My. The ambiguity is only likely to be solved from field evidence.

Finally, Table 6.3 contains three poles (LC, IA, IB) obtained by Duff and Embleton (1974) from a study of basic intrusions in the Mount Isa Block, western Queensland. Completely unaltered intrusives belong to each of the three groups of cleaned remanence directions recognized and on this basis it was concluded that their ages were less than 1450 My -

1400 My, the age of the last regional metamorphic event in the area (Richards *et al*, 1963). The intrusives of group IA cut the intrusive of group LC. The petrology of the intrusives of group IB closely resembles those of group IA and are therefore also inferred to be younger than group LC. The poles IA and IB, each based on two dykes, are considered here to be VGP's rather than palaeomagnetic poles because of the unlikelihood that results from only two dykes are sufficient to average out the effects of palaeosecular variation.

A third group of pole positions to be considered comprises those derived from various haematite ore bodies outcropping in Western Australia and South Australia. They were studied by Porath (1967a) and the results reported in Chamalaun and Porath (1968) and Porath and Chamalaun (1968). The poles are based on magnetic remanence whose stability was demonstrated by laboratory demagnetization procedures. However, age control was poor. The poles are listed in Table 6.4 and sampling localities shown in Fig. 6.6a. Further description is deferred to Section 6.2 where it is shown that the apparent polar wander path enables limits to be put on the time of ore formation for each of the ore bodies.

Fig. 6.3 illustrates the apparent polar wander path for the Precambrian drawn through the key pole data of Table 6.2. It is shown as the continuous stippled curve. The Early Palaeozoic section considered earlier (Fig. 6.1) is shown as the thin continuous, solid line. The dashed stippled curves represent variations to the main curve based on less reliable data.

The oldest segment of the path covers the time interval 2500 My to 1800 My and consists of a simple loop of 160° arc length connecting three poles from Yilgarn Block dykes (YE, WD, RD) with the pole from the Hart Dolerite (HD). Pole YE (Table 6.3) is considered a VGP but nevertheless may be used to indicate from which direction the apparent polar wander curve approaches the oldest group of key poles (WD, RD). The pole from

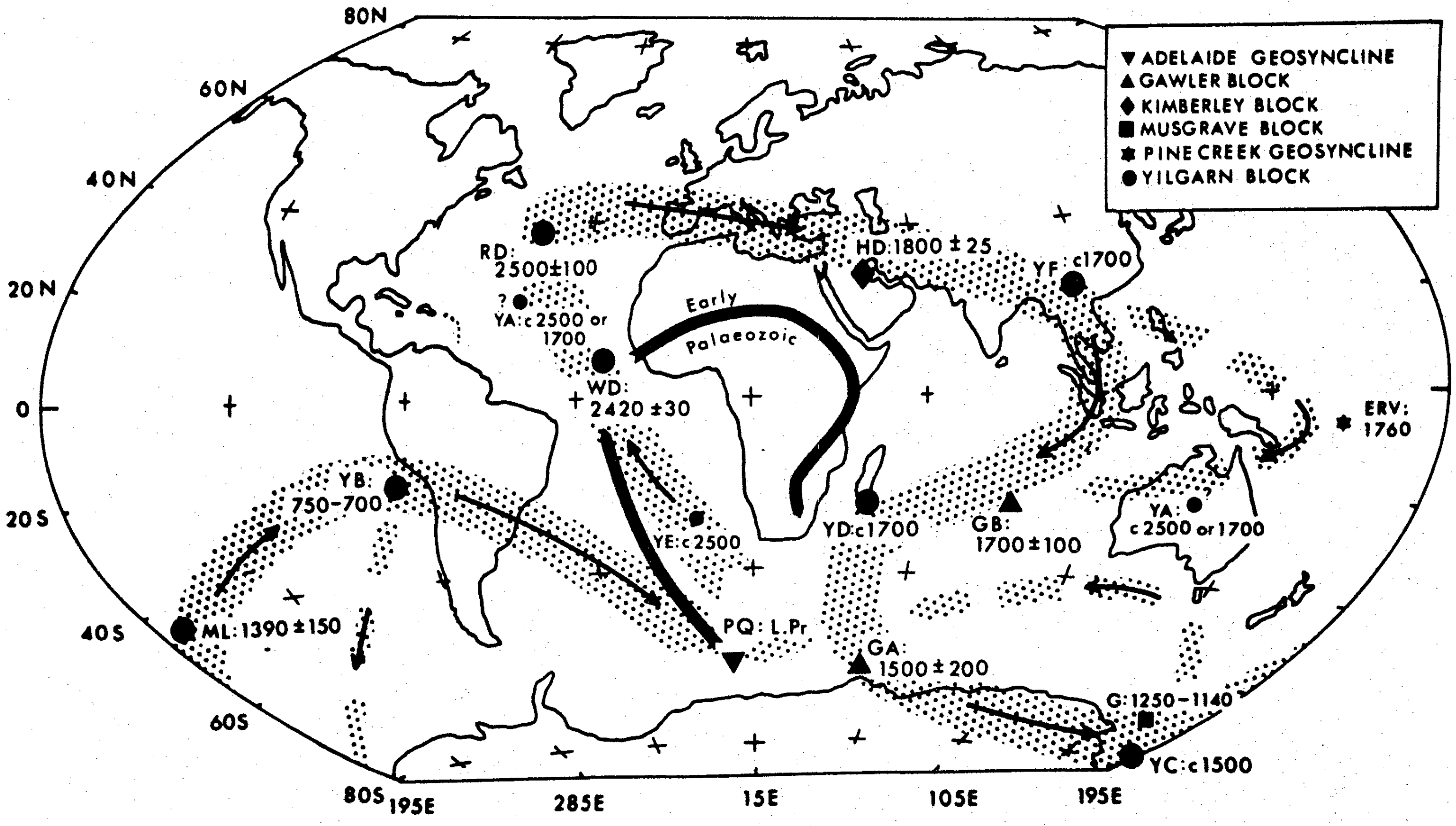

FIGURE 6.3 The Precambrian apparent polar wander path for platform Australia. The dashed curves represent less well established modifications to the basic curve (see text). The solid black line represents the latest Precambrian to Early Palaeozoic path segment (shown in more detail in Figure 6.1). Key poles are denoted by large symbols and ages quoted are in My. The palaeomagnetic data are listed in Tables 6.1, 6.2 and 6.3.

the Ravensthorpe dykes (RD) at 2500 ± 100 My is in good agreement with the more precisely dated (2420 ± 30 My) Widgiemooltha Dykes pole (WD) obtained by Evans (1968). The YA pole for Yilgarn dykes falls nearby, consistent with the older of its two possible ages (~ 2500 My). Assumption that the RD pole is the oldest (YE is definitely not older than 2500 My) would involve postulating a more complicated shape for the path with YE joining to HD and is considered unwarranted on available evidence. A 600 My gap is represented by the 70° segment between the RD and HD poles. Only more information for this period will determine whether the sequence YE to RD as shown is the correct sequence to link to HD or whether it should be the antipole sequence.

The best defined segment of the path connects the HD pole with the pole for the 1390 ± 140 My Morawa Lavas (ML). It represents all of Carpentarian time (1800 My - 1400 My) and possibly a part of the early Adelaidean. The key poles (YF, GB, YD, GA, YC, ML) defining this section are based mainly on the Western Australian and South Australian dyke swarms. In chronological sequence they define a relatively simple path that suggests two sharp changes in direction of apparent polar wandering, one between 1800 My - 1700 My and the other at about 1600 My. However, the reality of these changes needs to be firmly established before the tectonic implications of such changes are seriously considered (Irving and Park, 1972).

The segment of the path between the poles GA and ML is more clearly illustrated in Fig. 6.4a. It is noted that the pole for the Giles Complex (GC) falls between the YC and ML poles. Bearing in mind that the GC pole is not well-defined and that the Morawa Lavas could be as young as 1240 My — the approximate maximum age of the Giles Complex — the position of the GC pole is not anomalous with respect to the ML pole. In fact, although the angular separation of the two poles is about 35°, the circle of confidence on the GC pole overlaps that of the ML pole.

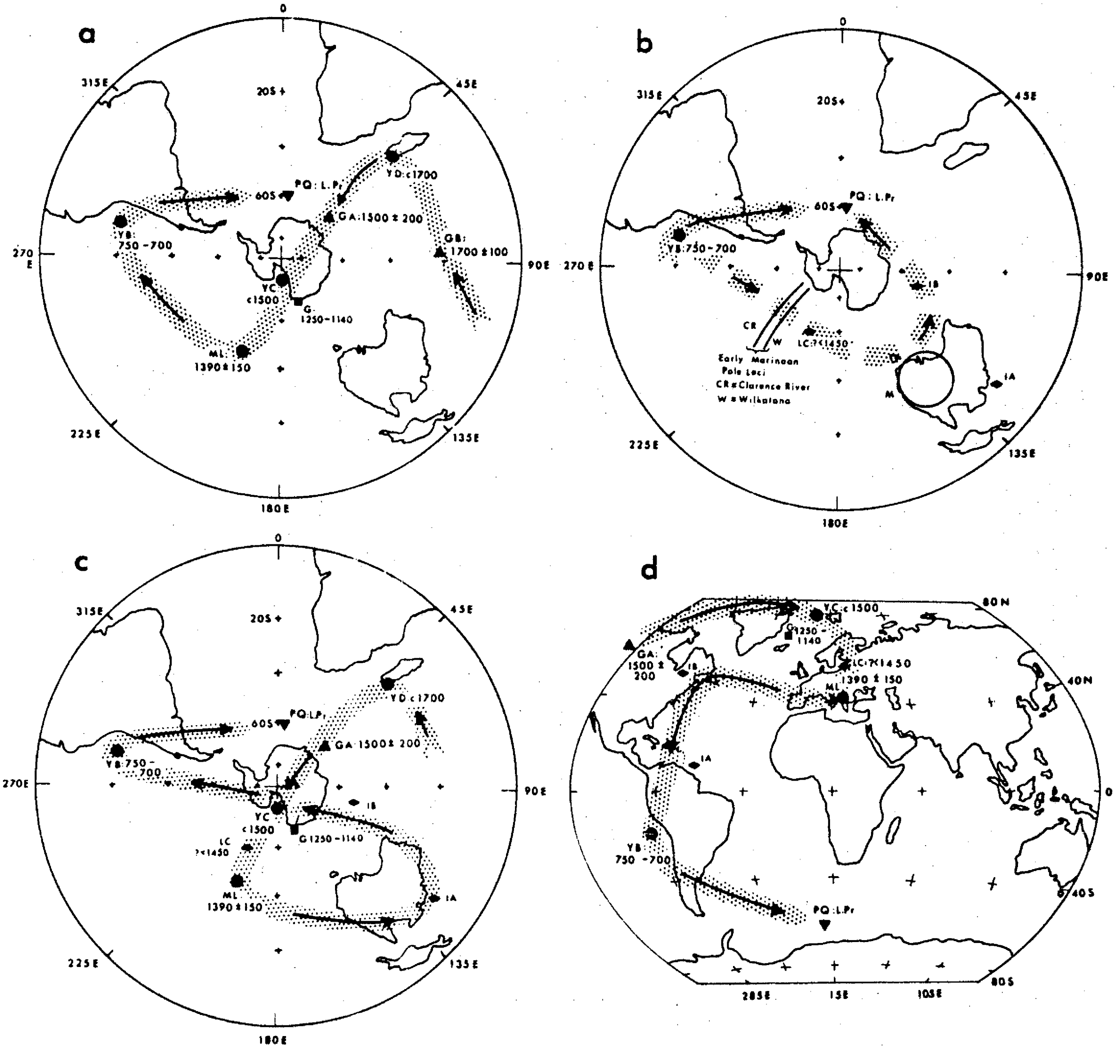

FIGURE 6.4 (a) The apparent polar wander path for platform Australia for the interval c1700 My to latest Precambrian from a different perspective.

(b) The proposed loop in the apparent polar wander curve between the poles for the YB group of dykes and the Pound Quartzite (see text). The three solid lines represent the loci of the poles obtained by Briden (1964, 1967a) from studies of the magnetic inclination in Marinoan sediments penetrated by two borecores (Wilkatana No.1 and Clarence River No.1) located in South Australia (see text). The circle, denoted by M, refers to the pole locus derived from the steep magnetic inclination observed in the upper part of the Wilkatana No.1 borecore.

(c) & (d) Possible modifications to the Precambrian apparent polar wander path depending on the ages of the three Mt Isa Block poles LC, IA and IB (Table 6.3).

The Carpentarian segment represents about 230° of apparent polar wandering in about 500 My. Fig. 6.5 shows sketches of the palaeolatitude of Australia at various times in the Carpentarian. From initially tropical (pole HD), conditions became progressively more temperate until about 1700 My (poles YF, GB). However, from 1700 My until the close of the Carpentarian and possibly into the early Adelaidean (assuming the minimum age for the Morawa Lavas of 1240 My), northern Australia remained in tropical latitudes. This is in excellent agreement with the palaeoclimatic evidence derived from the types of sediment deposited in the various basins of northern Australia. According to Brown *et al* (1968, p. 40) '...the widespread accumulation at this time [Carpentarian] of carbonates, including stromatolitic reefs, suggests, if uniformitarian principles can be applied to this distant time, that a tropical climate then prevailed over northern Australia'.

The Edith River Volcanics pole (ERV) at 1760 My can be accommodated by the main Carpentarian path by accentuating the 1800 - 1700 My loop. The modification is shown by the dashed path (Fig. 6.3). Apart from the questionable reliability of the pole, there are two arguments against this extension. It adds an extra 150° of arc making the average rate of apparent polar wandering for the Carpentarian about 0.8° per My, nearly a factor of three higher than the average rate found for the Phanerozoic and Precambrian (McElhinny, 1973). The extension also has the effect of placing Australia in polar latitudes. Despite detailed geological mapping, no evidence has yet been found in the Carpentarian period of deposits typical of polar latitudes e.g. tillites. However, it is noted that the YA pole, if associated with the younger of its two possible ages (~ 1700 My), is in better agreement with the path if it is modified to include the ERV pole. A reinvestigation of the Edith River Volcanics should decide the issue.

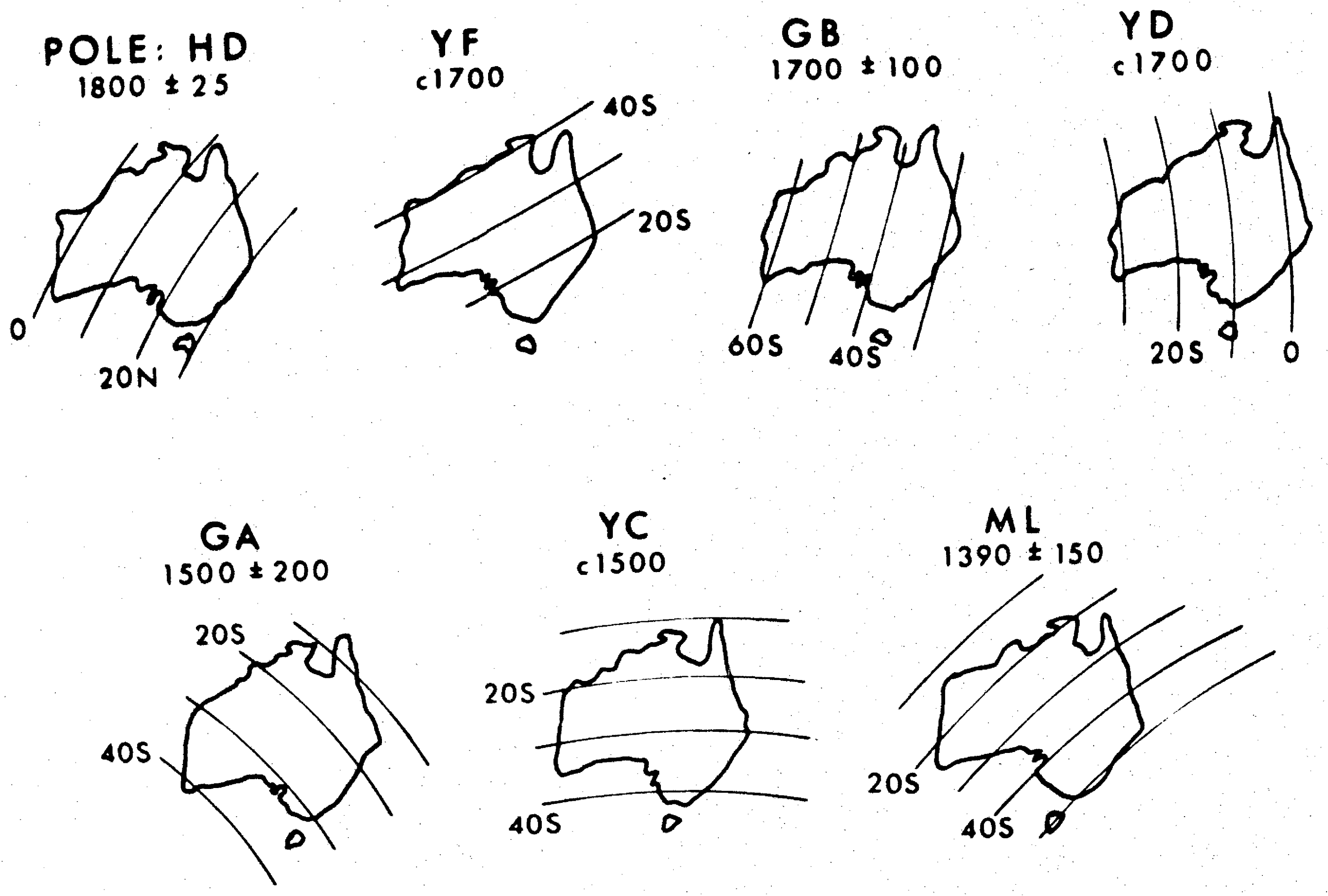

FIGURE 6.5 A sketch of the palaeolatitude of Australia through Carpentarian time (c1800 My - c1400 My). Ages are in My.

There is no information for a period of at least 500 My between the ML pole and the YB pole (750 - 700 My) from Yilgarn Block dykes. The two poles are therefore connected by the shortest path, representing 70° of arc. Further data for this period may well demonstrate that the antipole sequence of all poles older than YB is the correct sequence to join to YB.

The path connecting the YB pole with the latest Precambrian Pound Quartzite pole (PQ) represents the final segment of the apparent polar wander path to be discussed. It could be represented by connecting the two poles with the shortest path of 65° arc length as shown. However, evidence favouring a more complicated path is presented. The path is shown as a dashed loop in Fig. 6.4b. Throughout Australia sedimentary sequences deposited in the late Precambrian record the presence of generally two distinct tillite horizons (reviewed by Dunn *et al*, 1971), indicating glaciations of continental proportions. Rb-Sr dating of shales in the Kimberley Region of Western Australia by Bofinger (1967) suggests that the older, or Sturtian glaciation, has a minimum age of 739 ± 30 My and the younger, Marinoan glaciation, a minimum age of 653 ± 48 My. Other radiometric data related to the glaciations (in Dunn *et al*, 1971) are consistent with those ages. The younger glaciation would suggest that Australia lay in high palaeolatitudes at some time in the age interval separating the YB and PQ poles. The direct linking of the two poles however, would effectively place Australia only in equatorial to mid-latitudes.

A measure of latitude control between YB and PQ is provided by values of magnetic inclination reported by Briden and Ward (1966) and Briden (1967a) obtained from flat-lying, Marinoan sediments, penetrated by two borecores located in South Australia. There, both tillites occur within the Umberatana Group (Thomson, 1969b) and are separated by hundreds of metres of interglacial sediments. The Umberatana Group is overlain by the Wilpena Group of which the Pound Quartzite is the youngest member. The Wilpena Group, the younger tillite and the interglacial sequence are Marinoan in age. One borecore locality was near Port Augusta at the head of the Spencer Gulf (Wilkatana No. 1) and the second at Woomera (Clarence River No. 1) — see Fig. 6.2b. From the Wilkatana borecore, between 406 m and 530 m, a mean inclination of 85° was measured (equivalent palaeolatitude = 80°) whilst in the interval 530 m - 559 m the mean inclination was 41° (equivalent palaeolatitude = 24°). Briden argued that the steep inclination was due to remagnetization during the Early Tertiary. The 41° inclination was considered primary. It is maintained that it is unnecessary to invoke remagnetization as an explanation of the steep inclination in one section of the borecore. It is more likely that both inclinations are primary; the steep inclination being associated with the period of the Marinoan Glaciation and the intermediate inclination with the upper part of the Interglacial Sequence. The original interpretation required the remagnetization mechanism to cease operating over about 10 m of sediment (Briden, 1964). It follows that the sediments with the lower inclination are likely to be Early Marinoan in age. Supporting evidence is found in the results from Lower Marinoan sediments penetrated by the Clarence River borecore. There, a magnetic inclination of 36° was obtained (equivalent palaeolatitude = 20°).

Earlier, in the discussion of the Early Palaeozoic section of the apparent polar wander path, it was demonstrated that Early and Late Cambrian borecore data are consistent with results obtained by investigation of surface material. Fig. 6.4b shows the locus of the pole corresponding to the steep inclination measured in the Wilkatana borecore — it provides rather narrow constraints upon the position of the pole. The dashed path between YB and PQ takes account of this. The two small circles which define the pole locii of the older sediments in the Wilkatana and

Clarence Rivers borecores intersect the apparent polar wander curve in correct chronological sequence with respect to the time of the Marinoan Glaciation.

The proposed loop involves an extra 100° of apparent polar wander than the direct link between YB and PQ. Further work is necessary to establish its reliability. In the following chapter (Section 7.1) it is shown that the loop is supported by late Precambrian palaeomagnetic data for Africa and the apparent migration in age of glacial sequences consistent with this model of polar wandering. The evidence considered strongly opposes the view that the Marinoan tillites were formed in low or equatorial palaeolatitudes. Harland and Bidgood (1959) provide some palaeomagnetic evidence they interpret as supporting the formation of glacial beds in low latitudes but the results are based on uncleaned NRM data. Similar material was recently investigated by Tarling (1974) but he regarded the results as inconclusive — both steep and shallow inclinations were present but the age of the shallow inclination, indicating low palaeolatitudes, was not established equivocally.

The older Sturtian Glaciation can be accommodated by a more northerly track of the path between the YB and ML poles, a reasonable assumption in view of the time gap between them.

The arc length of the Precambrian apparent polar wander path presented (excluding the dubious modification to accommodate the ERV pole, but including the probable loop between the YB and PQ poles) is about 620° and its time span about 1900 My. This yields an average rate of apparent polar wandering of about 0.3° per My, the same as average rates determined for other Precambrian and Phanerozoic paths (McElhinny, 1973).

The path bears no similarity to the only other proposal (Fig. 6.6c) for a Precambrian apparent polar wander curve for Australia, recently published by Facer (1974). However, this is only to be expect of the 11 key poles used here to define the curve, only two were previously available.

In Fig. 6.6b, the poles from the haematite ore bodies (Table 6.4) are plotted against an outline of the new path. A remarkable feature is their excellent agreement with the main curve as defined. The significance in terms of potentially dating formation of the ores is discussed in Section 6.2.

Three poles (LC, IA, IB) yet to be discussed are those from intrusives into the Mount Isa Block (Duff and Embleton, 1974). Age constraints governing the times of formation of the dolerites and gabbros were described earlier in this section. Their possible maximum age is 1450 My and on field relationships, the Lunch Creek Lopolith is older than the dolerites constituting groups IA and IB. The significance of the pole positions can be assessed in three ways:

(a) If the three poles are older than the Pound Quartzite (PQ) but younger than the YB pole (750 - 700 My), the data are consistent with the apparent polar wander path as defined. They would confirm (Fig. 6.4b) the presence of a loop between YB and PQ. However, if LC were older than YB, age constraints would require it to belong to the path segment connecting the ML and YC poles (see Fig. 6.4a). In this case, the correct sequence of older poles to join to IA would be the antipole sequence. The loop would disappear and the pole path would pass straight across Australia (still consistent with the Marinoan Glaciation).

(b) If all poles were older than the Giles Complex pole, the situation in Fig. 6.4c would result and a loop is defined for the late Carpentarian. The GC pole would be younger than the ML pole and the occurrence of a glaciation would be predicted for the period around 1400 - 1200 My. No evidence in the geological record of Australia has yet been found to support this prediction.

(c) If IA and IB are older than the YB pole but younger than the GC or ML poles i.e. lying between c1250 - 750 My, the curve shown in Fig. 6.4d can be drawn. This involves using the antipole sequence of all poles older than the YB pole. This intriguing possibility predicts the older Sturtian Glaciation since between YB and GC, the north pole would pass across Australia.

Verification of one of these three main possibilities relies upon more precise determination of the ages of the three poles — a project currently being undertaken by Dr R.W. Page of the Bureau of Mineral Resources using the Rb-Sr dating technique.

### 6.1.4 Implications of the Apparent Polar Wander Path for the Structural Integrity of Australia

The agreement of Early Palaeozoic palaeomagnetic results (Section 6.1.2) from the constituent shield nucleii which constitute the main Australian platform (a description of the platform is outlined in Chapter 1, Section 1.2) are compatible with the platform having maintained its physical integrity since latest Precambrian time. Tectonic events such as the Alice Springs Orogeny (Wells *et al*, 1970) probably result from intra-plate compression (Duff and Langworthy, 1974).

Whether the constituent shield nucleii of the main platform maintained their relative positions throughout the Precambrian is a matter for speculation at present because of the paucity of palaeomagnetic data. Application of plate tectonic concepts (Dewey and Horsefield, 1969; Burke and Dewey, 1972) to the younger intervening mobile belts would suggest that the mobile belts represent zones of suturing between Precambrian blocks which were originally widely separated.

This would support the earlier views of Rod (1966). Again more recently, Arriens (1971), has suggested that the Pilbara and Yilgarn Blocks may not have been juxtaposed for the whole of the Precambrian.

A particular example of a mobile belt separating regions sampled for palaeomagnetic investigation is the Petermann Ranges, central Australia. The Petermann Ranges Orogeny occurred in the late Precambrian (Wells *et al*, 1970) and affected the southern margin of the Amadeus Basin. The belt physically separates the sampling locality for the Arumbera Sandstone (pole AS — Table 6.1) from the sampling locality of the Pound Quartzite (pole PQ — Table 6.1). The PQ pole is pre-Petermann Ranges Orogeny in age (Daily *et al*, 1973); it may therefore not strictly refer to northern and central Australia.

A further example is the Albany-Fraser Belt (Chapter 1, Section 1.2) between the Yilgarn and Gawler Blocks. In the Fraser Range area of the belt, intense folding and metamorphism dates from about 1330 My (Wilson, 1969). It is separated from the Archaean granites and gneisses of the Yilgarn Block by an extensive mylonite zone — the Fraser Fault, likened by Wilson (1969) to the Grenville Front in Canada — and abruptly truncates structures typical of the Yilgarn Block (Daniels, 1971). The two poles yielded by the Gawler Block dykes are older than 1330 My and may therefore refer to a separated crustal nucleus i.e. a different plate.

Other views support an ensialic origin of the intervening mobile belts (Glikson and Lambert, 1973).

The 'first order' observation from the palaeomagnetic data is that all poles other than those from the Yilgarn Block fall on a path (in correct chronological sequence, where age constraints are known) described by the seven key poles obtained from rocks from the Yilgarn Block. Furthermore, there is consistency between Carpentarian palaeoclimatic data from sedimentary basins in northern Australia and Carpentarian palaeolatitude data derived from poles from southern Australia. Contiguity of blocks from the beginning of the Carpentarian is thus implied. It is noted that Precambrian palaeomagnetic data from Africa (Piper *et al*, 1973) also support the structural integrity of that continent from early Precambrian time despite a network of intervening mobile belts surrounding the older cratons.

## 6.2 THE AGE OF SOME AUSTRALIAN HAEMATITE ORE BODIES

### 6.2.1 Introduction

Banded iron formations of Precambrian age occur in all continents and are host to the world's most important source of iron ore. The banded iron formation is a chemically precipitated sediment comprising layers of chert alternating with layers of iron-rich material in the form of carbonate, silicate or oxide (James and Sims, 1973). The commercially exploited high-grade haematite ore bodies which occur within the iron formations are of secondary origin. Enrichment of the parent iron formation to produce an ore body is now generally accepted as resulting from a combination of processes involving selective leaching or removal of gangue materials and concurrent introduction and redeposition of iron oxides either by supergene or hypogene solutions (Miles, 1955; Door, 1965; Brandt, 1966; McCleod, 1966a).

Because of the secondary nature of the ore body, the age of ore formation, important for consideration of its genesis, is generally obscure. The material is unsuitable for application of radiometric methods. However, palaeomagnetism is potentially useful in this respect since haematite, the main ore mineral, can be the carrier of very stable magnetic remanence. Palaeomagnetic dating of an ore body therefore involves comparison of the pole(s) obtained from it with the apparent polar wander path of the same continent, defined by poles assigned radiometric ages (Symons, 1966).

Porath (1967a) reported the results of a detailed palaeomagnetic investigation of some Australian haematite ore bodies. Stable and well-grouped directions of magnetic remanence were obtained from most of those studied. The problem that arose in interpreting that data was that the pre-Silurian section of the apparent polar wander curve for Australia, as then defined, was poorly known and based on only five poles of questionable reliability obtained by Irving and Green (1958) from northern Australia (three poles were of Precambrian age — Buldiva Quartzite, Nullagine Lavas and Edith River Volcanics — and two of Cambrian age — Antrim Plateau Volcanics and Elder Mountain Sandstone). The reliability of the three Precambrian poles was considered in Section 6.1.3. The two Cambrian poles were based on NRM measurements from few samples (Irving, 1964).

Comparison of the ore body poles (Chamalaun and Porath, 1968; Porath and Chamalaun, 1968) with the apparent polar wander path led to the conclusion that the ore bodies were all of Precambrian age. Because of the paucity of palaeomagnetic data for the Australian Precambrian and its questionable reliability, Porath (1967b) also compared the ore body poles with reliable Precambrian poles from radiometrically dated rocks from Africa in order to obtain preliminary absolute estimates of the ages of the ore bodies within the Precambrian. The reconstruction of Gondwanaland chosen for this purpose was the one proposed by Carey (1958) and based on unwinding the major oroclines. A 'Middle Precambrian' age [2000 My - 1300 My] could be assigned to most of the ore bodies on this basis. However, the procedure involved the assumptions that Carey's arrangement of the Gondwanic continents prior to the Mesozoic drift episode was essentially correct and that this arrangement had existed since early Precambrian times. Porath (1967a) concluded that '...the main point that arises from the work on the iron ore bodies is the need for detailed palaeomagnetic measurements on datable rocks of Precambrian age in order to finally settle the question of the age of ore formation'.

In the elapsed time since that conclusion, the following developments have taken place:

(i) Many new, reliable, radiometrically dated Precambrian poles for Australia are now available.

(ii) New palaeomagnetic data from the main Australian platform for the period latest Precambrian to Early Palaeozoic and recent plate tectonic models concerning the evolution of the Tasman Orogenic zone of eastern Australia have led to a better understanding of apparent polar wandering with respect to Australia for that period (McElhinny and Embleton, 1974; Embleton and Giddings, 1974). Thus, the Silurian and Early to Middle Devonian poles of the apparent polar wander path available to Chamalaun and Porath (1968) and Porath and Chamalaun (1968) are now known to refer to a plate which was separate from that of the main Australian platform. Also, with respect to the main platform, a loop of 180° arc length has been identified in the apparent polar wander curve for the latest Precambrian to Early Palaeozoic (Embleton and Giddings, 1974) (the two Cambrian poles of Irving and Green (1958) were shown by recent, more rigorous studies of the same formations — McElhinny and Luck, 1970b and Luck, 1972 — to be in considerable error).

(iii) Using the magnetic lineations preserved in the rocks which underlie the present-day ocean basins separating the constituent continents of Gondwanaland, it has been possible to deduce the post-Mesozoic relative motions of those continents (Heirtzler *et al*, 1968; Sclater and Fisher, 1974).

The motional history demonstrates the incorrectness of Carey's (1958) pre-Mesozoic reconstruction of Gondwanaland and favours one similar to that proposed by Du Toit (1937) and Smith and Hallam (1970).

In view of the new data now available, a reappraisal of the ages of the haematite ore bodies is considered timely.

### 6.2.2 Palaeomagnetic Dating of the Ore Bodies

The localities of the ore bodies which yielded reliable palaeomagnetic data (Chamalaun and Porath, 1968; Porath and Chamalaun, 1968) are shown in Fig. 6.6a and the poles listed in Table 6.4. Brief geological data relating to each ore body are given for the purpose of illustrating the interpretation.

#### (a) Western Australian ore bodies

The haematite ore bodies occur in both Archaean (Mt Goldsworthy and Koolyanobbing) and Proterozoic (Mt Newman and Mt Tom Price) banded iron formations. The Archaean banded iron formations occur within the sedimentary sequences of the greenstone belts of the Yilgarn and Pilbara Blocks (Chapter 1, Section 1.2). They are strongly folded and metamorphosed (McCleod, 1965). The Proterozoic banded iron formations on the other hand are unmetamorphosed, generally gently or moderately folded and extensively developed in the sedimentary, intercratonic Hamersley Basin (Chapter 1, Section 1.2).

<u>Ore bodies in Archaean banded iron formations</u>: In the Mt Goldsworthy region of the Pilbara Block, two types of ore body of the replacement type have been recognized (Brandt, 1966). Lode ores are deep lenses of massive haematite within steeply dipping beds of the banded iron formation. Development of the lenses has been controlled by tectonic structures such as faults. A post-tectonic hypogene enrichment of the banded iron formation by hydrothermal-metamorphic reconcentration of the iron is favoured for the genesis of this type of ore.

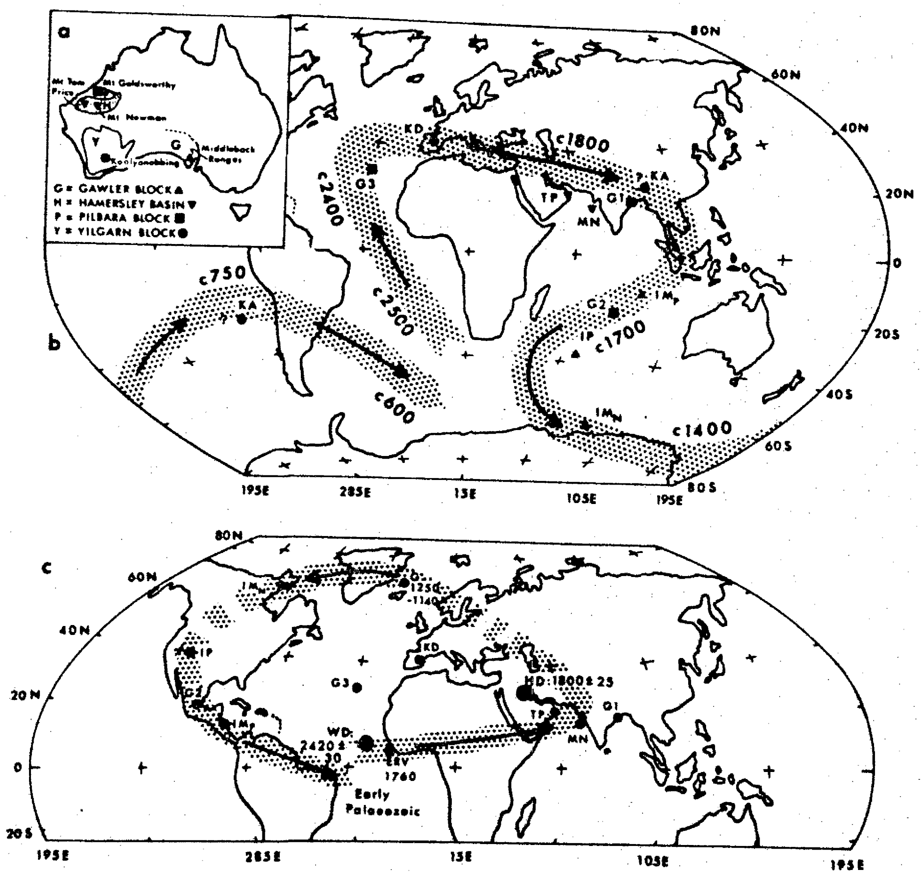

FIGURE 6.6 (a) The locations of the haematite ore bodies studied by Porath (1967a).
(b) The pole positions of the haematite ore bodies plotted against the background of the Precambrian apparent polar wander curve for Australia. The poles are denoted by symbols which correspond to those used in (a) to denote the structural units to which the ore bodies belong. The ore body poles are listed in Table 6.4. The approximate ages shown of various points of the path, are in My.
(c) The Precambrian apparent polar wander curve for Australia proposed by Facer (1974). Note that only two of the poles used to define this path are key poles, compared with the eleven available to define the path depicted in (b) and shown in more detail in Figure 6.3. The pole abbreviations are those used in Tables 6.2, 6.3 and 6.4.

TABLE 6.4

The haematite ore body poles

| Ore Body | Symbol | Pole Position* |  | A |
|---|---|---|---|---|
|  |  | Lat.° | Long.° |  |
| WESTERN AUSTRALIA |  |  |  |  |
| Mt. Goldsworthy (Lode Ore) | G1 | 20N | 84E | 6 |
| Mt. Goldsworthy (Lode Ore) | G3 | 31N | 330E | 13 |
| Mt. Goldsworthy (Crust Ore) | G2 | 22S | 79E | 19 |
| Mt. Tom Price | TP | 22N | 57E | 12 |
| Mt. Newman | MN | 17N | 66E | 10 |
| Koolyanobbing (Dowd's Hill) | KD | 43N | 356E | 9 |
| Koolyanobbing ('A' Deposit) | KA | 26N | 92E | 17 |
| SOUTH AUSTRALIA |  |  |  |  |
| Iron Monarch (positive group) | $IM_p$ | 15S | 92E | 12 |
| Iron Monarch (negative group) | $IM_n$ | 64S | 87E | 9 |
| Iron Prince | IP | 39S | 67E | 10 |

*See text for reference

Crust ores occur as shallow cappings to the upturned edges of the banded iron formation where these intersect the present surface. They have also formed over (and subsequently to) the upper parts of lode deposits (Brandt, 1964). They are considered to be of supergene origin.

Porath (1967a) investigated two ore bodies, one of the lode type, the other of the crust type. Three poles were obtained; two relate to the lode deposit (poles G1 and G3, Table 6.4) and one to the crust deposit (pole G2). The following evidence provides constraints on the age of the ores:

(i) Two periods of granite intrusion are recognized in the Pilbara Block (de Laeter and Blockley, 1972). The older granites give an age of 3050 ± 180 My and intrude the relict greenstone-whitestone sequences in which the banded iron formations are found. The age of those formations is therefore 3000 My or older. The lode ores (by nature of their genesis) post-date the minimum age of the parent iron formation.

(ii) A conglomerate belonging to the Lower Proterozoic Mt Bruce Supergroup contains cobbles of lode ore (Brandt, 1964). The Mt Bruce Supergroup covers the time span 2240 My - 1950 My (Compston and Arriens, 1968) so that source lode ore was in existence prior to 1950 My.

(iii) The crust ore pole (G2) is younger than the lode ore poles (G1 and G3) since crust ore post-dates the lode ore.

No direct evidence is available on the relative ages of G1 and G3. However, the lode ore pole G3 is based on samples which come from the outer zones of the lode ore deposit. Porath and Chamalaun (1968) suggested that those samples may represent the early stages of the ore forming process, envisaged as progressing inwards from the outer zones.

This would suggest that pole G3 is older than pole G1.

The three poles are shown in Fig. 6.6b against the background of the Precambrian to Early Palaeozoic apparent polar wander curve. They lie on the curve in a chronological sequence consistent with points (i) - (iii) above and the suggestion of Porath and Chamalaun (1968) relating the age of G3 to G1. Any other sequence consistent with the age information would lack such excellent agreement of the poles with the path as currently known. The data suggest therefore that the lode ore was formed in two distinct phases, one occurring at about 2450 My - 2400 My (pole G3) and the other at about 1800 My - 1750 My (pole G1). The crust ore appears to have developed somewhat later at about 1700 My, very much older than the speculated Mesozoic or younger age for this type of ore (Brandt, 1966).

The ore bodies of the Koolyanobbing Hills in the Yilgarn Block comprise a number of irregular lenses. The greenstone-whitestone sequence, to which the parent banded iron formation belongs, has been intruded by granite (Miles, 1953). Two ore bodies were studied by Porath (1967a), the Dowd's Hill and 'A' deposits.

In the Dowd's Hill deposit, two generations of haematite ore are recognized, the younger being in the form of veins of specular haematite resulting from hydrothermal activity in the area. The veins cut the older massive goethite ore. Both types of ore, however, yielded similar directions of magnetic remanence. Porath (1967a) therefore concluded that the magnetization of the ore body was related to the hydrothermal activity (which could be related to the intrusive granite). The most likely age of that activity is within the time span 2750 My - 2200 My, a period of widespread granite emplacement and basic intrusion in the Yilgarn Block (Compston and Arriens, 1968; Arriens, 1971). The Dowd's Hill pole (KD in Fig. 6.6b) lies on the apparent polar wander path in a position consistent with that time span. The age of the Dowd's Hill ore body is estimated at 2300 My - 2200 My.

The directions of remanence of the 'A' deposit fell into two distinct groups. One group, comprising only two samples, possessed directions reminiscent of those from the YE group of dykes from the Yilgarn Block (Chapter 3); the other group comprised six samples. In neither case was a pole calculated because the data were considered too few. However, for the purpose of a 'first order geophysical fit', a pole position was calculated for the group comprising six samples (KA in Fig. 6.6b). The pole and its antipole lie on the apparent polar wander path and in the absence of geological control favouring either possible age, the time of the ore body's formation remains ambiguous. It could be either about 1750 My or 750 My - 700 My old, but is clearly Precambrian in age.

Both suggested ages for pole KA do not relate to known igneous activity in the area, implying that the ore body is of supergene origin with the two axes of magnetization possibly reflecting two distinct periods of enrichment. The ore is mainly goethite and because no veins of specularite were evident Porath (1967a) suggested that the 'A' deposit might have experienced a different geological history from the Dowd's Hill deposit. Owen and McEwen (cited in Porath, 1967a) strongly favour a supergene origin for the goethite ore while McCleod (1966b) noted that '...there is a great variation over short distances in the mineralogical composition and texture of the ore...and it is apparent that the entire ore body has been profoundly modified by protracted supergene alteration through the agency of oxygenated groundwaters'.

<u>Ore bodies in Proterozoic banded iron formations</u>: Banded iron formations in the Hamersley Basin (Chapter 1, Section 1.2) between the Yilgarn and Pilbara Blocks belong to the Hamersley Group member of the Mt Bruce Supergroup. Three iron formations have been recognized in the Hamersley Group and of these the Brockman Iron Formation is host to the

the largest ore deposits. The Woongarra volcanics which occur towards the top of the Hamersley Group above the Brockman Iron Formation have been dated at 2000 ± 100 My and lavas in the upper part of the Fortescue Group, which is conformably overlain by the Hamersley Group, have been dated at 2190 ± 100 My (Compston and Arriens, 1968). The major episode of folding to affect the Mt Bruce Supergroup sediments belongs to the Opthalmian Orogeny (Daniels, 1966) which occurred prior to deposition of the younger, overlying, Proterozoic Bresnahan Group. Compston and Arriens (1968) have suggested the Bresnahan Group to be of similar age to Carpentarian sediments in the McArthur Basin of Northern Territory, which were deposited between about 1800 My and 1500 My.

The ore bodies are located in favourable structures, such as synclinal troughs, generated by the folding of the Opthalmian Orogeny. The synclinal troughs have acted as impounding structures to enriching fluids considered to be of supergene origin (McCleod, 1966a). Porath (1967a) sampled two ore bodies, one at Mt Tom Price and the other at Mt Newman, both developed in the basal member of the Brockman Iron Formation. The ores have a maximum age of 2100 My since they are post-folding developments and, using the suggestion of Compston and Arriens (1968), a likely maximum of about 1800 My.

Two pole positions were obtained, one from each ore body. The poles (TP for Mt Tom Price and MN for Mt Newman) lie on the apparent polar wander curve (Fig. 6.6b) in a position somewhat younger than the Hart Dolerite pole at 1800 ± 25 My. Nielson (1965) associated the requirements of ore formation with an episode of folding which, he suggests, culminated in the late Precambrian. On this basis he argued a late Precambrian age for the ores. However, the synclinal structures to which the ores relate were produced in the earlier Opthalmian Orogeny. The arguments of Nielson should therefore relate to that episode of folding, implying an age for the ores similar to that of the Orogeny. The approximate 1800 - 1750 My age for both ore bodies using the apparent polar wander curve is consistent with the age of that Orogeny as currently defined and other age data relating to the host banded iron formations.

(b) South Australian ore bodies

The haematite ore bodies studied by Porath (1967a) are located within the banded iron formations of the Middleback Group (Miles, 1955) which outcrops in the Middleback Ranges of the northeastern Eyre Peninsula. The metamorphosed sequence of sediments to which the banded iron formations belong has been folded into a series of north-south trending synclines and anticlines. The age of the basement is about 1780 ± 120 My (Compston and Arriens, 1968) and a minimum age of the Middleback Group is provided by a 1535 ± 20 My age determined for the locally outcropping Corunna Conglomerate (Compston *et al*, 1966). The Conglomerate (Miles, 1955) contains pebbles of haematite ore, (contrary to the statement cited by Chamalaun and Porath (1968)) as well as cobbles of banded iron formation. Thus, the maximum age of the ore bodies is probably around 1800 My, while some ore had been formed by 1535 ± 20 My. In addition, the Iron Monarch ore body is older than 584 ± 20 My, the minimum age of a highly-altered dolerite dyke which intrudes that ore body.

Two ore bodies, Iron Monarch and Iron Prince, yielded reliable palaeomagnetic data and three pole positions were obtained, one relating to the Iron Prince deposit (pole IP) and two to the Iron Monarch deposit (poles $IM_p$ and $IM_n$). The two ore bodies occupy synclinal structures and after an exhaustive geological investigation of the area, Miles (1955) favoured enrichment of the parent banded iron formations by hydrothermal solutions leaching the silica and introducing iron. The source of the hot fluids was considered to be contemporaneous igneous activity. Porath's (1967a) work on the ore bodies does not contradict the suggestion of Miles (1955).

The three poles (IP, $IM_p$, $IM_n$) lie on the 1700 - 1500 My section of the apparent polar wander path (Fig. 6.6b). The ages thus implied for the ore bodies are consistent with the geological constraints regarding their age. Furthermore, the age span represents a period for which there is abundant evidence of igneous activity in the region (Compston *et al*, 1966), consistent with the interpretation regarding the genesis of the ores (Miles, 1955). Indeed, the agreement of the two Iron Monarch poles with the two poles derived from the South Australian dykes (GA and GB in Chapter 4) is particularly good. It is concluded therefore that the Iron Prince ore body has an age of about 1600 My and that the Iron Monarch ore body formed in two phases, the earlier phase having an age of about 1700 My and the later phase an age of about 1500 My.

## 6.3 PALAEOMAGNETIC EVIDENCE RELATING TO THE TECTONIC HISTORY OF SOUTH AUSTRALIA AND TASMANIA

### 6.3.1 Introduction

Crawford and Campbell (1973a) have postulated large-scale intra-continental shearing within Australo-Antarctica culminating in the Early Ordovician. One major shear forms what is now the southern boundary of Australia between longitude 131°E and 143°E (Fig. 6.7). They regarded the southern part of the Adelaide Orogen as having been bent in a westerly direction by large-scale fault-drag along this shear, a suggestion which appeared to provide the first satisfactory explanation of that deflection. Furthermore they went on to propose that the effects of gradual bending, which ultimately produced east-west structural trends in Kangaroo Island and the Fleurieu Peninsula, also involved the southeastern corner of the Gawler Block, '...slightly

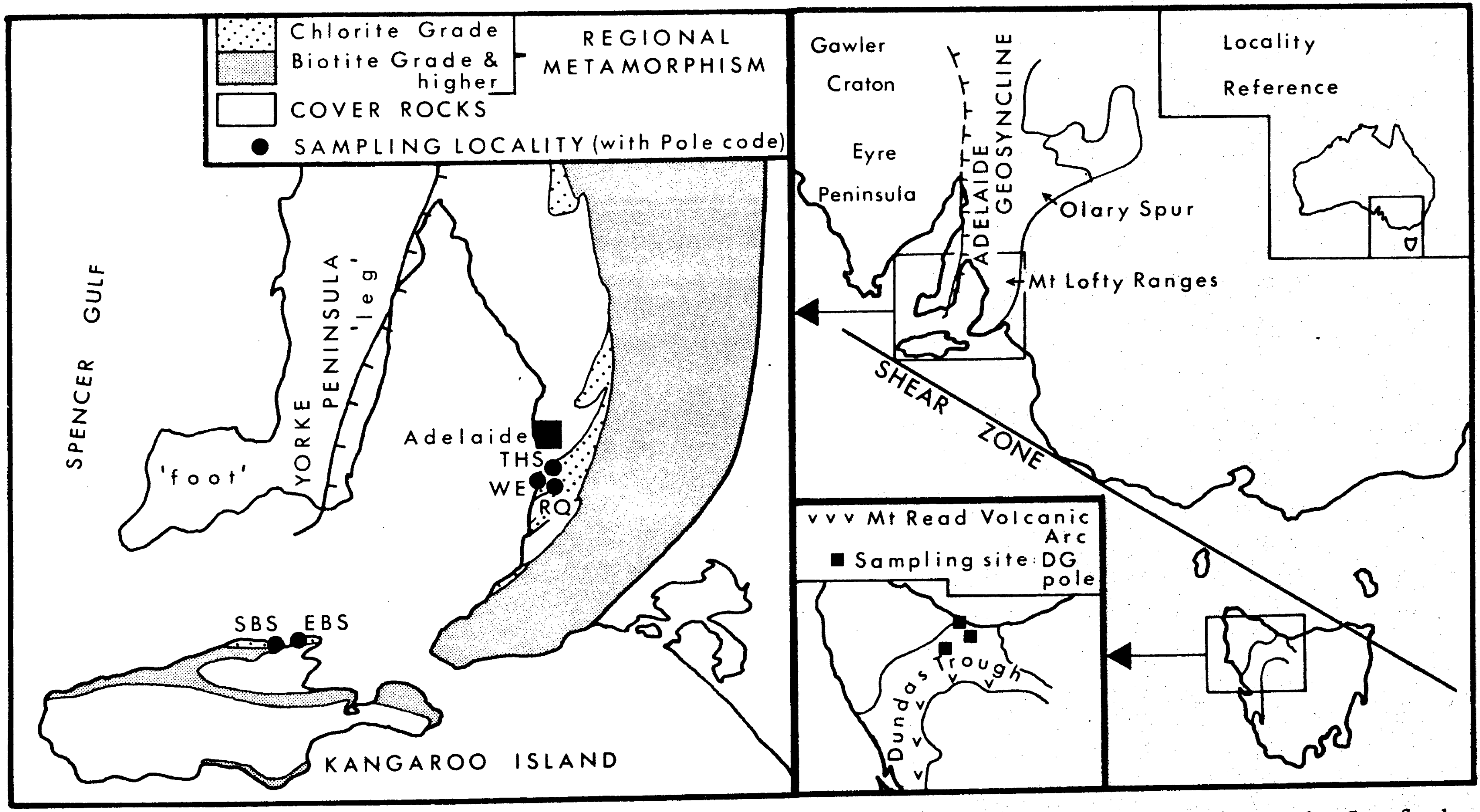

FIGURE 6.7 The principal structural elements in South Australia and Tasmania which, according to the Crawford and Campbell (1973a) hypothesis initially occupied meridional trends. Sampling localities for the earlier palaeomagnetic investigations of Briden (1964) are indicated. THS - Tapley Hill Slates, RQ - Marinoan Sandstones (Reynella Quarries), WE - Marinoan Sandstones (Wilmington equivalents), SBS - Stokes Bay Sandstones and Smith Bay Shale, EBS - Emu Bay Sandstone and DG - Dundas Group.

rotating the leg of Yorke Peninsula and, as the southernmost part of the Orogen was bent through ninety degrees, snapped the extremity of the Block round into an east-west position...', i.e. producing the 'foot' of Yorke Peninsula. At the other end of the shear in Tasmania, the arcuate shape of the Dundas Trough-Mount Read volcanic arc (Spry and Banks, 1962) was also attributed to fault-drag resulting from shearing. In both areas, the features mentioned were postulated to have been originally linear. Opposing views (Daily *et al*, 1973; Harrington *et al*, 1973) also based on qualitative geological arguments, maintain that the structural features are primary.

The palaeomagnetic results obtained from the Precambrian dykes intruding Eyre Peninsula and the foot and leg of Yorke Peninsula (Chapter 4) have made it possible to check the suggestion of rotation of parts of Yorke Peninsula relative to Eyre Peninsula. Since the dykes pre-date the proposed Early Palaeozoic shearing, differences in magnetic declinations between each of the three sampling areas will provide estimates of the amount of rotation if it occurred at all.

Earlier studies of late Precambrian-Cambrian sedimentary rock formations collected from Kangaroo Island, the southern Mount Lofty Ranges and the Dundas Trough (Briden, 1964, 1967a,b) were considered inconclusive at the time of their publication. Palaeomagnetic results now available from late Precambrian-Early Palaeozoic rock formations from widely separated localities throughout Australia (McElhinny and Luck, 1970b; Luck, 1972; Embleton, 1972a,b; Embleton and Giddings, 1974) support the contention that the main Australian platform has retained its gross structural unity since at least late Precambrian time (Section 6.1). A framework therefore now exists within which the earlier results of Briden may be reviewed and their bearing on the proposed bending of the southernmost part of the Adelaide Orogen and the Mount Read volcanic arc and Dundas Trough assessed.

### 6.3.2 Results from the Precambrian Dykes

Table 6.5 contains the mean directions of remanent magnetization of the principal populations of dyke-means for each of the three areas: Eyre Peninsula, leg of Yorke Peninsula and foot of Yorke Peninsula. Dyke-mean directions for each area are plotted in Fig. 6.8a. The single negatively magnetized dyke for each of the foot and leg of Yorke Peninsula is assumed to belong to the swarm of similarly magnetized dykes outcropping in Eyre Peninsula. It is evident from Fig. 6.8a and Table 6.5, that the directional distributions of the positively magnetized dykes for the three areas are coincident.

Crawford and Campbell (1973a) report that lineations thought to be bedding foliation in the basement gneisses of the foot of Yorke Peninsula differ by up to 90° from lineations measured in the leg and in the basement gneisses of Eyre Peninsula — following work by Crawford (1965) and Johns (1961).

The compass rose diagrams (inset in Fig. 6.8a) of the structural trends of the dykes sampled for palaeomagnetic work, show quite clearly that the dykes which intrude the basement gneisses of Yorke Peninsula conform to a unimodal distribution. Those intruding the foot strike between 270° to 320°, while those intruding the leg vary in strike from 290° to 340° with one dyke trending approximately north-south.

### 6.3.3 Appraisal of Previous Investigations of late Precambrian-Cambrian Sediments

Palaeomagnetic results have been described by Briden (1964) from the Upper Glacial and Interglacial beds of the late Precambrian Umberatana Group (Thomson, 1969b) sampled south of Adelaide (Fig. 6.7), and from red-beds of Early and Middle Cambrian age sampled on Kangaroo Island. The Cambrian material studied was considered '...remagnetized, not in recent times, but as long ago as the Early Tertiary', (Briden,

## TABLE 6.5

Summary of the palaeomagnetic data from
Yorke Peninsula and Eyre Peninsula

| Sampling Locality | N* | R | D | I | a |
|---|---|---|---|---|---|
| EYRE PENINSULA | | | | | |
| (a) positive group | 9 | 8.389 | 270 | +59 | 15° |
| (b) negative group | 10 | 9.665 | 032 | -48 | 9° |
| YORKE PENINSULA | | | | | |
| (a) 'leg' | 5 | 4.768 | 275 | +60 | 19° |
| (b) 'foot' | 8 | 7.379 | 275 | +65 | 17° |

*N = Number of dykes used to compute the mean

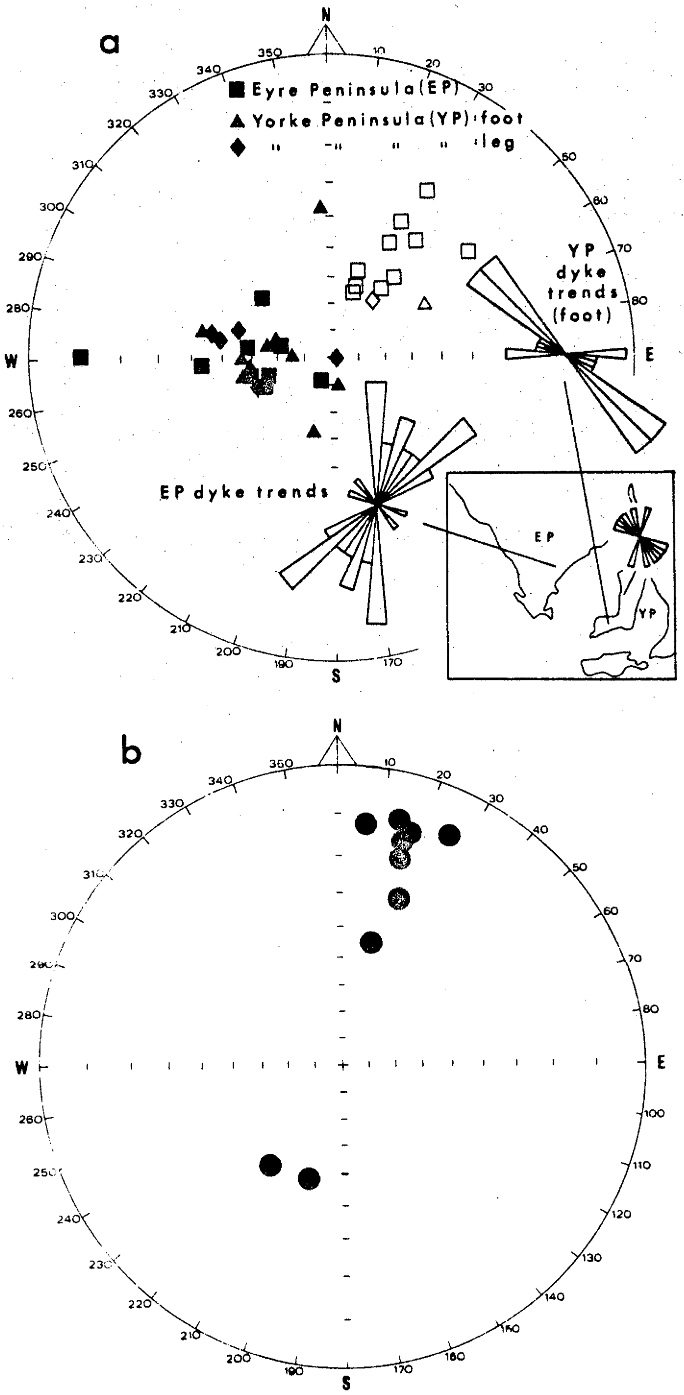

FIGURE 6.8 (a) Dyke-mean directions of primary magnetic remanence of the South Australian dykes grouped according to whether they were sampled from Eyre Peninsula, the 'foot' of Yorke Peninsula or the 'leg' of Yorke Peninsula. Inset compass rose diagrams depict the measured dyke trends in each of the two peninsulas.

(b) Thermally cleaned (at 400°C and after bedding correction) specimen directions of magnetization obtained by Briden (1964) from some sediments of lowermost Marinoan age exposed in Reynella Quarries, south of Adelaide.

1964, p. 98). This conclusion was reached for two principal reasons:

(i) The uncleaned directions of magnetization were considered steeper than the present field direction and clustered around the Early Tertiary field direction as it was then defined (Irving, 1964)

(ii) The postulated reheating effect of basalts, which outcrop on low hills above the Cambrian outcrops on Kangaroo Island.

It is now known from K-Ar geochronology (Wellman, 1971) that the Kangaroo Island basalts are significantly older — dated at about 170 My — than was previously thought. Extensive Early Tertiary remagnetization therefore looses credence.

Partial thermal demagnetization of the late Precambrian sediments, whose initial remanence was mainly scattered, and the Cambrian sediments, generally resulted in increased dispersion or random distributions of remanence, although at some sites in the late Precambrian sediments there was the '...possibility of a relic of an ancient and stable NRM' (Briden, 1964, p. 85). Briden reported the results of his investigation in meticulous detail because he acknowledged that '...some of these results will become more intelligible when further work is carried out on rocks of these ages in Australia' (Briden, 1964, p. 99).

The study of the palaeomagnetism of the Pound Quartzite (Chapter 5), indicated that it was necessary to follow very closely the response of individual specimens to thermal cleaning. Since the secondary magnetization in specimens cut from a sample often covered the stability spectrum, analysis of the data obtained at the sample level produced a confused pattern. Aware, therefore, that remagnetization and the acquisition of viscous remanent magnetization may take place inhomogeneously, the earlier results of Briden were scrutinized at the specimen level. It was possible to tentatively identify specimens which after partial thermal demagnetization appeared to contain a stable component of magnetization oblique to the present field axis. The formations which yielded the data are the Tapley Hill Slates (older than the Marinoan glacials), Marinoan Sandstones from the Fleurieu Peninsula (equivalent in age or older than the glacials) and the Stokes Bay Sandstone, the Smith Bay Shale and the Emu Bay Sandstone of Early-Middle Cambrian age from Kangaroo Island. The clearest example is the result obtained from the Marinoan Sandstones sampled in the Reynella Quarries — shown in Fig. 6.8c. Results from the other formations were more scattered but often exhibited a planar distribution trending NE to SW. The cleaned directions of remanence are thus not unlike those expected from Cambro-Ordovician formations (Embleton, 1972b; Luck, 1972; Embleton and Giddings, 1974). It appears that the formations in the southern part of the Adelaide Orogen may well have suffered remagnetization, but it was a Cambro-Ordovician rather than a Tertiary event. Regional metamorphism in the southern Mount Lofty Ranges and Kangaroo Island and the intrusion of granitic bodies, occurred during the Delamerian Orogeny in the Late Cambrian and Early Ordovician (Offler and Fleming, 1968; Thomson, 1969b). The localities Briden sampled (Fig. 6.7) for his investigation are situated within the chlorite zone of the greenschist facies. It is believed that the regional metamorphism created an environment suitable for remagnetization.

In Tasmania, Briden (1964, 1967b) collected material of Late Cambrian age from the northern part of the Dundas Trough (i.e. the most 'rotated' part). It comprised sediments and tuffs belonging to the Dundas Group (Spry and Banks, 1962) and a syenite intrusion. They were involved in the Late Cambrian Jukesian Orogeny (Daily *et al*, 1973). Samples were subjected to either alternating field or thermal demagnetization techniques. From the steep inclinations of NRM and the presence of Tertiary igneous activity in the area (Spry and Banks, 1962) Briden suggested that the material had been again substantially remagnetized in the Tertiary due to the acquisition of secondary components of viscous PTRM (Chamalaun, 1964). However for samples of the syenite boss, he noted '...that relics of ancient magnetization might be preserved' (Briden, 1964, p. 117).

From re-examination of the data at the specimen level, it is believed that a weak primary component of magnetization has been retained in specimens from eight samples of the tuff and syenite. Opposite polarities of magnetization are present and they give a positive fold test (Graham, 1949; McElhinny, 1964), the precision parameter, k (Fisher, 1953), undergoing a significant increase from 4.7 to 12.4. The mean axis of magnetization corresponds to a Late Cambrian pole position which is in agreement with poles of similar age from other parts of Australia (Section 6.1).

### 6.3.4 Implications for Large-Scale Horizontal Displacements in Southern Australia

The directions of magnetization measured for the dykes were argued to be records of the ambient geomagnetic field direction at the time of dyke intrusion (Chapter 4). Therefore, the coincidence of directions of the positively magnetized dykes from the three areas of the southeastern corner of the Gawler Block is inconsistent with a structural model involving local rotation in Yorke Peninsula (i.e. the foot with respect to the leg) and rotation of the entire Peninsula relative to Eyre Peninsula. Indeed, the consistency of the palaeomagnetic data may be considered particularly good and indicates that the region has maintained its physical integrity at least since the time of dyke intrusion (c1700 My). Furthermore, the trends of the dykes in the foot and the leg of Yorke Peninsula lend no support to the rotation hypothesis.

This result, acknowledged by Crawford and Campbell (1973b) only indicates that the southeastern margin of the Gawler Block has remained structurally intact. The data cannot be extrapolated to disprove bending in the southern part of the Adelaide Orogen since this constitutes a distinct tectonic unit. Unfortunately, Briden's (1964) data are inconclusive in this context. If the formations were remagnetized as believed, then the magnetic remanence would have been acquired syntectonically. Unknown variables in attempting to elucidate this problem include the time relationships of folding and metamorphism (Offler and Fleming, 1968), the degree of remagnetization, and whether secondary components of magnetization were completely removed by cleaning the samples in the laboratory at only 400°C.

The results from the Dundas Group and syenite boss of Tasmania (although based on few palaeomagnetic data) indicate that no detectable bending of the Dundas Trough (and the Mount Read volcanic arc) occurred during the Early Ordovician neither by fault drag nor some other mechanism.

### 6.3.5 Conclusion

The palaeomagnetic data presented dispute that the effects of shearing produced rotations of features adjacent to the shear zone on the scale envisaged by Crawford and Campbell (1973a). However, geological evidence in favour of activity along a structural lineament as described in the hypothesis is not disputed. Such activity has also been postulated by Harrington *et al* (1973) and Carey (cited in Harrington *et al*, 1973). It is unlikely that relatively simple linear displacements of a few hundred kilometres proposed would be resolved palaeomagnetically.

# CHAPTER 7

# PRECAMBRIAN PALAEOMAGNETISM OF GONDWANALAND

## 7.1 INTRODUCTION

Piper *et al* (1973) have tested whether the concepts of plate tectonic theory, as applied to several Phanerozoic orogenic belts (Dewey and Bird, 1970; Bird and Dewey, 1970; Hamilton, 1970; Oversby, 1971; Burret, 1972, 1974; Powell and Conaghan, 1973), can be invoked to explain the distribution of the ancient orogenic belts of Africa. Their analysis shows that all palaeomagnetic pole positions for Africa between 2200 My - 450 My lie on a single apparent polar wander path, irrespective of the cratonic region yielding the data. This suggests that the major cratonic areas of Africa (Clifford, 1970) were approximately in their present relative positions and orientations as early as 2200 My ago. The younger, intervening orogenic, or mobile, belts did not, therefore, result from plate accretion and subduction processes during episodes of major ocean closure which culminated in continent-continent collisions (Hurley, 1972; Burke and Dewey, 1972). Rather, the data support the view that those belts formed *in situ*, the stable cratonic nucleii remaining in place while the intervening belts themselves were reactivated (Clifford, 1968; Schackleton, 1969, 1973). Present data cannot, however, preclude the possibility that the belts resulted from the successive opening and closing of small intercratonic oceans.

Comparing the African data with American data, Piper *et al* (1973) further suggest that South America and, until about 1000 My ago, North America may have been joined to Africa. A further consequence of their interpretation is that Precambrian glaciations dating from 900 My to 600 My and which affected south-west, central and northern Africa, and parts of South America were formed in low latitudes (Piper, 1973a).

New results for the Precambrian and Early Palaeozoic of Australia (this thesis; McElhinny and Embleton, 1974; Embleton and Giddings, 1974) and India (Klootwijk, 1973,1974) and a new Precambrian result from Antarctica (Embleton and Arriens, 1973) enable the comparisons of Piper et al (1973) to be extended to include the whole of Gondwanaland (McElhinny et al, 1974). The results lead to a modified late Precambrian to Early Palaeozoic apparent polar wander path, a consequence of which is that the formation of the Gondwanic late Precambrian glaciations is restricted to high latitudes. The interpretation leads to some predictions concerning the apparent polar wander path for North America, but does not affect the general conclusions of Piper et al (1973).

## 7.2 GONDWANIC PALAEOMAGNETISM FOR THE LATE PRECAMBRIAN TO EARLY PALAEOZOIC (c900 My - 450 My)

### 7.2.1 A common Apparent Polar Wander Path for Gondwanaland

Palaeozoic and Mesozoic palaeomagnetic results from the Gondwanic continents, when referred to the reconstruction of Smith and Hallam (1970), suggest that a common apparent polar wander path can be applied to the supercontinent from sometime in the Early Palaeozoic until its break-up in the Mesozoic (McElhinny, 1973). Interpretation of the Early Palaeozoic section of the path has been uncertain because the poles tended to form a rather loose group in the region off northwest Africa. Recently however, palaeomagnetic investigations have been carried out on rock sequences of late Precambrian to Ordovician age in northern Australia (McElhinny and Luck, 1970b; Luck, 1972) and in the Amadeus Basin of central Australia (Embleton, 1972a,b). For each rock sequence a very large polar shift of $50^{o}$ - $60^{o}$ of arc is observed during the earliest Cambrian and in the Amadeus Basin the total shift during the Early Palaeozoic is about $90^{o}$. Fig. 7.1 compares those Australian results on the Smith and Hallam (1970) reconstruction of Gondwanaland

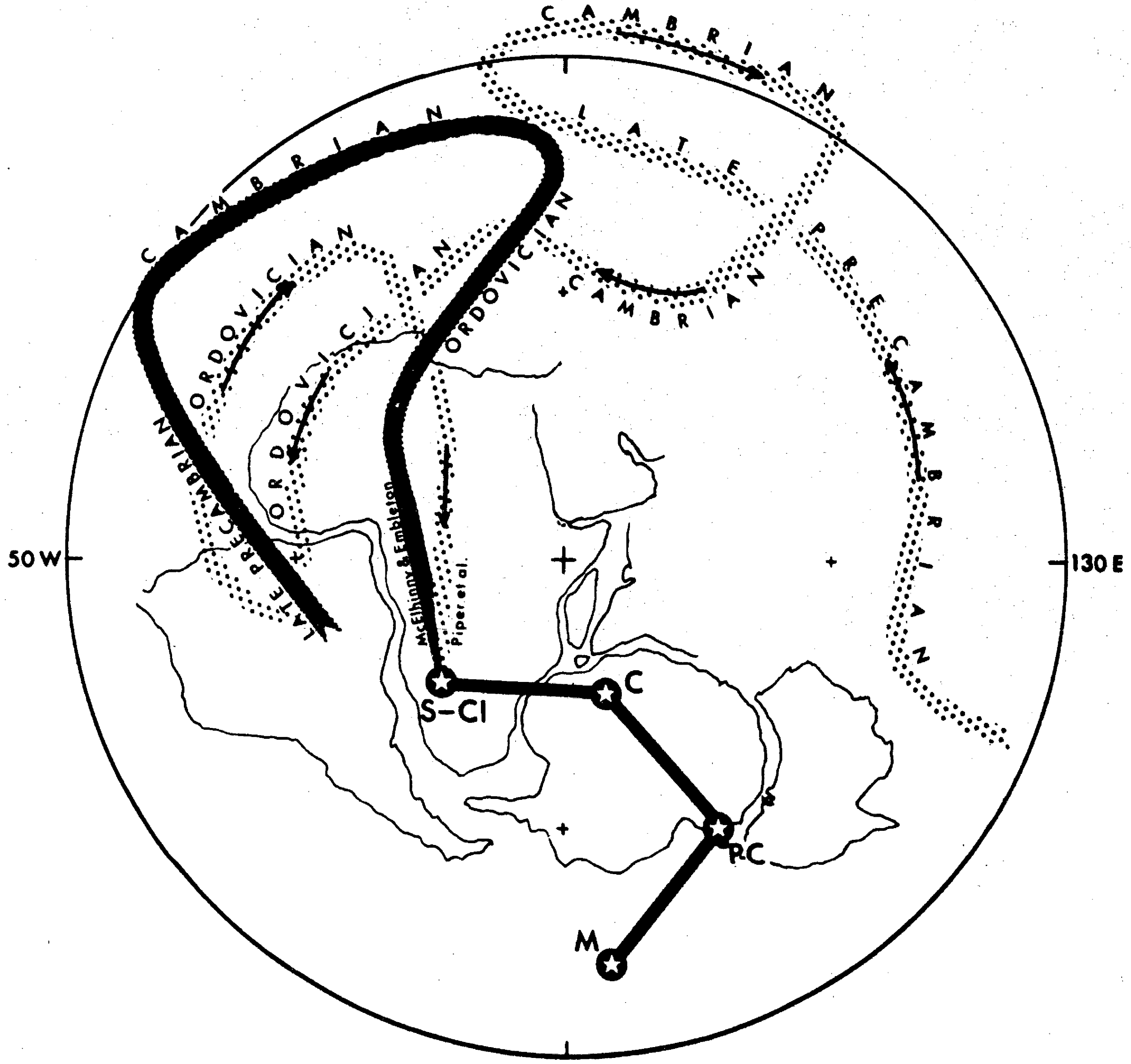

FIGURE 7.1 The late Precambrian-Early Palaeozoic apparent polar wander path for Africa and South America suggested by Piper *et al* (1973) — shown stippled — compared with the similar aged section of the path defined by McElhinny and Embleton (1974) for Australia (extended into the latest Precambrian by Embleton and Giddings, 1974). The reconstruction of Gondwanaland is that of Smith and Hallam (1970) with Africa in its present day position. Note that the path of Piper *et al* places Africa in equatorial latitudes during the latest Precambrian. The solid black line connecting the mean Silurian-Carboniferous (S-Cl), Carboniferous (C), Permo-Carboniferous (P-C) and Mesozoic (M) poles is the common path for this time interval (McElhinny and Embleton, 1974).

with the corresponding late Precambrian to Early Palaeozoic path for Africa and South America proposed by Piper *et al* (1973). It is evident that the two Cambrian sections of the curves disagree and in fact display polar shifts in opposite directions.

Two possible explanations of the disagreement present themselves. Firstly, the earliest Cambrian sections of the two paths could refer to separate plates which collided to form Gondwanaland during the Middle Cambrian. The timing then corresponds to the peak of the 550 ± 100 My pan-African orogeny, which was strongly argued by Piper *et al* (1973) not to have resulted from plate convergence. It thus seems unlikely that any one of those orogenic belts, such as the Mozambique belt (Clifford, 1970), represents the suture between an eastern and western Gondwanaland. Alternatively, the disagreement may not be real but merely reflects Piper *et al's* (1973) failure to appreciate the significance of the late Precambrian to Early Palaeozoic results from Australia in their interpretation. It is only in the Australian data that stratigraphic control on the sequence of poles during that period of time may be found (Embleton, 1972a,b; McElhinny and Embleton, 1974). Similar aged poles from Africa and South America are based on stratigraphically unrelated and generally poorly dated rocks. Therefore, the African and South American data have been reviewed in the light of this new data from Australia and the apparent anomalies between the data have been resolved.

Table 7.1 lists all palaeomagnetic poles for the Gondwanic continents between about 900 My and 450 My (close of the Ordovician).

All the palaeomagnetic poles of Table 7.1 have been plotted on the reconstruction of Gondwanaland of Smith and Hallam (1970) shown in Fig. 7.2. The Cambrian polar shift observed from Australia also appears to be recorded in the palaeomagnetic data of South America and Africa in this interpretation. A modification to the Smith and Hallam (1970)

TABLE 7.1[1]

Gondwanic Continents: Pole positions for the period c900 My - 450 My

| Rock Unit | Symbol | Age (My)[2] | | Pole Coords.[3] Lat.° | Long.° | A or dp,dm |
|---|---|---|---|---|---|---|
| AFRICA | | | | | | |
| Kigonero Flags | KF | Pr | (> 890) | 12N | 273E | 29 |
| KLEINKARAS DYKES | KK | Pr | (878 ± 41) | 20N | 294E | 35 |
| GAGWE LAVAS | G | Pr | (813 ± 30) | 29S | 293E | 11 |
| BUKOBAN INTRUSIVES | BI | Pr | (806 ± 30) | 11S | 281E | 17 |
| MBOZI COMPLEX | M | Pr | (743 ± 30) | 72S | 248E | 14 |
| Lower Buanji Series | LB | | (<1350) | 87S | 83E | — |
| PRE-NAMA DYKES | ND | Pr | (653 ± 70) | 85S | 48E | 25 |
| Plateau Series, Zambia (i) | PZA | | (<1000) | 71S | 353E | 15 |
| Plateau Series, Zambia (ii) | PZB | | (<1000) | 60N | 25E | 12 |
| Ouarzazate Volcanics[4] | OV | Pr/Є | | 30S | 57E | 17 |
| SIJARIRA GROUP | SG | Pr/Є | | 2N | 352E | 18 |
| NTONYA RING STRUCTURE | N | Pr | (630 ± 24) | 28N | 345E | 2 |
| Klipheuvel Formation[4] | K | Pr/Є1 | | 16N | 316E | (5)[6] |
| Amouslek Tuffs[4] | AT | Є1 | | 41N | 250E | 10 |
| Sabaloka Ring Structure | SR | | (> 540) | 83N | 339E | 10 |
| Fish River Series[5] | FR | Pr/Є | | 55S | 317E | 30 |
| JORDANIAN RED BEDS | JRB | Є(-O) | | 37N | 323E | 8 |
| Moroccan Lavas[4] | MRL | Єm | | 53N | 34E | — |
| TABLE MOUNTAIN SERIES | TM | O | | 50N | 349E | (2)[6] |
| Hook Intrusives[5] | HI | O1 | (500 ± 17) | 14N | 336E | 36 |
| Plateau Series, Zambia (iii) | PZC | Lr.Pal | | 10S | 352E | 14 |
| Plateau Series, Zambia (iv) | PZD | Lr.Pal | | 22N | 19E | 65 |
| ANTARCTICA | | | | | | |
| CHARNOCKITES | C | Єu-O1 | | 2S | 28E | — |
| SØR RONDANE INTRUSIVES | SRI | O1-m | (485 ± 25) | 28S | 10E | 5,6 |
| AUSTRALIA | | | | | | |
| DYKES, GROUP YB | YB | Pr | (750 - 700) | 20S | 282E | 28 |
| POUND QUARTZITE | PQ | Latest Pr | | 60S | 6E | 24 |
| ANTRIM PLATEAU VOLCANICS | AV | Pr/Є1 | | 9S | 340E | 17 |
| ARUMBERA SANDSTONE | AS | Pr/Є1 | | 8N | 325E | 25 |
| AROONA DAM SEDIMENTS | AD | Є1 | | 36S | 33E | 17 |
| HUGH RIVER SHALE | HS | Є1-m | | 11N | 37E | 8 |
| HUDSON FORMATION | HF | Єm | | 18N | 19E | 13 |
| LAKE FROME GROUP | LFG | Єm-u(?O1) | | 14S | 24E | 13 |
| Dundas Group | DG | Єu | | 23S | 13E | 12 |
| JINDUCKIN FORMATION | JF | O1 | | 13S | 25E | 11 |
| STAIRWAY SANDSTONE | SS | Om | | 2S | 50E | 8 |
| TUMBLAGOODA SANDSTONE | TS | O?(Єm-S1) | | 30S | 31E | 9 |
| MEREENIE SANDSTONE | MS | S?-D | | 41S | 40E | 10 |

Footnotes on following page

Continued

TABLE 7.1[1]

(Continued)

| Rock Unit | Symbol | Age (My)[2] | Pole Coords.[3] | | A or dp,dm |
|---|---|---|---|---|---|
| | | | Lat.° | Long. | |
| INDIA | | | | | |
| MALANI RHYOLITES | MR | Pr (745 ± 10) | 78S | 225E | 11,15 |
| BHANDER SANDSTONE | BH | Pr/Є | 49S | 33E | 3,6 |
| UPPER REWA SANDSTONE | UR | Pr/Є | 35S | 42E | 10,16 |
| UPPER BHANDER SANDSTONE | UB | Pr/Є | 32S | 19E | 3,6 |
| Purple Sandstone[5] | PS | Єl | 28S | 32E | 11 |
| Salt Pseudomorph Beds[5] | SP | Єm | 27S | 33E | 5 |
| SOUTH AMERICA[7] | | | | | |
| Purmamarca Village | PV | Є | 61N | 293E | 26 |
| South Tilcara | ST | Є | 52N | 27E | 23 |
| North Tilcara | NT | Є | 49N | 24E | 23 |
| Purmamarca | P | Є | 5N | 39E | 14 |
| Abra de Cajas | AC | Є | 2N | 28E | 50 |
| Salta and Jujuy | SJ | Є-O | 12N | 329E | — |
| Salta | S | O | 31N | 13E | 40 |
| Sediments, Bolivia | SB | O | 4N | 302E | 16 |
| Urucum Formation | UF | O-S | 17N | 347E | — |

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[1] An attempt has been made in this Table and Tables 7.2 and 7.3 to identify poles which may be considered key poles (see Chapter 6, Section 6.1.3). Apparent polar wandering is defined in the first instance in terms of the key poles. The remainder are used in a supporting capacity. All poles are based on cleaned remanence unless otherwise indicated. Key poles are shown in upper case type.

[2] Age Symbols: Pr = Precambrian; Є = Cambrian; O = Ordovician; S = Silurian; D = Devonian. Lower, Middle and Upper divisions denoted by l, m and u respectively.

[3] References: Africa (McElhinny *et al*, 1968; McElhinny, 1973; Piper, 1973b; Piper *et al*, 1973); Antarctica (McElhinny, 1973); Australia (this thesis; McElhinny and Embleton, 1974; Embleton and Giddings, 1974); India (Athavale *et al*, 1972; Wensink, 1972; McElhinny, 1973; Klootwijk, 1973); South America (McElhinny, 1973; Thompson, 1973).

[4] Only the pole position from an unpublished study is available. Until such time as more details of the study are published, the conservative view is taken here and the pole is not regarded as a key pole.

[5] See text for explanation of status.

[6] Circle of confidence refers to the formation-mean direction of magnetization.

[7] Ages of the South American poles are uncertain.

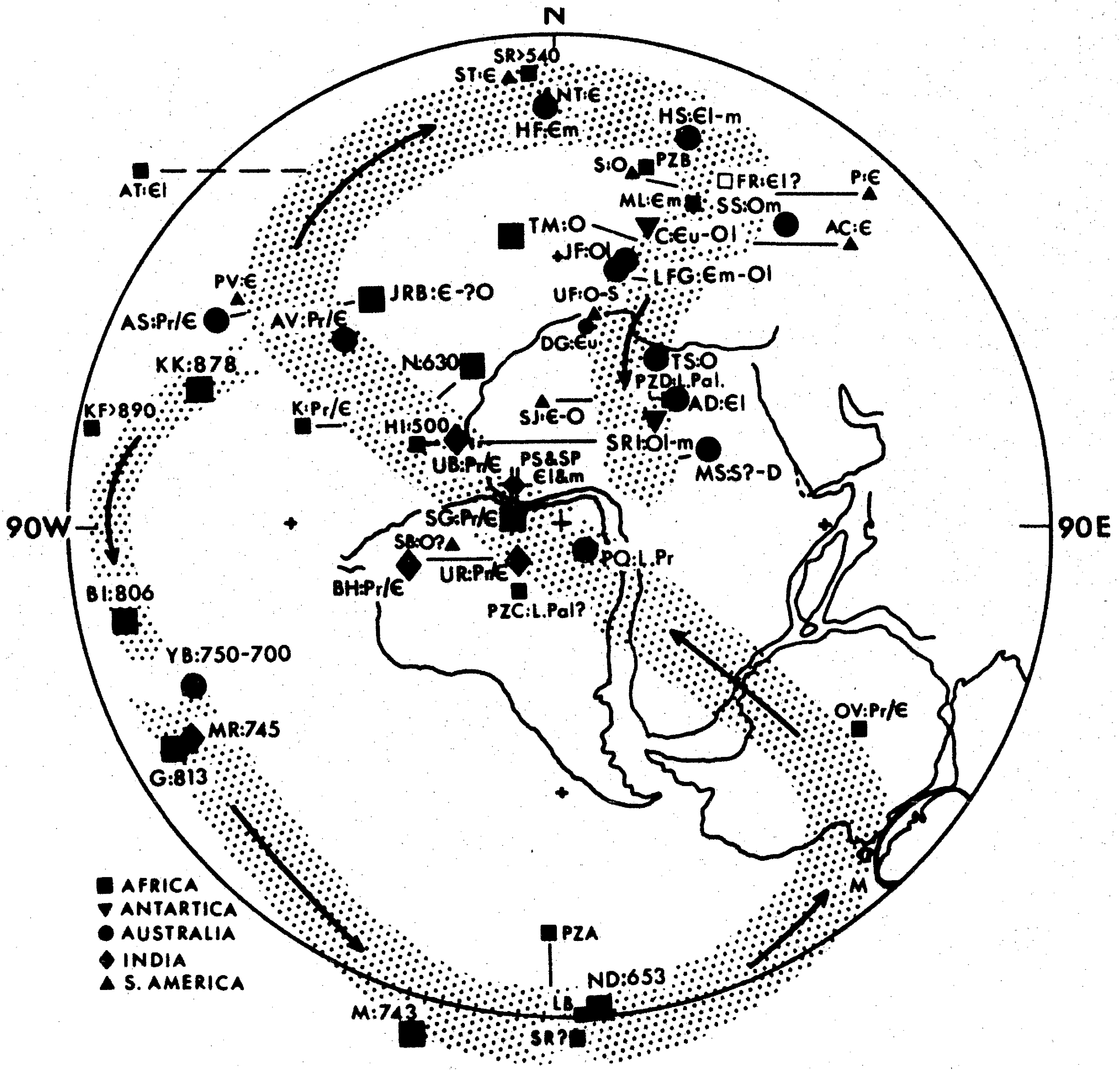

FIGURE 7.2 The late Precambrian-Early Palaeozoic (< c900 My - 450 My) apparent polar wander path for Gondwanaland using all the Gondwanic poles listed in Table 7.1. Large symbols refer to key poles. Bearing in mind the uncertainties in some of the ages and errors associated with the pole positions, all poles younger than about 800 My - 750 My are consistent with a common polar wander path when referred to the Smith and Hallam (1970) reconstruction of Gondwanaland. The path is indicated by the broad band drawn through the poles. Before 800 My - 750 My the sequence of poles is as yet only defined by African data indicated by the narrower band going back to about 900 My. The circle over southeastern Australia, denoted by M, refers to the pole locus obtained by Briden (1964, 1967a) from studies of magnetic inclination in borecore material from the Wilkatana No.1 borecore located near Port Augusta, South Australia. The sediments penetrated were probably deposited at about the time of the late Precambrian Marinoan Glaciation in Australia (see Chapter 6, Section 6.1.3).

reconstruction proposed by Thompson (1972) is thus not necessary in order to achieve consistency between Australian and South American Cambrian data (Thompson, 1973). African poles younger than about 700 My, but pre-Ordovician have poor age control, with the single exception of the 630 ± 24 My Nyonya Ring Structure of Malawi. These poles have been incorporated into the combined path by minor rearrangement of their sequence without violating the tolerances on their age control. Significantly, this places the Ntonya pole at a point on the path just before the Precambrian-Cambrian boundary, whereas in the African path proposed by Piper *et al* (1973), it was out of sequence and implied to have a much younger age.

Latest Precambrian poles tend to cluster in the region west or south of northwest Africa. The pole from the Cambro-Ordovician Hook Intrusives of Zambia is in this group but its circle of confidence is large enough for it to be associated with the later part of the curve in the region of the Sahara. The two Cambrian poles from the Salt Range, Pakistan are also out of sequence. However, it has recently been proposed (Crawford, 1974) that the Salt Range originally lay along the trend of the main Himalayan arc. As a result of late-stage tectonic activity associated with the collision of India against Asia, the Salt Range has undergone an anticlockwise rotation of about 75° into its present, approximately east-west, position. If that rotation is taken into account, the two poles lie on the combined path in correct chronostratigraphic position. The pole for the Bolivian sediments of supposed Ordovician age falls in a region which suggests that those sediments may be rather older than supposed. Likewise, the position of the pole from some Jordanian redbeds suggests that they are of earliest Cambrian age rather than Cambro-Ordovician.

Although agreement of the Early Cambrian pole of the Moroccan Amouslek Tuffs with the Early Cambrian path segment is not good the overall trend of the three Moroccan poles — Ouarzazate Volcanics, Amouslek Tuffs and Moroccan Lavas — is consistent with Australian, South American and other African data of similar age. The question of Morocco's affinity, whether with North America (Hailwood and Tarling, 1973) or with Africa (Wilson, 1966) cannot yet be resolved unambiguously although the data available are consistent with its Gondwanaland location.

The pole from the Fish River Series of South West Africa appears to occupy an anomalous position near the Middle Cambrian section of the combined path. The Series forms the uppermost member of the Nama Group, the exact age of which is still controversial (Germs, 1972). The Group has a firm minimum age of 550 My (Allsopp *et al*, 1974). The lower members of the Group contain fossils considered to be representatives of the *Ediacara* fauna found in the Pound Quartzite of South Australia (Chapter 5, Section 5.2). The upper members could be Early Cambrian (Germs, 1972), but the absence of Cambrian fossils led Truswell (1970, p. 92) to conclude that '...on balance, the fossil evidence would seem to suggest a late Precambrian rather than a Cambrian age for the Nama'. It is noted that those sediments were magnetically cleaned (the ability of the AF technique, to remove secondary magnetization in some sediments, is considered questionable). Of the nine sites studied, Piper (1973b) felt that the best record of the primary magnetization of the sediments was from three sites which showed a marked increase in precision after cleaning. However, the pole quoted by Piper and plotted in Fig. 7.2 was based on results from the nine sites. A mean pole is calculated here based on results from the three 'best' sites. The pole (324°E 2°S, $A_{95} = 22°$) is in reasonable agreement with other latest Precambrian poles which fall off the coast of West Africa, in particular with the pole of the Klipheuval Formation of Cape Province, South Africa, which is possibly equivalent to the Nama

Group (Truswell, 1970). The result does not conflict with the age of the Fish River Series as currently known. The pole listed in Table 7.1, quoted by Piper (1973b), appears to be based on magnetic remanence in which components of secondary magnetization have not been completely removed, probably as a consequence of only applying magnetic cleaning.

The apparent polar wander path is extended into the Precambrian from the latest Precambrian group of poles so that it roughly follows the loop proposed in Chapter 6, Section 6.1.3. The loop for Gondwanaland is defined by the Pound Quartzite, the YB group of dykes and the Marinoan Series for Australia; the Ouarzazate Volcanics, the pre-Nama Dykes, the Mbozi Complex and Gagwe Lavas for Africa and the Malani Rhyolites for India. The extension of the path beyond the Mbozi Complex pole therefore continues to represent the locus of the south pole. This interpretation differs significantly from that of Piper *et al* (1973) who regard the path segment beyond the Mbozi Complex pole (700 My and older) as the locus of the north pole (their Fig. 4). The 745 My pole for the Malani Rhyolites of India plots close to the 750 - 700 My Australian pole for the YB group of dykes. Those poles lie on the curve defined for Africa (Piper *et al*, 1973) near to poles dated at around 800 My. The consistency of these results for the Smith and Hallam (1970) reconstruction suggests that a single pole path can be defined extending at least to 750 My.

### 7.2.2 The Late Precambrian Glaciations

The occurrence of glacial deposits (tillites) in many late Precambrian formations throughout the world has led to the hypothesis that a widespread glaciation occurred just before Cambrian times (Harland and Rudwick, 1964; Harland, 1964, 1965). An essential point relating to this hypothesis is whether these glaciations occurred successively with polar migration or whether they occurred simultaneously and therefore perhaps extended to low latitudes. The interpretation of the late Precambrian to Early Palaeozoic apparent polar wander path for Africa is crucial in this context because many of the late Precambrian glacial deposits are located in that continent. The pole path deduced by Piper *et al* (1973) and Piper (1973a) implies that the glaciated regions occupied essentially low latitudes and that the glaciation was therefore widespread. The interpretation of the late Precambrian to Early Palaeozoic path presented leads however, to the conclusion that the pole migrated across Gondwanaland in a northwesterly direction during the late Precambrian, from a point just off southern Australia. This is consistent with the observed overall trend in age of glacial deposits which tend to become younger northwards towards northwest Africa.

In South West Africa correlations between the various tillite horizons suggest that there were two distinct periods of glaciation in late Precambrian time (Kröner, 1971; Kröner and Rankama, 1973). The Nama and Damara Groups are considered to be similar in age with the Nama Group possibly being a platform facies of the geosynclinal Damara Group (Martin, 1965; Kröner and Rankama, 1973). In the Nama Group evidence of widespread glaciation occurs in the Lower Schwarzrand member which overlies the basal Kuibis Series both of which contain *Ediacara* fauna (Germs, 1972) and therefore are between 700 My - 600 My old (Glaessner, 1971). In the Damara Group there are the Chuos and Otavi tillites which are correlated with the Lower Schwarzrand tillites (Kröner and Rankama, 1973). The Nama Group unconformably overlies tillites of the Blaubecker and Buschmannsklippe Formations which are correlated and placed in the Nosib Group (Kröner, 1971). Those two tillites are correlated with the Numees tillite of the upper part of the Gariep Group (Kröner and Rankama, 1973). Acid volcanics of the Kapok Formation forming the lower part of the Gariep Group have been dated at 719 ± 28 My (Allsopp *et al*, 1974). These pre-Nama tillites are therefore likely to be younger than 700 My.

Evidence for late Precambrian tillites in central Africa is widespread (Haughton, 1961). Two tillite horizons are present in the Katangan (Cahen, 1970) and West Congolian (Cahen and Lepersonne, 1967) Systems and tillites have been found in correlatives of these Systems. Both Systems have a minimum age of about 620 My and are generally correlated on lithological grounds (Cahen and Lepersonne, 1967). In the Katangan System, the Petit Conglomérat appears to have an age of 710 My - 670 My based on lead ages of mineralization associated with orogenic activity. The stratigraphically lower Grand Conglomérat could be older than 840 My but has a maximum age of c950 My (Cahen, 1970). Lead mineralization in the West Congolian System suggests that its two tillites are older than about 740 My (Cahen and Lepersonne, 1967). Sediments of glaciogenic origin are also found in the late Precambrian Sijarira group of Rhodesia (Kröner and Rankama, 1973) and Bunyoro Series of Uganda (Bjørlykke, 1973). In the Saharan region of north and west Africa widespread 'Eocambrian' tillites have an age of about 650 My - 620 My (Biju-Duval and Gariel, 1969; Trompette, 1972).

In Australia, Dunn *et al* (1971) have reviewed the widespread occurrences of tillites belonging to two distinct stratigraphic horizons. The older Sturtian Glaciation has a minimum age of 739 ± 30 My and the younger Marinoan Glaciation a minimum age of 653 ± 48 My (Bofinger, 1967). Evidence of late Precambrian glaciation in India and South America is not so well documented. For India, the deposits listed by Harland (1964) as being of glacial origin, belong mainly to the Lower Vindhyan System. Recent work has shown that not only are the Lower Vindhyans considerably older than late Precambrian, having an age of about 1400 My - 1200 My (Crawford and Compston, 1970), but that the deposits are unlikely to be of glacial origin (Bhattacharjee, 1972).

However, recent work in the Hazara area of Pakistan (Latif, 1972), near the Salt Range, indicates that a tillite (Tanakki Boulder Bed) originally correlated with tillites of Upper Palaeozoic age is now of late Precambrian age (Rushton, 1973). The glacial Blaini Boulder Bed is therefore also likely to be of late Precambrian age (Latif, 1972). In South America a number of instances of deposits suggesting glacial conditions have been reported from Brazil (Kröner and Rankama, 1973). Re-examination of the Lavras and Iapó tillites however, indicates that they are not of glacial origin, but the tillites of the Jequitaí Formation (Isotta *et al*, 1969) and the Puga beds do appear to be genuine. A shale from the Bambuí Formation, which overlies the Jequitaí Formation gives an isochron indicating an age of 600 ± 25 My (Isotta *et al*, 1969).

In general, therefore, most of the tillites fall in the approximate range 700 My - 600 My, the tillites in northern Gondwanaland being younger than those in southern and southeastern Gondwanaland. This age trend strongly suggests that the centre of glaciation followed the path of the pole during the late Precambrian as it swept in a northwesterly direction across Gondwanaland, starting from Australia at around 700 My and reaching northwest Africa at about 620 My (Fig. 7.3). This model is consistent with preliminary palaeomagnetic measurements on the Numees Formation of South West Africa (Reid and Kröner, 1974) which show that its sediments and tillite were deposited at high palaeolatitudes. It is also significant that the best dated African late Precambrian pole, the 630 ± 24 My Ntonya result, plots just off northwest Africa (Fig. 7.2) corresponding to the time when this region was extensively glaciated.

The inconsistency of the ages of some of the tillites from Central Africa with the model of apparent polar wander proposed may be more apparent than real. Their ages are by no means well-established and it might be that the tillites refer to an earlier period of polar

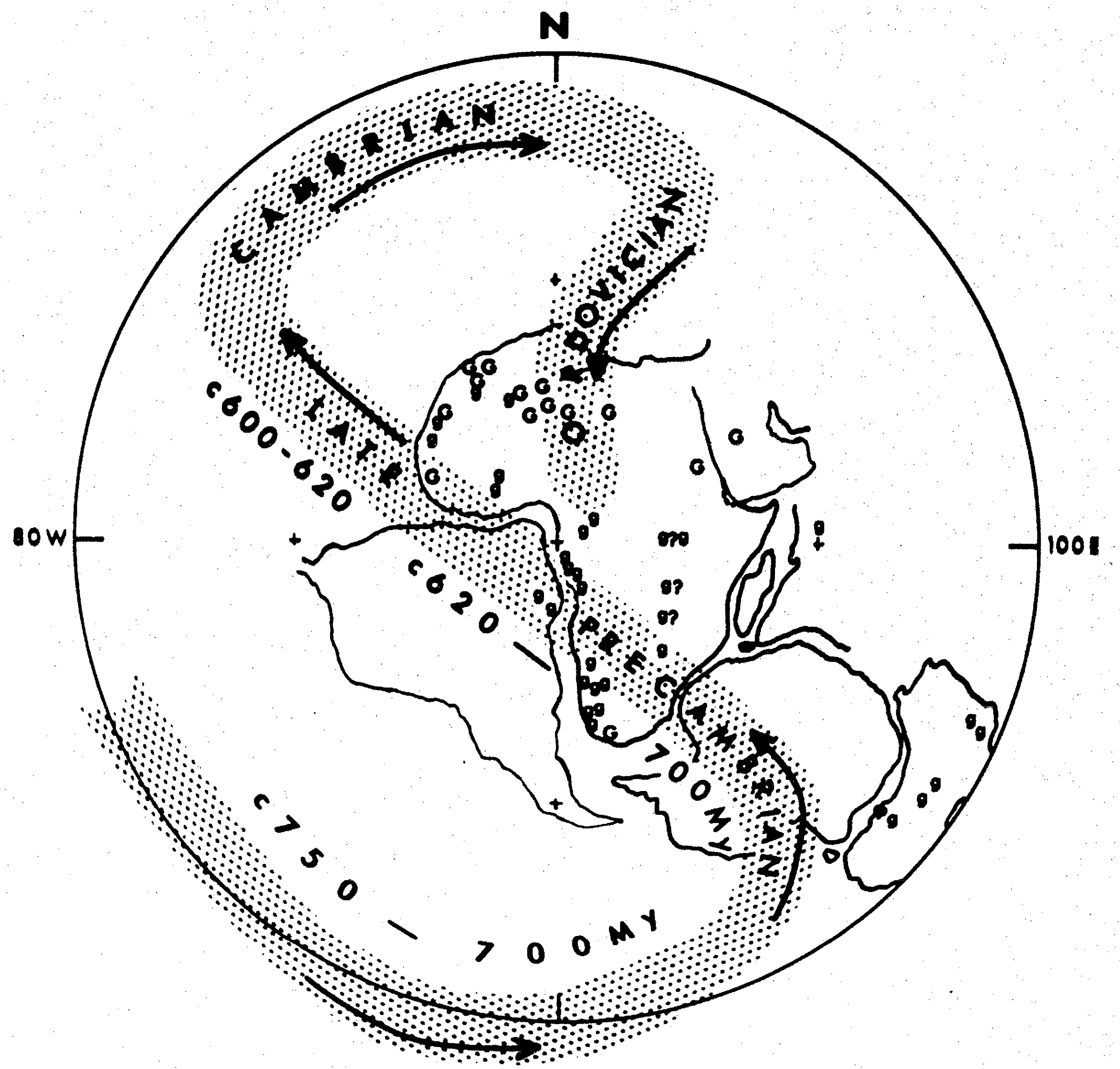

FIGURE 7.3 The late Precambrian-Early Palaeozoic apparent polar wander path for Gondwanaland compared with the distribution of glacial tillites of Ordovician and late Precambrian age (denoted by G and g respectively). Glacial deposits in Africa older than about 700 My and therefore not related to the drawn path have question marks. The overall trend in age of the late Precambrian glacials (those in northern Gondwanaland being younger than those in southern and southeastern Gondwanaland) is matched by the northwesterly migration of the pole.

migration across the region. In Australia, the age of the older period of glaciation is better documented. The model provides an explanation for the presence of the younger glaciation. The older glaciation, however, appears to be associated with an older part of the apparent polar wander curve, viz. the approach of the pole to northern Australia (antipole sequence) suggested by the path segment between the group of poles comprising the Gagwe Lavas, Malani Rhyolites and the YB group of dykes, and the poles of the Kigonero Flags and the Klein Karas dykes. These latter two poles are shown in Section 7.3 to lie on a path segment which, from data currently available, can be considered common to Gondwanaland. However, it is noted that the age of the older glaciation indicated by this interpretation is somewhat older than the radiometric age quoted, but Bofinger (1967) points out that shale isochrons define only minimum ages, and that actual depositional ages are likely to be older.

During the Cambrian, the broad trends of climatic change are perceptible (King, 1961). In North Africa the occurrence of thick successions of Lower Cambrian warm water deposits includes *Archaeocyathid* reefs. Cambrian rocks are frequently brightly coloured, indicating a warm climate, but give way to more drab Ordovician sequences which culminate in the Late Ordovician, Saharan glaciation (Beuf *et al*, 1966; Dow *et al*, 1971; Tucker and Reid, 1973) extending from the coast of west Africa to Ethiopia and Saudi Arabia. These broad trends are not only compatible with the Cambrian and Ordovician sections of the combined path but resolve a previously puzzling palaeoclimatic anomaly (Hailwood and Tarling, 1973), viz. the occurrence of warm climate deposits at a time when North Africa appeared to remain in high latitudes from the late Precambrian to the late Ordovician (based on the assumption that poles for this period of time formed a loose group off the coast of northwest Africa — Briden, 1967c). From near polar conditions in northwest Africa for the latest Precambrian, the broad loop taken by the pole during the Cambrian placed North Africa in low latitudes, with a return to intermediate and finally polar latitudes during the Ordovician.

A model is presented therefore describing a drift history for Gondwanaland during the late Precambrian and Early Palaeozoic which is consistent with the palaeoclimatic evidence available. The model suggests that it is unnecessary to invoke the hypothesis of a synchronous world-wide glaciation that extended to low latitudes to explain the ubiquitous occurrence of late Precambrian tillites in Gondwanaland. Rather, evidence presented supports the view that records of glaciated regions were left in the various continents by a migrating polar region (see also Crawford and Daily, 1971). The decisive test between the two hypotheses, of course, will come from palaeomagnetic measurements on the actual glacial horizons in various places of the world.

## 7.3 GONDWANIC PALAEOMAGNETISM FOR THE OLDER PRECAMBRIAN (2700 - c900 My)

### 7.3.1 A Model of Apparent Polar Wandering

From studies of the nature and patterns of orogenic belts formed from the early Archaean to the Recent, Engel and Kelm (1972) suggested '...that global tectonics between 2500 My and 700 My did not involve the large scale rifting, dispersion, re-orientation and reagglomeration of the progressively fractionating and thickening continental clusters that is typical of the post-Permian. Rather Archaean tectonics [which appear to involve dispersionary-accretionary processes] culminated in the evolution of one or two proto-continents [of which proto-Gondwanaland was one] some 2500 My ago'. The existence of such a proto-Gondwanaland in the early Precambrian is also supported by the geochronological studies of Hurley and Rand (1969), the distribution of unusual rock types (Herz, 1969) and arguments favouring an ensialic origin for the various Proterozoic and older mobile belts surrounding the cratonic nucleii of the Gondwanic continents (Shackleton, 1969, 1973; Clifford, 1970; Hurley, 1972; Piper *et al*, 1973).

Palaeomagnetic data provide the only means of assessing quantitatively the reality of a proto-Gondwanaland in the early Precambrian. It is the purpose of this section to review Gondwanic palaeomagnetic data for the period 2700 My - 900 My in the light of the new Australian results to determine whether the data are consistent with a common apparent polar wander path for Gondwanaland and if so how far back into the Precambrian this may be applicable. Palaeomagnetic data from Africa and South America (Piper *et al*, 1973) have already been interpreted to suggest that the two continents were joined in their pre-Mesozoic drift positions (Bullard *et al*, 1965) as early as 2000 My ago.

Africa still remains the only Gondwanic continent for which palaeomagnetic data are available that provide a reasonably comprehensive coverage for the time span between 900 My and 2700 My, the age of the oldest Gondwanic rocks which have yielded palaeomagnetic results. Since the review of African Precambrian data by McElhinny *et al* (1968), in which results related mainly to the Rhodesia-Transvaal craton, much new data has been obtained from South West Africa, East Africa, West Africa and North Africa. Recent reviews of the African data now available (Piper, 1973c; Piper *et al*, 1973) permit the conclusion that Africa has retained its gross structural integrity since at least 2200 My. The oldest section (2700 My - 2300 My) of the African apparent polar wander curve (Piper, 1973c) is the same as that defined by McElhinny *et al* (1968) and refers only to the Rhodesia-Transvaal craton. Absence of data of this age from other cratonic regions makes it uncertain whether this curve segment is applicable to the whole of Africa. The only other ill-defined section of the African curve covers the time span between the poles of the Mashonaland Dolerites (1850 ± 20 My) and the Pilanesberg Dykes (1310 ± 60 My). Within this interval, of at least 400 My duration, only one pole is available and the shape of the path segment connecting the two poles remains uncertain.

Compared with the African and Australian data coverage, results from the other Gondwanic continents must be considered sparse. Only four poles are available from South America (Hargraves, 1968; Veldkamp *et al*, 1971), concentrated in the time interval of 1750 My - 1500 My, and only one pole from Antarctica (Embleton and Arriens, 1973) whose age is about 1400 My (Arriens, pers. comm., 1974). Indian results, recently reviewed by Bhimasankaram and Pal (1970), Pal (1974) and Klootwijk (1974), generally suffer from poor age control and so do not permit delineation of a meaningful apparent polar wander curve. (One Indian pole not considered in the present analysis is that for the Mundwara Complex which has generally been accorded an age of about 900 My from its association with the similar aged Erinpura Granite (Crawford, 1969). Recent fission track dating of the Complex by Subrahmanyan *et al* (1972) has established its age at 56 ± 8 My). For Australia, the new data presented in this thesis, in conjunction with published results, have enabled delineation of a path segment between 1800 My and 1300 My with some confidence. However, between 2400 My and 1800 My and 1300 My and 750 My data is poor.

Because of the paucity of Precambrian palaeomagnetic data, intercontinental comparison cannot be effected by comparing the shapes of the apparent polar wander paths for the individual Gondwanic continents since, with the exception of Africa and Australia, the curves are poorly defined or non-existent. Until such time as more data is available a rather different approach is required. In the approach adopted here, a model of apparent polar wandering is proposed based on comparing the curves for Africa and Australia. It will be shown that the pole positions can be plotted such that they define a common polar wander curve from about 1800 My. The best defined portion of the Australian curve (1800 My - 1300 My) corresponds in time to the least well-defined section of the African curve (between the Mashonaland Dolerites pole at 1850 ± 20 My and the Pilanesberg Dykes pole at 1310 ± 60 My). Therefore, this section of the Australian path has been grafted onto the African path to define the master curve which is initially assumed to be applicable to Gondwanaland. Other Gondwanic palaeomagnetic data are then compared with the master curve. Consistency of that data with the model would favour the conclusion that the master curve represents a common apparent polar wander path for Gondwanaland. The base map of Gondwanaland used was the reconstruction of Smith and Hallam (1970), which appears valid back to at least 750 My (Section 7.2.1).

The African apparent polar wander curve used was that of Piper *et al* (1973). The data defining this curve are listed in Table 7.2, and were taken from the reviews of Piper (1972, 1973c) and Piper *et al* (1973). The Australian data are listed in Tables 6.2, 6.3 and 6.4 of the previous chapter and South American, Indian and Antarctic data given in Table 7.3.

The modification to the African base curve resulting from the introduction of the 1800 My - 1300 My Australian path segment is shown in Figs. 7.4 and 7.5. It essentially involves an eastward loop between the African poles of the Mashonaland Dolerites and Pilanesberg Dykes (Fig. 7.4) and a southward loop between the latter pole and the poorly dated poles of the O'okiep Intrusives and the Kisii lavas (Fig. 7.5), neither of which loops involve major modifications to the African base curve. At the younger end of the grafted Australian path segment (Fig.

TABLE 7.2[1]

Precambrian palaeomagnetic data for Africa (> c900 My)

| Rock Unit | Symbol | Age (My) | Pole Coords.[2] | | A or |
|---|---|---|---|---|---|
| | | | Lat.° | Long.° | dp,dm |
| MODIPE GABBRO | MG | 2670 ± 470 | 33N | 211E | 11 |
| GREAT DYKE | GD | 2530 ± 30 | 22S | 242E | 9 |
| GABERONES GRANITE | GG | 2340 ± 50 | 35S | 284E | 16 |
| Lower Ventersdorp Lavas[3,4] | LVL | c2300 | 4S | 40E | — |
| Upper Ventersdorp Lavas[4] | UVL | 2300 ± 100 | 71S | 353E | — |
| VENTERSDORP LAVAS | VL | 2300 | 55S | 355E | 22 |
| Transvaal System Lavas[4] | TS | c2250 | 42S | 14E | — |
| TARKWAIAN INTRUSIONS | TI | c2200 | 53S | 36E | 9 |
| Obuasi Greenstone Body[5] | OG | 2200 | 50S | 102E | 15 |
| Obuasi Dolerite Dyke | OD | <2200 | 56S | 68E | 9 |
| Angola Anorthosite[4] | AA | 2600 - 1300 | 9S | 69E | — |
| Orange River Lavas[4] | OR | >1850 | 19S | 74E | — |
| Aftout Gabbro[4] | AG | 1950 | 29N | 55E | — |
| VREDEFORT RING COMPLEX | VRC | 1970 | 22N | 27E | 12 |
| BUSHVELD GABBRO (NRM)[6] | BG | 1950 ± 50 | 23N | 36E | 12 |
| Losberg Intrusion | LI | c1950 | 33N | 36E | (9)[7] |
| Waterberg System Sediments | W1 | 1950 - 1750 | 36N | 48E | 15,24 |
| Waterberg System Sediments | W2 | 1950 - 1750 | 8N | 10E | — |
| Waterberg System Sediments | W3 | 1950 - 1750 | 3N | 333E | 14,21 |
| Waterberg System Sediments | W4 | 1950 - 1750 | 41N | 33E | — |
| Waterberg System Sediments | W5 | 1950 - 1750[8] | 67N | 44E | — |
| MASHONALAND DOLERITES | MD | 1850 ± 20[9] | 7N | 340E | 8 |
| Ivory Coast Dolerite Intrusion | ICD | 1740 ± 170 | 11S | 102E | 9 |
| Van Dyke Mine Dolerite | VDD | 1620 ± 25[9] | 13N | 14E | 8 |
| PILANESBERG DYKES | PD | 1310 ± 60 | 8N | 43E | 11 |
| Kisii Lavas | KL | > 930 | 6N | 348E | 15 |
| O'okiep Intrusions | OI | >1040 | 15N | 335E | 15 |
| PREMIER MINE KIMBERLITE | PM | 1250 ± 50[9] | 51N | 38E | 8 |
| UMKONDO LAVAS | UL | } 1100 ± 20[9] | 62N | 15E | 12 |
| UMKONDO DOLERITES | UD | | 66N | 40E | 7 |
| WATERBERG DOLERITES | WD | 1100 ± 10[9] | 66N | 51E | 5 |
| Sinclair Lavas | SL | 1200 - 1020±80 | 68N | 28E | 14 |
| Guperas Lavas | GL | <SL,> Latest Pr | 63N | 317E | 3 |
| Auborus Formation (NRM) | A | <GL,> Latest Pr | 43N | 354E | 11 |
| Bukoba Sandstone | BS | >c1000 | 40N | 317E | 17 |

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[1] See footnote 1, Table 7.1.

[2] References: McElhinny *et al* (1968); Piper (1973b,c); Piper *et al* (1973).

[3] Magnetization may date from metasomatism at 2150 My (Piper *et al*, 1973).

[4] See footnote 4, Table 7.1.

[5] Magnetization may date from metasomatism at 2200 My (Piper *et al*, 1973).

[6] McElhinny *et al* (1968, p. 225) state that '...the increase in precision on correcting for pseudostratification observed in the gabbro is significant at the 95% confidence level (McElhinny, 1964)'.

[7] Circle of confidence refers to the formation mean direction of magnetization.

[8] May have been remagnetized by an overlying sill of the Waterberg dolerites. Magnetization may therefore date from 1100 ± 10 My (Briden and McElhinny, in preparation).

[9] New age information reported in Briden and McElhinny, in preparation.

## TABLE 7.3[1]

### Precambrian palaeomagnetic data for Antarctica, India and South America (> c900 My)

| Rock Unit | Symbol | Age (My) | Pole Coords.[2] |  | A or dp,dm |
|---|---|---|---|---|---|
|  |  |  | Lat.° | Long.° |  |
| ANTARCTICA |  |  |  |  |  |
| VESTFOLD HILLS DYKES | VHD | c1400 | 17S | 13E | (11)[3] |
| INDIA |  |  |  |  |  |
| Gawlior Traps | GT | 1830 ± 200 | 19N | 156E | 3,6 |
| Hyderabad Dyke | HD | c1750 | 43S | 8E | 3,5 |
| Visakhapatnam Charnockites | VC1 | ?1800 - 1650 | 9S | 185E | — |
| Visakhapatnam Charnockites | VC2 | ?1800 - 1650 | 48N | 152E | — |
| Banded Haematite Jasper,<br>Banded Haematite Quartzite | BJQ | ?>1400 | 7S | 162E | — |
| Diamond Pipes (i) Lattavaram[4] | DPL | ?1340 | 46S | 105E | (4)[3] |
| Diamond Pipes (ii) Wajrakarur[4] | DPW | ?1340 | 18S | 186E | (11)[3] |
| Cuddapah Sandstones[4] | CS | 1400 - 1300 | 23S | 157E | — |
| Ongole Magnetite Quartzites[4] | MQ1 | 1350 - 1160 | 2S | 328E | — |
| Ongole Magnetite Quartzites[4] | MQ2 | 1350 - 1160 | 73S | 113E | — |
| Ongole Magnetite Quartzites[4] | MQ3 | 1350 - 1160 | 59N | 287E | — |
| Ongole Magnetite Quartzites[4] | MQ4 | 1350 - 1160 | 61N | 260E | — |
| Veldurthi Haematites | VH1 | ?1200 - 900 | 45S | 182E | (14)[3] |
| Veldurthi Haematites[4] | VH2 | ?1200 - 900 | 71S | 41E | (10)[3] |
| Veldurthi Haematites[4] | VH3 | ?1200 - 900 | 70S | 188E | (21)[3] |
| Veldurthi Haematites[4] | VH4 | ?1200 - 900 | 43N | 316E | (17)[3] |
| Chitloor Dyke[4] | CD | ?1200 - 1100 | 21S | 148E | (5)[3] |
| KAIMUR SANDSTONES | KS | 1140 ± 12 | 82S | 106E | 4,7 |
| SOUTH AMERICA |  |  |  |  |  |
| RORAIMA DOLERITES I | RD1 | 1700 - 1500 | 63S | 51E | 9 |
| RORAIMA DOLERITES II | RD2 | 1700 - 1500 | 45S | 347E | 10 |
| Kabalebo Dolerites | KBD | 1750 | 44S | 30E | — |
| Blakawatra Dolerites | BD | 1650 - 1550 | 8S | 53E | — |

[1] See footnote 1, Table 7.1.

[2] References: Antarctica (Embleton and Arriens, 1973); India (Bhimansankaram and Pal, 1970; Klootwijk, 1974; Pal, 1974); South America (Hargraves, 1968; Veldkamp *et al*, 1971).

[3] Circle of confidence refers to the formation mean direction of magnetization.

[4] See footnote 4, Table 7.1.

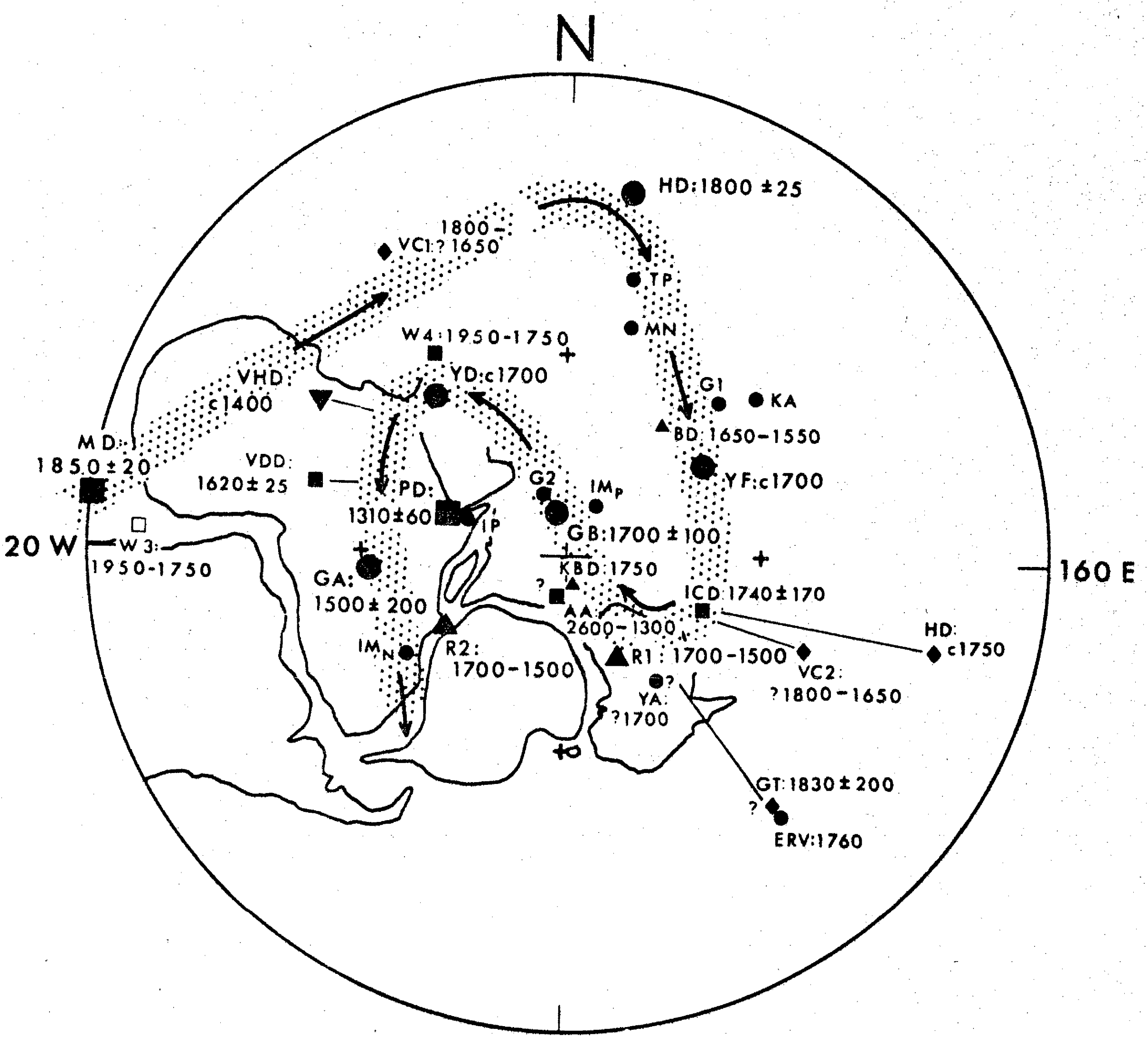

FIGURE 7.4 The model apparent polar wander curve for Gondwanaland for the interval c1800 My - c1400 My showing the 'eastward' loop between the African poles for the Mashonaland dolerites (MD) and Pilanesberg dykes (PD). The break in the curve between the African MD pole and the Australian HD pole indicates uncertainty in whether the older section of the curve, based on African data alone, is applicable to the rest of Gondwanaland. Large symbols denote key poles. Palaeomagnetic data are listed in Tables 6.2, 6.3, 6.4, 7.2 and 7.3. The reconstruction is that of Smith and Hallam (1970) with Africa in its present day position. Question marks against poles indicate that those poles may belong to older parts of the curve. Ages shown are in My.

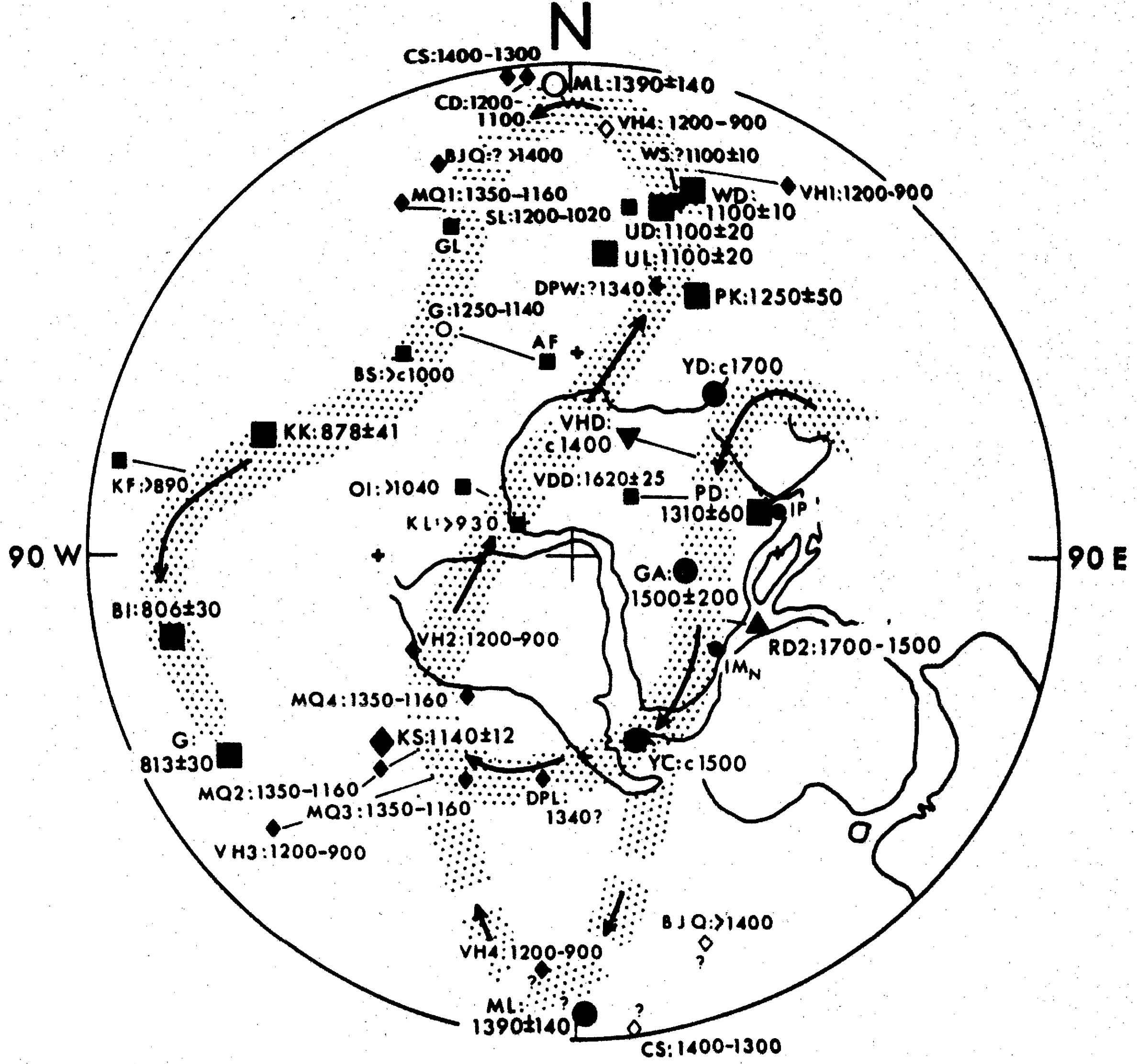

FIGURE 7.5 The model apparent polar wander curve for Gondwanaland for the interval c1400 My - c800 My showing the 'southward' loop between the African poles for the Pilanesberg dykes and the Kisii lavas and O'okiep intrusives. The dashed curve represents the deeper, but less preferred, 'southward' loop (see text). Key poles are denoted by large symbols. Palaeomagnetic data are listed in Tables 6.2, 6.3, 6.4, 7.2 and 7.3. The reconstruction is that of Smith and Hallam (1970) with Africa in its present day position.

7.4), the GA pole at 1500 ± 200 My is in good agreement with the similar aged African Pilanesberg Dykes pole and the Vestfold Hills Dykes pole of Antarctica. The African Ivory Coast Dolerite pole at 1740 ± 170 My lies on the eastern loop (Fig. 7.4) in the correct chronological position. On the apparent polar wander curve defined for Africa on the basis of African data alone (Piper *et al*, 1973), this pole occupied an apparently anomalous position adjacent to the 2200 - 2000 My section of the curve (Fig. 7.6b). The presence of the eastern loop removes this anomaly. The pole for the African Angola Anorthosite is not well dated (2600 - 1300 My). Although it could lie on the 2200 My - 2000 My (Fig. 7.6b) section just mentioned and as suggested by Piper *et al* (1973), it is also observed to lie on the eastern loop in a position that would indicate it to have an age of 1750 My - 1700 My.

The presence of both loops is supported by both South American and Indian data. The consistency of the South American data with the loops is particularly compelling (Fig. 7.4). There has been considerable controversy over the age of the dolerites of the South American Roraima Intrusive Suite (McDougall, 1968; Snelling and McConnell, 1969) from which Hargraves (1968) obtained two poles, denoted by R(I) and R(II) in Fig. 7.4. The Roraima dolerites intrude the Roraima Formation. K-Ar ages for the Roraima dolerites, ranging from 1500 My - 2100 My, have been found by three independent studies (McDougall *et al*, 1963; Priem *et al*, 1968; McDougall, 1968), although the majority of data points fall in range of 1500 My - 1800 My. Making allowance for isotopic disturbance, McDougall *et al* (1963) favoured a minimum age for some of the dolerites of about 2100 My. By eliminating some samples from those for which Rb and Sr ratios were available, an isochron was obtained which was consistent with this age. The study of McDougall (1968) enabled the confident assertion that the dolerites were older than about 1500 My, but a single value of 2070 My obtained from one of 14 new K-Ar age determinations on plagioclases and pyroxenes was suggested to support the older age of about 2100 My. Priem *et al* (1968) and Snelling and McConnell (1969) however, believe such an old age to be anomalous and prefer a younger age(s). As McDougall (1968) pointed out the '...question as to the age or ages of emplacement of the dolerites will only be resolved by detailed and precise Rb-Sr whole rock measurements on many samples. An older limit to their age would be provided by Rb-Sr isochron studies on basement rocks'. Rb-Sr data are now available from the basement underlying the Roraima Formation (Priem *et al,* 1971) and from intercalated pyroclastic volcanic rocks within the Formation (Priem *et al,* 1973), possibly within the Middle member. The basement gives an age of 1910 ± 40 My (allowing for a decay constant of $1.39 \times 10^{-11}$ per yr instead of the $1.47 \times 10^{-11}$ per yr employed) while the volcanics give 1692 ± 18 My. Snelling and McConnell (1969) have argued that in the interpretation of the Rb-Sr data from the Roraima dolerites given by McDougall *et al* (1963), it was unjustifiable to exclude any of the data points because of the few points available. Accordingly equal weight was assigned to all that data by Snelling and McConnell and an isochron for the Roraima dolerites was obtained indicating a 'best estimate' age of 1695 ± 66 My — 'best estimate' because of the possibility (substantiated by the palaeomagnetic results) that the dolerites may be of more than one age. This isochron age is consistent with the latest data concerning the maximum possible age of the dolerites. By combining the minimum K-Ar ages with the Rb-Sr data, it is concluded that the Roraima dolerites are between 1700 My to 1500 My old.

In their review of African and South American data, Piper *et al* (1973) assumed an age of 2070 My for the two Roraima poles and associated them and the Kabalebo dolerites pole with the 2200 - 1950 My section of the African curve (Fig. 7.6b). The Kabalebo dolerites pole, although lying on this path segment, was chronologically out of sequence unless its age was assumed too young by at least 250 My. The Blakawatra dykes pole could not be accommodated to their path at all. Because of the consistency of the South American data with present interpretation, the conclusions of Piper *et al* (1973) regarding the contiguity of South America and Africa remain valid.

The Hyderabad Dyke pole of India lies away from the eastern loop (Fig. 7.4) as drawn but generally supports its presence. The pole is based on results from only one dyke and is regarded as a VGP. The Gwalior Traps pole (1830 ± 200 My) is based on results from only two sills. It is also regarded as a VGP. Three possibilities exist for fitting of the pole to the curve. It may be associated with (a) the eastern loop, (b) an older part of the curve (Fig. 7.6b) if its maximum age is assumed or (c) a position between the poles for the Mashonaland dolerites and Hart dolerite, if its antipole is plotted (Fig. 7.4).

In Fig. 7.5, rigorous adherence to the Australian data for the youngest part of the 1800 My - 1300 My period would have required southward extension (shown dashed) of the southern loop (between the African poles for the Pilanesberg Dykes and the O'okiep Intrusives and Kisii Lavas) to include the Morawa Lavas pole. Such an extension is supported by two Indian poles of similar age. However, it would involve an extra 50° of apparent polar wandering than the preferred shallower loop and was considered unjustified in view of the fact that the antipoles of the three poles are consistent with the African curve between the poles of the Guperas and Sinclair Lavas without violation of the age limits of that part of the curve. This interpretation suggests that the Indian Veldurti Haematite poles VH2 and VH3 and the Kaimur Sandstone pole, which fall on the southern loop, are between ~ 1400 My - 1250 My old. The reliability of the 1200 My - 900 My age assigned to the Veldurti Haematite poles (Athavale *et al*, 1970) is unknown, but the 1140 ± 12 My age for the Kaimur Sandstone (Crawford and Compston, 1970) is a minimum since it relates to an intrusive Kimberlite pipe.

The large confidence limits of the poorly defined Australian Giles Complex pole (Chapter 6, Section 6.1.3) enable it also to be associated with the Guperas Lavas to Sinclair Lavas section of the apparent polar wander path.

The only non-African palaeomagnetic data available for the period older than about 1800 My are a few poles from Australia for the interval 2500 My - 2400 My. Also, beyond 2300 My, the applicability of the African curve to regions of Africa other than the Rhodesia-Transvaal cration is questionable. Conclusions drawn from the comparison of this older data are therefore very speculative at this stage. Figs. 7.6a and 7.6b show possible interpretations of the Australian data *vis-a-vis* the African data. Fig. 7.6a shows the Australian polar sequence for 2500 My - 2400 My that plots closest to similar aged African data. Fig. 7.6b shows the antipole sequence of the Australian data. In either case, it is evident that the Australian data cannot be readily accommodated to the African data, the Australian sequence becoming younger from right to left, whereas the African data becomes younger from left to right (shown as full curves). It can be tentatively concluded therefore, that the two continents belonged to separate 'plates' at that time and that joining of the two curves, the signature of 'plate-collision' and the formation of a 'single plate', took place some time between 2400 My and 1800 My (possibly 2400 My - 2300 My ago — Fig. 7.6a — or at 2200 My — Fig. 7.6b, which involves the assumption that Australia was latitudinally stationary with respect to the pole between 2400 My and 2200 My). The interpretation involving coalescing

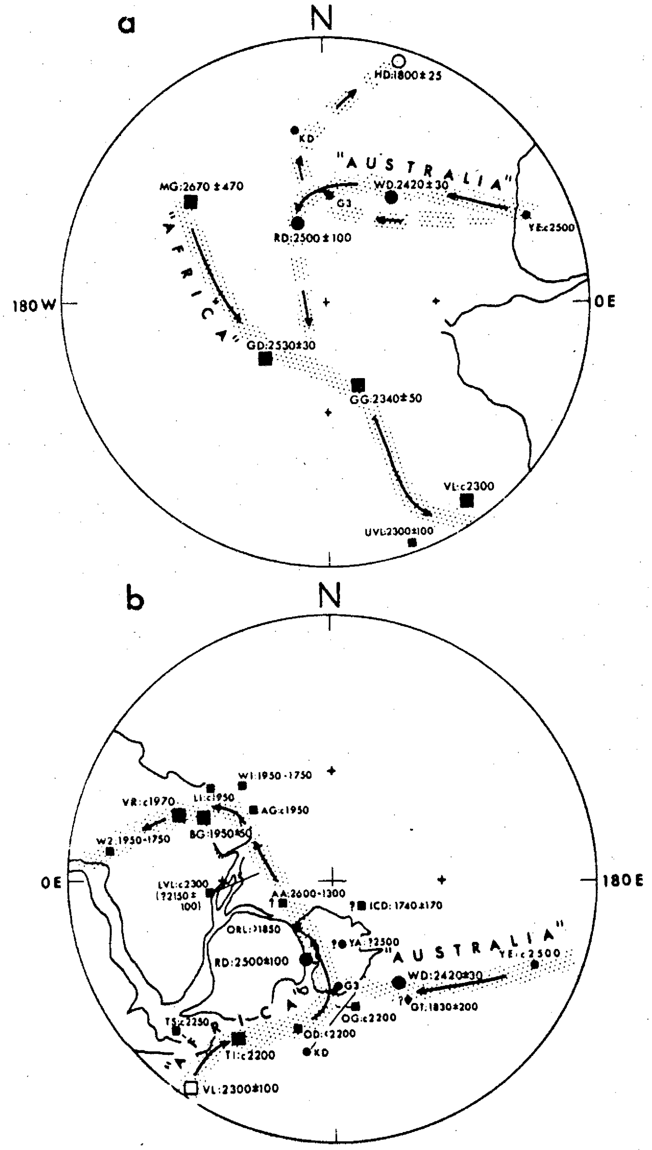

FIGURE 7.6 Australian palaeomagnetic data for the interval 2500 My - 2400 My compared with similar aged data from Africa. Large symbols refer to key poles. Three possible interpretations of the Australian data are illustrated, the least favoured, in the context of the African data, being the dashed path between the YE and HD poles in (a). Note that the Australian data refers only to poles from the Yilgarn Block, and the African data, older than about 2200 My, only to poles from the Rhodesia-Transvaal Craton. Question marks against poles in (b) indicate that these poles may belong to younger sections of the path. (Smith and Hallam (1970) reconstruction; Africa in its present day position).

of the two paths at 1800 My (dashed path, Fig. 7.6a) is not favoured as this would involve the assumption that while African mobile belts of this age are palaeomagnetically supported to be of ensialic origin (Piper *et al*, 1973), elsewhere in Gondwanaland, plate convergeance would be the dominant process. More likely, they would all result from the same process (ensialic), as demonstrated for the mobile belts of the pan-African event at 550 ± 100 My (Section 7.2.1).

### 7.3.2 Implications of the Model

A model of apparent polar wandering for Gondwanaland during the Precambrian (> c900 My) has been set up and tested. For the period 1800 My - 900 My, it has been demonstrated that virtually all Gondwanic palaeomagnetic data not used in setting up the model is nevertheless consistent with it. Therefore, it is concluded that, to a first approximation, the master curve defined for the period 1800 My - 900 My represents a common path for the Gondwanic continents. This path is illustrated in Fig. 7.7 where it is linked up with the younger part of the common curve (Section 7.2.1). Since the 1800 My mobile belts do not appear to have resulted from an episode of major ocean closure between separated cratonic nucleii, the implication of the common curve is that all Gondwanic mobile belts less than say 1900 My old have been generated essentially *in situ*. This extends to the whole of Gondwanaland a similar conclusion of Piper *et al* (1973) relating to Africa.

Preliminary indications from older Australian and African data suggest that Gondwanaland may have resulted from agglomeration of widely separated nucleii sometime in the Archaean or early Proterozoic. This is consistent with the suggestion of Katz (1974) that the 2500 My - 2000 My old paired-metamorphic belts he recognizes between Australia-Antarctica, India and Africa may represent the legacy of an accretionary process. A picture is thus starting to emerge which is remarkably in

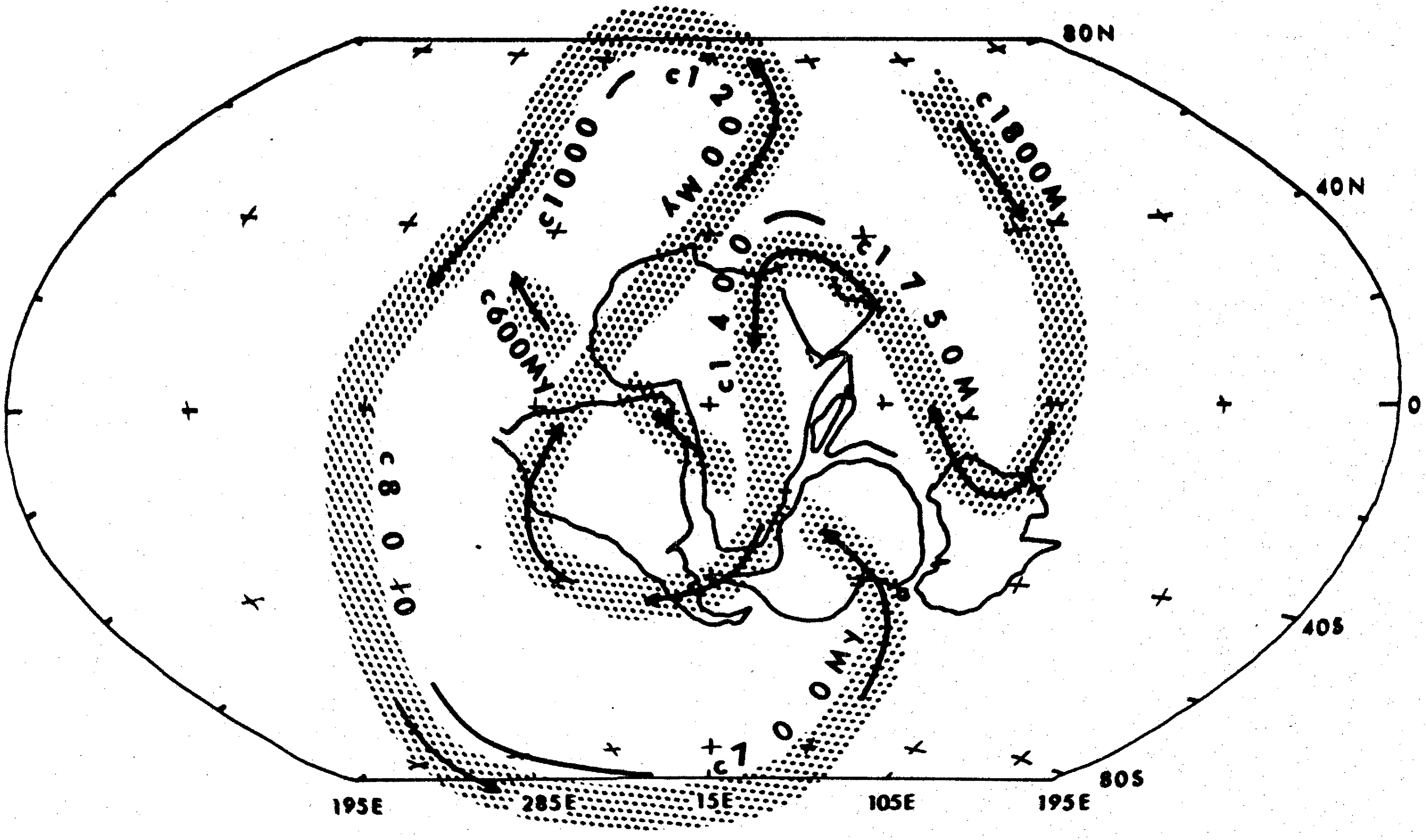

FIGURE 7.7 The model apparent polar wander curve for Gondwanaland for the interval c1800 My to the base of the Cambrian. The reconstruction of Gondwanaland is that of Smith and Hallam (1970) with Africa in its present day position.

tune with those views expressed by Engel and Kelm (1972) and quoted at the beginning of this section (Section 7.3.1).

## 7.4 GENERAL COMMENTS ON THE POSSIBILITY OF A PRECAMBRIAN 'PANGAEA'

Piper *et al* (1973) recently compared the Precambrian apparent polar wander paths for North America and Africa in the time interval 2700 My - 1000 My. They found that the North American data could be rotated into fair agreement with the African data, the similarities in the curves being more striking than their differences. The best agreement was found for the interval 1400 My - 1000 My. It included a particularly impressive correspondence between an extended loop in the African curve and the so-called Great Logan Loop (Robertson and Fahrig, 1971) of the North American curve, both of which cover the time range 1250 My - 1000 My (Fig. 7.8a). They suggested therefore, that for the period 1400 My - 1000 My North America may have been part of a supercontinent which included Africa and South America and speculated that North America may have joined this supercontinent before 2700 My.

The interpretation of the late Precambrian segment of the African apparent polar wander path given in Section 7.2.1 means that the poles in the time range 1400 My - 1000 My are now south poles (north poles on the interpretation of Piper *et al*, 1973) and that accordingly a match exists with the presumed North American north poles for the same period. The fit of the two path segments is impressive, so it is tentatively suggested that the late Precambrian to Early Palaeozoic section of the North American polar wander path may be much more complicated than previously supposed. Irving and Park (1972) have already drawn attention to the very tentative nature of this section of the North American curve, with poles between about 1000 My and the Cambrian tending to form a diffuse group at the younger end of the Logan Loop. During the same period in Gondwanaland the polar shift was well

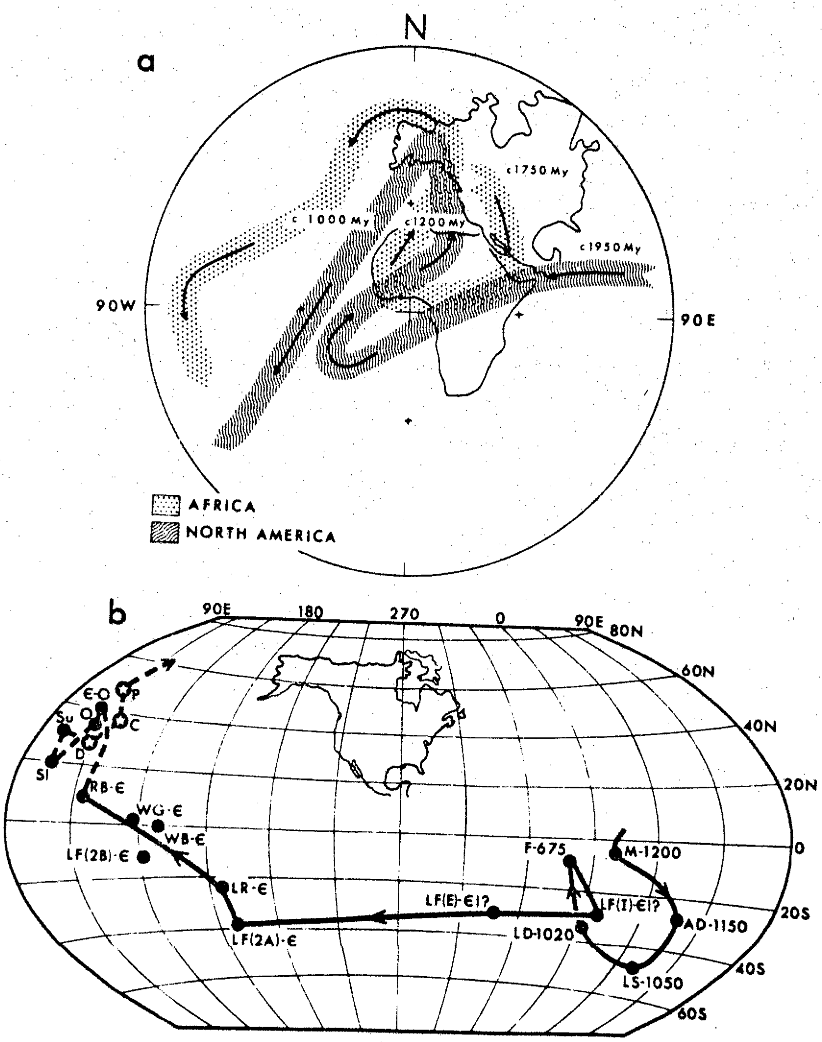

FIGURE 7.8 (a) Piper *et al's* (1973) comparison of the African apparent polar wander curve for the interval c1750 My - c900 My with the similar aged section of the North American curve (after Irving and Park, 1972). Note that the African path shown is that of the *North pole* on Piper *et al's* (1973) interpretation of African and South American palaeomagnetic data for the time interval c900 My - c500 My. The North American path is believed to be that of the North pole. The Logan Loop of the North American curve occupies the approximate time interval c1200 My - c1000 My.

(b) Suggested revised North Pole apparent polar wander path for North America, which joins the Great Logan Loop (Robertson and Fahrig (1971) — 1200 My to 1020 My) to the Ordovician part of the curve by means of a large Cambrian shift. Cambrian poles from: RB - Ratcliffe-Brook Formation (Black, 1964); WG - Wichita Granites (Spall, 1968); WB - Wilberns Formation (Howell and Martinez, 1957); LR - Lodore Formation (Collinson and Runcorn, 1960); LF-I, 2A, 2B and E - Lamotte Formation (Al-Khafaji and Vincenz, 1971). Anchor points for the Great Logan Loop are shown together with the Franklin pole - F (Robertson and Fahrig, 1971). Post-Cambrian Palaeozoic poles are joined by a dashed line, the stars representing mean Devonian (D), Carboniferous (C) and Permian (P) poles (from McElhinny, 1973).

over 180° (Fig. 7.2). In the Cambrian alone it was about 90°. Furthermore, Cambrian results from the Bohemian Massif have previously been interpreted in terms of a large polar shift of about 130° (Bucha, 1965) and a large polar shift is recorded in the Cambrian of Siberia (McElhinny, 1973).

The Lamotte Formation of Missouri (Cambrian in age although the fossil evidence is poor) shows four distinct palaeomagnetic poles (Al-Khafaji and Vincenz, 1971). Poles from the higher horizons are in two groups (IIA and IIB), related to their stratigraphical positions, and suggest a polar migration during the Late(?) Cambrian. No reason is apparent for group I and the other (Locality E) is close to the Carboniferous pole for North America (McElhinny, 1973). Carboniferous remagnetization has been proposed, although no evidence has been given either to suggest how this arose or why it occurred selectively at one locality. Studies of the Ordovician Trenton Limestone (McElhinny and Opdyke, 1973) have demonstrated that the hypothesis of widespread late Palaeozoic remagnetization of Lower Palaeozoic rocks of North America is no longer tenable. The two 'anomalous' poles are here accepted as valid Cambrian poles (taking their antipoles) and are interpreted as representing a polar migration during the Cambrian.

Fig. 7.8b shows how it is possible to join the later Palaeozoic poles for North America through an extended Cambrian path to the antipoles of the Logan Loop and older part of the Precambrian apparent polar wander path. These poles become the north pole path for North America with the consequence that the plot of the North American curve in the Pacific (Irving and Park, 1972; Fahrig *et al*, 1974) represents the south pole path. The 1400 My - 1000 My segment of the path is then readily matched with the African data and the interpretation and conclusions of Piper *et al* (1973) relating to the possibility of a Precambrian supercontinent remain valid. In addition, if the

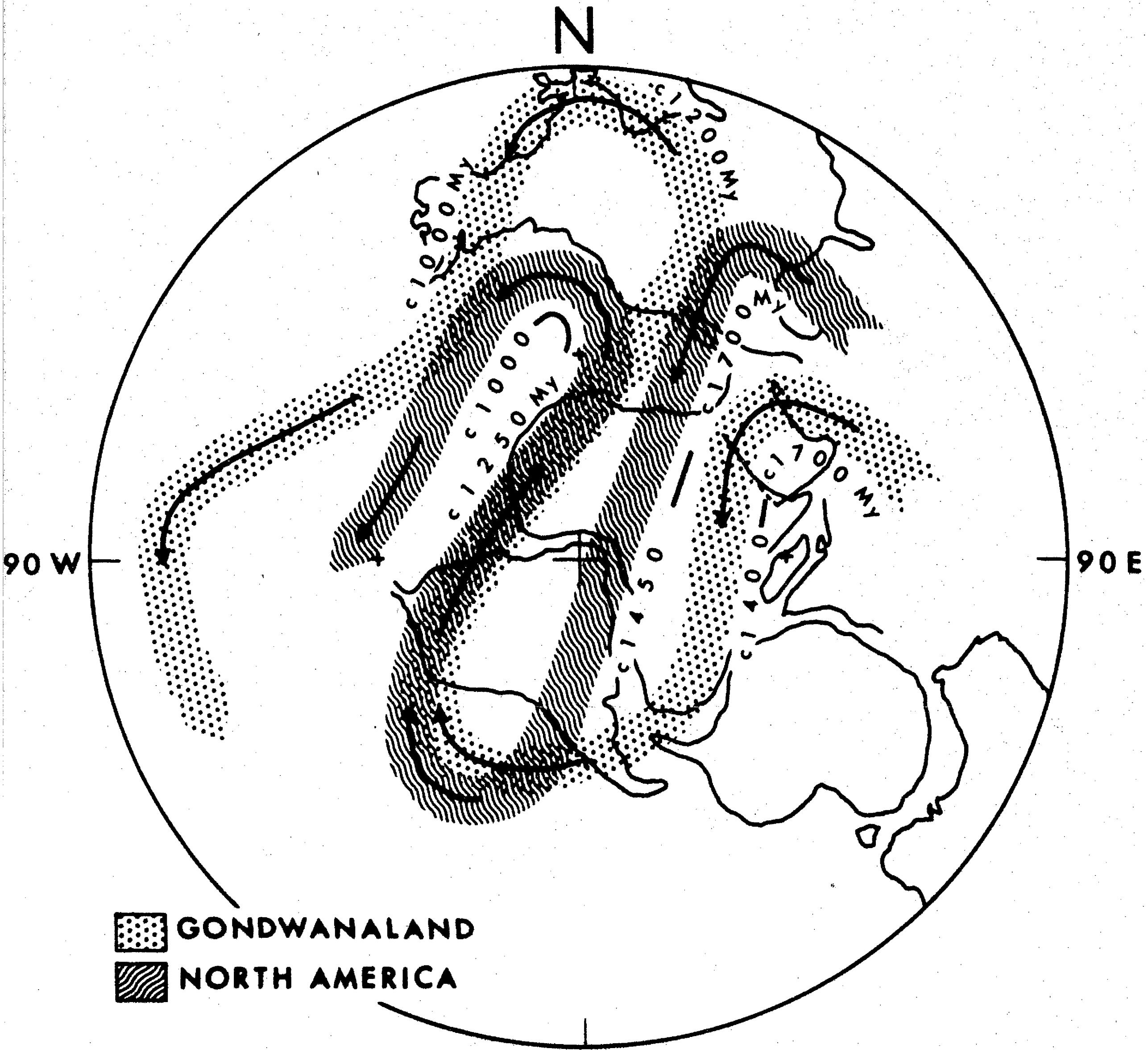

FIGURE 7.9 Comparison of the North American apparent polar wander curve for the interval c1700 My - c1000 My, as defined by Fahrig *et al* (1974), with the similar aged section of the model curve defined for Gondwanaland (shown in greater detail in Figure 7.5). The reconstruction of Gondwanaland is that of Smith and Hallam (1970) with Africa in its present day position.

interpretation of Gondwanic Precambrian palaeomagnetic data, as given in Section 7.3, is essentially correct, and a common path can be defined to at least 1800 My, then the Precambrian supercontinent of Piper *et al* (1973) may be extended to include the whole of Gondwanaland rather than just Africa and South America. Comparison of the common path defined for Gondwanaland for the interval 1400 My - 1000 My (Fig. 7.9) with a recent interpretation of the North American path (Roy and Fahrig, 1973; Fahrig *et al*, 1974) shows an even more impressive similarity with that curve than the curve based on African data alone, if due allowance is made for the ambiguity of the Australian Morawa Lavas pole (Section 7.3.1). It may be therefore, that as more data becomes available, the discrepancies between the older parts of the African and North American curves will be resolved.

Thus if the prediction that extensive studies of late Precambrian and Cambrian rocks of North America (1000 My - 500 My) will reveal a complicated apparent polar wander path involving a polar shift through at least 180°, is substantiated, it is evident that a Precambrian 'Pangaea' including all of Gondwanaland and North America becomes a distinct possibility for the period at least 1400 My - 1000 My.

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# LATE PRECAMBRIAN AND LOWER PALAEOZOIC PALAEOMAGNETIC RESULTS FROM SOUTH AUSTRALIA AND WESTERN AUSTRALIA

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The late Precambrian to Lower Palaeozoic apparent polar wander curve previously defined from palaeomagnetic studies in central and northern Australia has now been shown to be valid for southern and western Australia. During the latest Precambrian and Lower Palaeozoic a pole path of length 180° is now identified. In the northern Flinders Ranges, South Australia, palaeomagnetic poles have been obtained from the late Precambrian Pound Quartzite (60°S, 6°E; $N = 10, A_{95} = 23.5°$), Lower Cambrian sediments (36°S, 33°E; $N = 11, A_{95} = 16.5°$) and the Middle Cambrian–?Lower Ordovician Lake Frome Group (16°S, 25°E; $N = 20, A_{95} = 12.5°$). From Western Australia the Tumblagooda Sandstone of probable Ordovician age yields a palaeomagnetic pole at 30°S, 31°E ($N = 17, A_{95} = 9°$). Reappraisal of some previous studies on the Dundas Group of Tasmania and on bore cores from the Georgina Basin (northern Australia) and Yorke Peninsula (South Australia) indicates those results are compatible with the data presented.

## 1. Introduction

Since the early work of Irving and Green [1] on the Palaeozoic of northern Australia and southeastern Australia subsequent investigations in those regions [2–7] and in central Australia [8,9] have led to a fuller appreciation of their spatial relationships to one another during late Precambrian and Palaeozoic time [10]. The purpose of the present study is to assess whether palaeomagnetic results from South Australia and Western Australia also match the common polar wander curve previously identified from central and northern Australia [11].

Although we report the first palaeomagnetic results from Western Australia, Briden has previously collected from late Precambrian and Lower Palaeozoic formations in South Australia [12–14]. Unfortunately, he was unable positively to identify a primary magnetization and concluded that during the Early Tertiary, remagnetization had occurred. Studies of magnetic inclination measured in bore-core material also proved difficult to interpret [13] since definitive palaeomagnetic studies were not then available. A consequence of the new results reported here is that a framework is now provided within which the bore-core results can be interpreted and the results previously reported from South Australian formations assume new significance [15].

## 2. Geology of the sampling localities

Rock samples were collected from the Pound Quartzite (late Precambrian), Lower and Middle Cambrian and Upper Cambrian-Lower Ordovician formations in the northern Flinders Ranges, South Australia, and from the Lower Palaeozoic Tumblagooda Sandstone, Western Australia.

### *2.1. South Australia*

The Adelaide Geosyncline, of which the Flinders Ranges comprise the northern part (Fig. 1), consists pri-

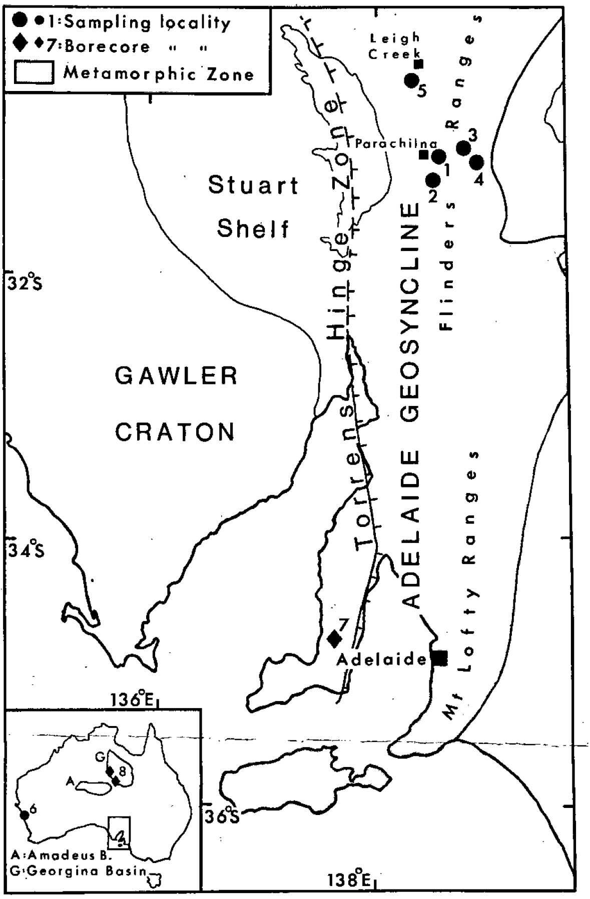


Fig. 1. The sampling localities in South Australia (full dots) are shown in relation to the principal structural elements of the Adelaide Geosyncline. 1,2,3 = Pound Quartzite; 5 = Lower Cambrian; 2,5 = Middle Cambrian (lower beds of the Lake Frome Group); 4 = Upper Cambrian–?Lower Ordovician (upper beds of the Lake Frome Group). Locality 6 represents the Tumblagooda Sandstone, Western Australia – it outcrops west of the Darling Fault, a major Late Jurassic structural line which parallels the west Australian coastline. The bore-core localities, referred to in the text, are marked as full diamonds, 7 = Lower Cambrian, Yorke Peninsula, and 8 = two Upper Cambrian bore sites (marked on the inset) in the Georgina Basin.

marily of a sequence of shallow marine and continental sediments of late Precambrian (Adelaidean System) and Cambrian age. The Gawler craton to the west was the major source of clastics during the depositional history of the geosyncline [16]. Sedimentation sporadically overlapped onto the eastern part of the craton (the Stuart Shelf) where thin, generally undisturbed, correlatives of parts of the Precambrian–Cambrian sequence occur. In the geosyncline zone, the sequence reaches a thickness in excess of 15 km. The sediments were folded during the Late Cambrian–Early Ordovician Delamerian Orogeny [17]. Radiometric ages obtained from metamorphosed shales and granites associated with the tectonic activity fall within the range 490–460 m.y. [18–21]. Effects of regional metamorphism are confined mainly to the southern and eastern regions of the orogen [22], the metamorphic grade decreasing in a northwesterly direction. In the northern Flinders Ranges the Upper Precambrian and Cambrian sediments are unmetamorphosed and preserved in open folds with predominantly north–south trending axes.

The Pound Quartzite, the youngest unit of the Wilpena Group, comprises two members; the lower red sandstone and siltone member was ampled for palaeomagnetic study. The upper member contains an Ediacaran fauna of latest Precambrian age [23]. It is overlain by thick sequences of Lower Cambrian Archaeocyathid limestones of the Hawker Group. The lower member was sampled in three localities (Fig. 1), (a) 22 samples were collected in Brachina Gorge at 5 sites spaced over 1000 m, the beds dip at 40° to the WNW, (b) 7 samples were collected from near the top of the member in Eregunda Creek where the beds dip at 35° to the NNE, and (c) 9 samples from the middle of the member were collected in Parachilna Gorge. The beds there dip at 70° to the SW.

A notable feature of the Cambrian sequences in the Adelaide Geosyncline is the widespread occurrence of red-beds [16]. 15 samples were collected from the Lower Cambrian beds (dipping at 45° to the NE) in a 70 m long section near Aroona Dam (see Fig. 1). The Lower and Middle Cambrian beds at that locality are separated by a limestone which contains a Redlichia fauna. 29 samples representing the Middle Cambrian include 13 from Aroona Creek and 16 samples from a separate fold limb (dip 80° to the W) which outcrops over 200 m in Brachina Gorge. The Upper Cambrian sequence which represents the highest beds of the Lake Frome Group (and may be as young as Early Ordovician [24]) was sampled in Balcoracana Creek. 11 samples were collected from a 150 m long section in beds dipping at 70° to the E.

### 2.2. *Western Australia*

On the eastern margin of the Carnarvon Basin a red-bed sequence known as the Tumblagooda Sandstone outcrops. The beds total more than 1800 m and rest with steep angular unconformity on Precambrian gneiss [25,26]. The Sandstone is overlain with slight unconformity by glacials which belong to the Lower Permian Lyons Group. Index fossils are absent, estimates of the age of the Tumblagooda Sandstone relying heavily on the presence of intertwined burrows and trails [27]. Several geologists have considered the evidence relating to its age [25–28]: it is now generally considered to be Ordovician although it may be as old as Middle Cambrian or as young as Early Silurian. 17 samples were collected from a coastal sequence near Bluff Point, about 10 km south of the Murchison River mouth (lat. 27.7°S, long. 114.5°E). Above sea level, the sequence is about 150 m thick; sampling covered about 100 m. The beds are near-horizontal, and according to Condon [26] it is likely that the sequence was deposited with the dips currently displayed.

## 3. Experimental procedure and results

All samples were collected as blocks and oriented using a sun compass of modified design [29]. Wherever possible, at least 3 specimens (28 X 28 mm cylinders) were cut from each block. Measurements of intensity and direction of magnetization were made using either a model SM1 P.A.R. spinner magnetometer or a ,,complete results" DIGIGO spinner magnetometer [30]. Thermal cleaning was carried out in air and in zero magnetic field using equipment similar to that described by McElhinny et al. [31]. Directions of magnetization were analysed using Fisher's statistics [32] and randomness of mean directions was tested with statistical methods described by Watson [33] and Vincenz and Bruckshaw [34].

### *3.1. Pound Quartzite*

Intensities of magnetization of the samples were weak, ranging from 0.6 to 6.9 mA $m^{-1}$, with an arithmetic mean value of 2.0 mA $m^{-1}$. Mean directions of natural remanent magnetization (NRM) for samples considered non-random at the 95% probability level are shown in Fig. 2a prior to correction for bedding tilt. Application of Graham's fold test [35] increased the scatter (see Table 1). Pilot specimens were subjected to careful stepwise thermal demagnetization up to 670°C to test for the presence of a primary component of magnetization. Three types of behaviour were observed during those experiments:

(a) Directions initially oblique to the present field axis remained unchanged, their remanence was of the thermally discrete type [36].

(b) Specimen directions which were initially grouped around the present field axis underwent substantial angular changes at low temperatures and realized stable end-points in the temperature range 440–630°C. Their components of magnetic remanence were thermally distributed. We interpret these results to indicate the removal of a secondary viscous remanent magnetization at temperatures less than about 150–200°C (when a sharp drop in intensity occurred) and subsequent removal of a more stable secondary, possibly chemical, remanent magnetization.

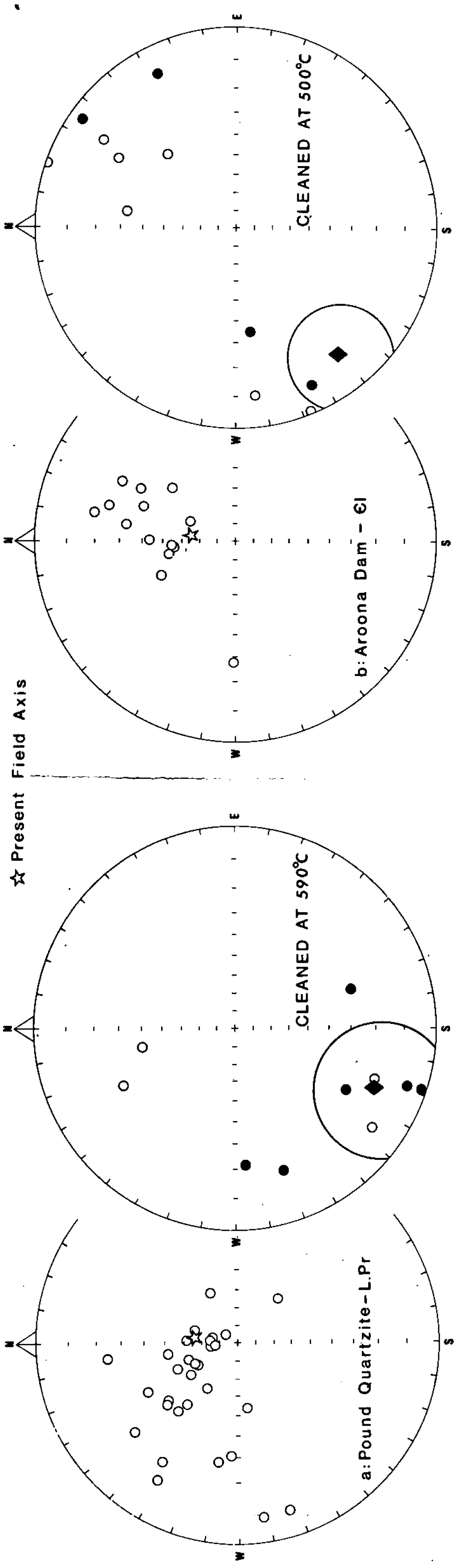
(c) Specimen directions, which were initially grouped about the present field axis, remained unchanged. The highest blocking temperatures lay in the region 630–650°C. Within the practical limits of the investigation those specimens have probably lost their primary component of magnetization.

Although the pilot specimens were weakly magnetized after treatment (intensities < 1 mA $m^{-1}$), they indicated that a stable component of magnetization could be isolated in the temperature range 440–630°C. All remaining specimens were thermally cleaned at 590°C After bulk cleaning, within sample directions of 33 of

TABLE 1
Fold test data

| | $N$* | $k$ | |
|---|---|---|---|
| | | uncorrected | corrected |
| Pound Quartzite | | | |
| NRM | 30 | 6.0 | 3.2 |
| cleaned | 10 | 4.7 | 4.7 |
| Lake Frome Group (Єm) (lower beds) | | | |
| NRM | 29 | 4.3 | 1.4 |
| cleaned | 15 | 1.9 | 5.9 |

*$N$ = number of samples, $k$ = estimate of Fisher's precision parameter.


a: Pound Quartzite-L.Pr
CLEANED AT 590°C
☆ Present Field Axis
b: Aroona Dam - Єl
CLEANED AT 500°C
N
E
S
W

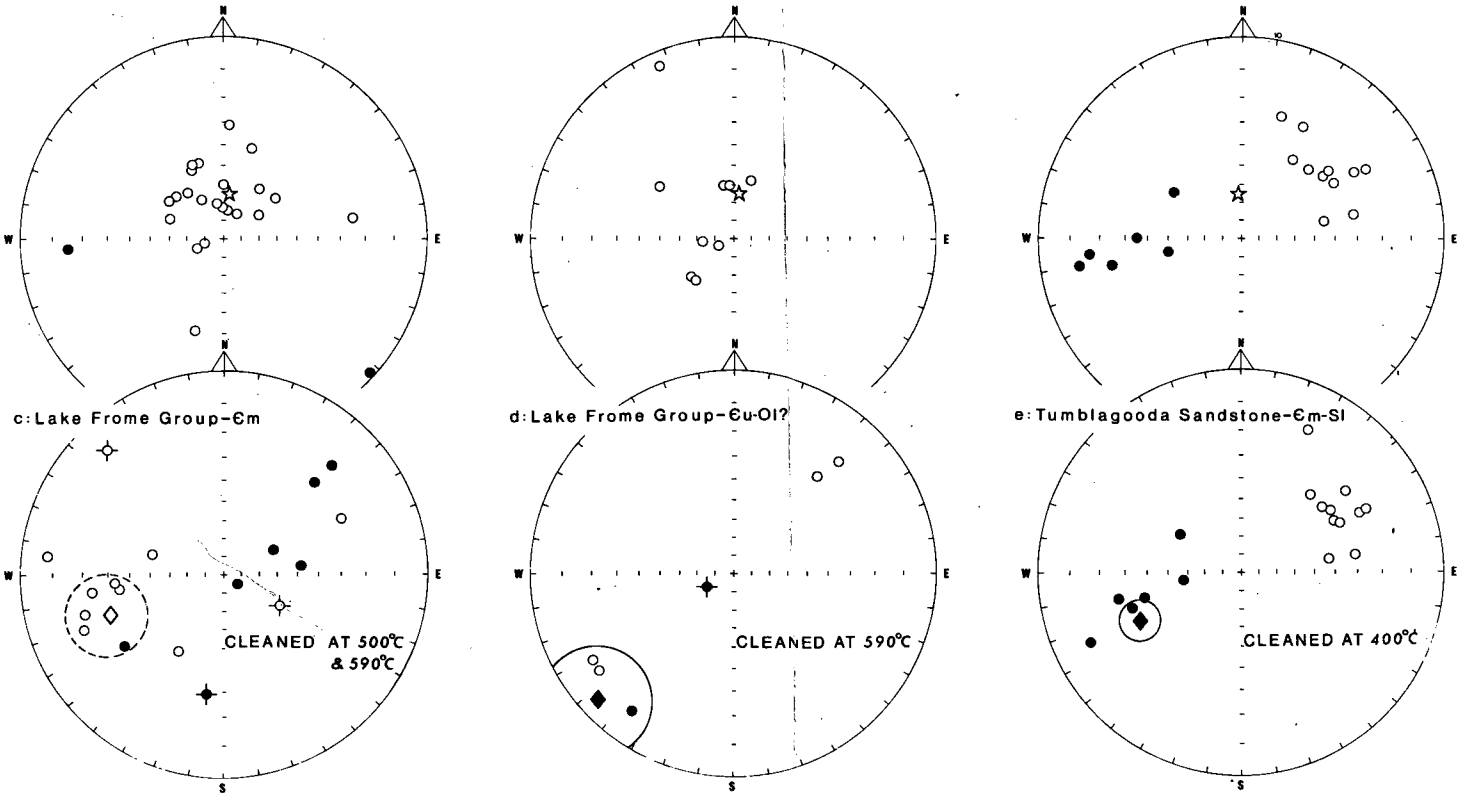


Fig. 2 Sample-mean directions of magetization for all age groups (dots) plotted on the Wulff equal angle stereographic projection. Full symbols represent positive (downward) directions and open symbols negative (upward pointing) directions. For each group of samples two plots are shown; one, NRM directions with respect to the present horizontal, includes the direction of the present geomagnetic field at the respective sampling locality and two, direction after treatment at temperatures indicated, and after bedding correction (where appropriate). The circles represent cones of confidence at the 95% probability level associated with each mean direction (indicated by a diamond). Crossed symbols represent sample-mean directions sufficiently oblique to the mean axes of magnetization that they may record intermediate field directions.

the 38 samples were considered random [34]. Closer examination of individual specimen directions from those 33 samples however, revealed that whilst some remained magnetized near the present field, others underwent systematic angular changes in excess of 90°. For 5 samples, it was possible to eliminate an aberrant specimen, leaving 2 specimens in which the primary component was present.

The 10 cleaned sample-means are shown in Fig. 2a after correction for bedding tilt; 2 samples are magnetised in the opposite sense. Comparison of directions before and after cleaning shows that they experienced an average systematic angular rotation of 80° away from the present field axis along an approximate N–S trend. The precision of the formation mean (see Table 1) was unchanged after correction for bedding tilt (before cleaning, this test relied heavily on samples from Eregunda Creek and Parachilna Gorge – most of those samples were rejected after treatment).

### 3.2. *Cambrian sediments*

NRM sample-mean directions of magnetization for the Early, Middle and Late Cambrian groups are plotted with respect to the present horizontal in Fig. 2b–d respectively. Their intensities lay in the range 0.5–33.0 mA $m^{-1}$. Directions in the Middle Cambrian sediments, with respect to the present horizontal, clustered around the present field axis, correction for bedding tilt increased the dispersion (see Table 1). Samples of Early and Late Cambrian age exhibited a planar distribution towards the present field axis. Preliminary experiments with pilot specimens indicated that stable components of magnetic remanence (regarded as primary) were isolated after partial thermal demagnetization at 500°C and 590°C. Following bulk treatment, results from 4 Lower Cambrian samples, 11 Middle Cambrian samples and 5 Upper Cambrian samples were rejected on the grounds that they either remained magnetized in a direction near the present field axis or that their remanence proved thermally unstable so resulting in low within-sample precision.

The remaining 11 sample-means of the Lower Cambrian sediments rotated systematically away from the present field by ca. 70° along an approximate NE–SW axis. Those directions are plotted with respect to the palaeohorizontal in Fig. 2b, they fall into two groups with opposite polarity.

Stable components of remanent magnetization were isolated in specimens from 18 samples of the Middle Cambrian sediments. 3 samples whose mean directions lay between 60° and 90° away from the formation mean were not included in the calculation of the pole position. Their directions were sufficiently oblique as to be considered possible records of genuine intermediate field directions. Fig. 2c shows the two groups with opposite polarities. After treatment the fold test was positive (see Table 1 and McElhinny [44]).

Results from the Upper Cambrian (?Lower Ordovician) sediments showed that only 6 samples responded succesfully to treatment. Directions in 5 samples indicate a reversal is present. One sample (see Fig. 2d) retained a rather steep inclination, it has been disregarded for the purpose of calculating the formation mean direction. Whether it records an intermediate fiels direction is uncertain. Lower, Middle and Upper Cambrian pole positions are listed in Table 2.

### 3.3. *Tumblagooda Sandstone*

All samples apparently contained only one component of magnetization. The NRM directions plot in two, almost antiparallel, groups strongly oblique to the present field axis – see Fig. 2e. Pilot specimens, one from each sample, were heated in 100°C steps up to 600°C and at 650°C. No appreciable changes in their directions were produced below 600°C. At 650°C the scatter increased due to approaching the limit of the blocking temperature spectrum. In Fig. 3 the mean demagnetization–intensity curve obtained from the group of pilots with negative polarity shows a smooth decrease to 650°C. The mean curve obtained from the group of specimens with positive polarity firstly indicated an increase in intensity before decreasing smoothly to 650°C. It would appear that a very weak secondary component of magnetization was removed. The remaining specimens were measured after treatment at 400°C – the results are plotted in Fig. 2e. Samples from approximately the upper two-thirds of the sequence comprise the negative group of directions and samples from the lower one-third fall in the positive group. During sampling, estimates were made of the thicknesses of sediment separating the various sampled horizons. Using that field information it would seem that a field reversal occurs within about 2m. The formation mean direction of magnetization obtained after cleaning is given in Table 2.

The palaeomagnetic results described in this section

TABLE 2
Summary of the new palaeomagnetic results

| Rock unit | Symbol | Age | *N* | *R* | Mean direction | | South pole | $A_{95}$ |
|---|---|---|---|---|---|---|---|---|
| | | | | | *D* | *I* | | |
| *South Australia* | | | | | | | | |
| Pound Quartzite | PQ | Latest Pr | 10 | 8.091 | 203 | 17 | 6E 60S | 23.5 |
| Aroona Dam Sediments (Billy Creek equivalents?) | AD | €l | 11 | 9.567 | 231 | 13 | 33E 36S | 16.5 |
| Lake Frome Group (lower) | LFG | €m | 15 | 12.641 | 251 | -29 | 25E 8S | 14.5 |
| Lake Frome Group (upper) | LFG | €u(?Ol) | 5 | 4.775 | 227 | 6 | 26E 38S | 12.0 |
| Lake Frome Group (combined) | LFG | €m-u(?Ol) | 20 | 16.508 | 243 | -20 | 25E 16S | 12.5 |
| *Western Australia* | | | | | | | | |
| Tumblagooda Sandstone | TS | O?(€m–Sl) | 17 | 16.005 | 245 | 33 | 31E 30S | 9.0 |

Notes: (1) Age symbols : Pr = Precambrian; € = Cambrian; O = Ordovician; S = Silurian; D = Devonian, Upper, Middle and Lower divisions denoted by u, m and l.

(2) *N* = number of samples, *R* = length of resultant vector, *D* and *I* = mean declination and the inclination of remanent magnetization vector, and $A_{95}$ = semi-angle of the cone of confidence at the 95% probability level (Fisher, 1953).

(3) The label „south pole" is assigned by continuity of these poles onto the Phanerozoic polar wandering curve for Australia.

demonstrate the presence of reversed polarities in each age group. This is taken as evidence that the magnetization, upon which the palaeomagnetic poles are based, is primary. In addition, the Middle Cambrian results from South Australia include a positive fold test (see Table 1) – the main phase of folding took place at the end of the Cambrian Period. Furthermore, the cleaned directions of magnetization are different from directions yet measured in younger Australian rock formations. The tropical palaeolatitudes indicated by the

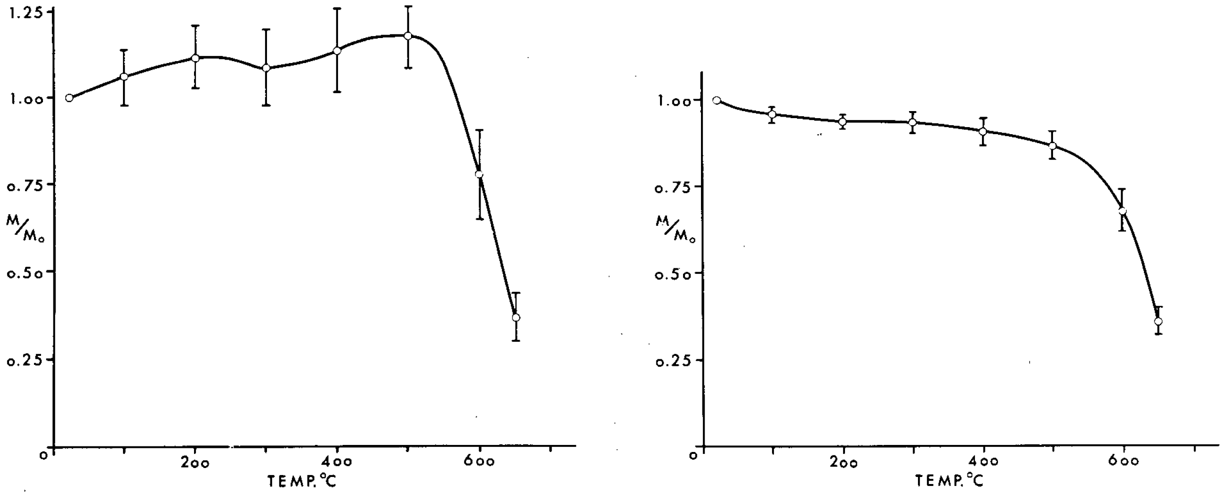


Fig. 3. Demagnetization–intensity curves for pilot specimens from the Tumblagooda Sandstone. The graph which indicates an initial increase of intensity with increasing treatment refers to specimens with positive polarities (see Fig. 2e). The graph which shows a smooth decrease of intensity from room temperature to 650°C refers to specimens with negative polarities. Error bars indicate the standard error of the mean intensity at each temperature.

results agree well with the palaeoclimatic data [37,38], e.g. the occurrence throughout the latest Precambrian and Cambrian of thick sequences of dolomites and limestones, some of which contain an Archaeocythid fauna [16]. The pole positions given in Table 2 are based on results which provide sufficient time-averages of the palaeomagnetic field such that secular changes are accounted for. In this context we considered it necessary to combine results from the upper and lower Lake Frome Group since only 5 samples from the younger section responded successfully to thermal treatment. The scatter of directions was frequently very high; Thompson [39] has previously commented upon similar problems and suggested a contributory cause particularly affecting Lower Palaeozoic rocks.

## 4. Discussion

Partial remagnetization is a problem often encountered during palaeomagnetic investigations. Rather than affecting preferred horizons (especially in sediments) degrees of remagnetization may be inhomogeneously distributed within individual beds and even, as in the case of the Pound Quartzite, within a single hand sample. Luck [7] encountered similar problems during his study of Lower Palaeozoic sediments from northern Australia. Also, during a study of the Permian red-beds from the Colorado Plateau, Farrell and May [40] rejected 90% of the specimens from their Monument Valley collection. The implication is that information relating to the primary magnetization might be retrievable if results are scrutinized at the specimen, rather than sample, level. This procedure was adopted with the palaeomagnetic data obtained by Briden [12, 13] from an earlier extensive study of South Australian late Precambrian and Cambrian formations. Giddings and Embleton [15] discuss those results more fully in terms of their particular relevance to the structural history of the Lower Palaeozoic in South Australia. Briden's material suffered severe remagnetization during the Late Cambrian–Early Ordovician orogenic activity and our interpretation of that data supports results presented here for the Late Cambrian–Early Ordovician of South Australia.

Briden also studied samples of sediments and tuffs belonging to the Dundas Group [12,41] and a syenite intrusion from Tasmania. They are Late Cambrian in age and were involved in the Late Cambrian Jukesian Orogeny [24]. Samples were subjected to laboratory stability tests – AF and thermal techniques. Upon re-examination of the data at the specimen level [15] we believe that a weak primary component has been re-

TABLE 3
Late Precambrian to Lower Palaeozoic palaeomagnetic poles used to define the polar wander curve with respect to the main Australian platform.

| Rock unit | Symbol | Age | South pole | | $A_{95}$ | Ref. |
|---|---|---|---|---|---|---|
| *Northern Australia* | | | | | | |
| Antrim Plateau Volcanics | AV | Pr/Єl | 9S | 340E | 17 | [6] |
| Hudson Formation | HF | Єm | 18N | 19E | 13 | [7] |
| Jinduckin Formation | JF | Єu–Ol | 13S | 25E | 11 | [7] |
| *Central Australia* | | | | | | |
| Arumbera Sandstone | AS | Pr/Єl | 8N | 325E | 25 | [8] |
| Hugh River Shale | HS | Єl–m | 11N | 37E | 8 | [8] |
| Stairway Sandstone | SS | Ol | 2S | 50E | 8 | [9] |
| Mereenie Sandstone | MS | S?–D | 41S | 40E | 10 | [9] |
| *Tasmania* | | | | | | |
| Dundas Group | DG | Єu | 23S | 13E | 11.5 | [2,15] |
| Housetop Granite plus aureole | HG | Dm | 67S | 94E | 27 | [41] |

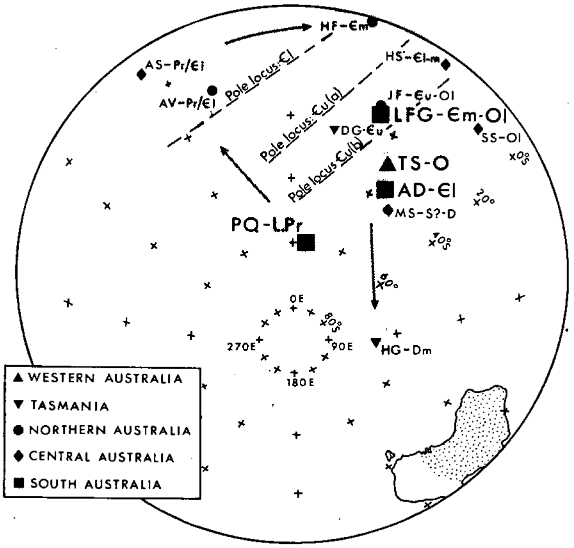


Fig. 4. The late Precambrian–Lower Palaeozoic apparent polar wander curve for the main Australian platform. Large symbols refer to palaeomagnetic poles obtained from studies described in this paper (see Table 2) and the small symbols refer to palaeomagnetic poles obtained from studies in other parts of Australia, presented previously (see Table 3). The Upper Cambrian pole (*DG*) obtained from the Dundas Group of Tasmania is also seen to lie on the curve in such a position that we need not invoke local rotation or translation of that region relative to the main Australian platform. For this reason and other evidence cited by McElhinny and Embleton [11], the Middle Devonian pole reported by Briden [41] from the Housetop Granite of Tasmania may also be regarded as relating to the main platform (stippled) – the Precambrian outcrop in Tasmania is the most easterly occurrence in Australia. That pole tentatively allows us to extend the apparent polar wander curve into the Upper Palaeozoic. The dashed lines represent the loci of the poles. obtained by Briden [13] from studies of bore-core material from Yorke Peninsula (Lower Cambrian) and the Georgina Basin (Upper Cambrian – *a* and *b*).

tained in specimens from 8 samples of the tuffs and syenite. They constitute two groups with opposite polarities and provide a positive fold test. The mean axis of magnetization corresponds to the direction of the Late Cambrian geomagnetic field defined from other regions of Australia: the south pole positions are given in Table 3 (see also Fig. 4).

The apparent polar wander curve for the Lower Palaeozoic now provides a suitable framework for the interpretation of results also obtained by Briden from investigations with bore-core material [13]. He calculated the colatitude (declination was indeterminate) of the sampling sites ( the sites are shown in Fig.1). Arcs of three small circles relating to measurements from 2 bore-cores through Upper Cambrian sediments in the Georgina Basin (northern Australia) and a bore-core through Lower Cambrian sediments on Yorke Peninsula (South Australia) are drawn in Fig.4. They describe the loci of the palaeomagnetic poles inferred from colatitude estimates. These data are consistent with the rest of the Lower Palaeozoic results.

The Lower Cambrian pole (labelled *AD* in Fig.4) lies in correct chronological sequence with respect to the Pound Quartzite pole and the Arumbera Sandstone pole [8]. An Early Cambrian fossil found in the uppermost beds of the Arumbera Sandstone (central Australia) is also present in the Parachilna Formation [16,23]. That formation disconformably overlies the Pound Quartzite and is separated from the Aroona Dam sediments by several thousand metres of Archaeocyathid limestones belonging to the Lower Cambrian Hawker Group. However, the Aroona Dam pole apparently lies in an anomalous position when compared with the pole yielded by the Hudson Formation. Samples from the South Australian sediments were collected just below a thin Redlichia bearing limestone (separating them from the Lake Frome Group) and the Hudson Formation was sampled above the main Redlichia horizon in the Negri Group, Northern Territory [7]. At present we have no explanation for this but await additional palaeomagnetic and palaeontological evidence which may help resolve the question.

The results from the Pound Quartzite allow us to extend the apparent polar wander path into the latest Precambrian (see Fig. 4). The next youngest group of poles belong to the Arumbera Sandstone and the Antrim Plateau Volcanics [6]. Initial deposition of the Arumbera Sandstone occurred during the final stages of the Petermann Ranges Orogeny and continued when orogenic activity ceased [42]. Daily et al. [24] regard the principal phase of that orogeny as post-Ediacaran, i.e. the fauna preserved in the upper member of the Pound Quartzite. It is therefore older than the Arumbera Sandstone and that it could be substantially so is suggested by (a) the presence of an orogeny between the two, and (b) the Pound Quartzite pole was derived from the pre-Ediacaran lower member.

Results reported here from South Australia and Western Australia provide independent support for the polar wander curve previously considered common only to northern and central Australia. They are compatible with the main platform having maintained its physical integrity since late Precambrian time. During the period latest Precambrian to Lower Palaeozoic the apparent polar wander curve describes a loop of approximately 180°. Events such as the late Palaeozoic Alice Springs Orogeny probably result from intraplate compression, the effects of which are not detectable palaeomagnetically. Southeastern Australia (excluding Tasmania) which is apparently not underlain by Precambrian rocks [43], has however suffered a relatively complex tectonic history, partly decipherable with the palaeomagnetic method [10].

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**Geog Soc GIDDINGS—1**

# LARGE-SCALE HORIZONTAL DISPLACEMENTS IN SOUTHERN AUSTRALIA — CONTRARY EVIDENCE FROM PALAEOMAGNETISM

by J. W. GIDDINGS and B. J. J. EMBLETON

(With 1 Table and 3 Figures)

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## ABSTRACT

Palaeomagnetic results from 40 dykes sampled on Eyre Peninsula and Yorke Peninsula, South Australia, are inconsistent with the clockwise rotation of the 'foot' of Yorke Peninsula by fault-drag during the Early Ordovician. A reinterpretation of earlier data from Tasmania also indicates that the east-west structural trends in the Mount Reed volcanic arc and Dundas Trough are primary. The effects of shearing were probably restricted to linear displacements without causing rotation of adjacent structural elements. Late Precambrian and Cambrian palaeomagnetic data from Fleurieu Peninsula and Kangaroo Island have also been analysed. They do not clarify the pattern of structural evolution in the southern part of the Adelaide Orogen because the magnetic remanence was probably acquired syntectonically.

## INTRODUCTION

Crawford & Campbell (1973*a*) postulated large-scale intra-continental shearing within Australo-Antarctica culminating in the Ordovician. One major shear forms what is now the southern boundary of Australia, and of the Gawler Block in part—see Figure 1. They regarded the southern part of the Adelaide Orogen as having been bent in a westerly direction by large-scale fault-drag along this shear. This appeared to provide the first satisfactory explanation of that deflection. They went on to suggest that the effects of gradual bending, which ultimately produced east-west structural trends in Kangaroo Island and the Fleurieu Peninsula, also involved the south-eastern part of the Gawler Block, 'slightly rotating the leg of Yorke Peninsula and, as the southernmost part of the Orogen was bent through ninety degrees, snapped the extremity of the Block round into an east-west position, . . .', that is, producing the 'foot' of Yorke Peninsula. The arcuate shape of the Dundas Trough—Mount Reed volcanic arc in Tasmania was also attributed to deformation caused by shearing. They postulated that those features were originally linear, and bent by subsequent compression associated with the shear. Opposing views (Daily *et al.*, 1973; Harrington *et al.*, 1973) also based on geological arguments, maintain that the structural features are primary.

A combined program of palaeomagnetic and geochronological studies of Precambrian dyke swarms in Western and South Australia is near completion. It was designed primarily to investigate relationships between the major Precambrian blocks of southern Western Australia and South Australia for the times of the emplacement of the dykes. During the main study it has been possible to check palaeomagnetically the suggestion of rotation of parts of Yorke Peninsula relative to Eyre Peninsula. Rock samples were collected from 13 dykes which outcrop on the north and west coasts of the 'foot' of Yorke Peninsula and from 6 dykes on the west coast of the 'leg' of the Peninsula—see Figure 2. Twenty-one dykes were sampled on the east coast of southern Eyre Peninsula. All the dykes intrude crystalline basement and are Precambrian in age. Since they ante-date the proposed Lower Palaeozoic shear, differences in magnetic declinations between each of the three sampling localities will provide estimates of the amounts of rotation if it ocurred at all.

Many palaeomagnetic directions have also been determined from late Precambrian and Lower Palaeozoic rock formations from widely separated localities throughout Australia (McElhinny & Luck, 1970; Luck, 1972; Embleton, 1972*a, b;* Embleton & Giddings, 1974). They support the contention that the main Australian platform has retained its gross structural unity since at least late Precambrian time (Embleton & Giddings, 1974). Earlier studies of late Precambrian and Cambrian sedimentary rock formations collected from Kangaroo Island, the southern Mount Lofty Ranges, and the Dundas Trough

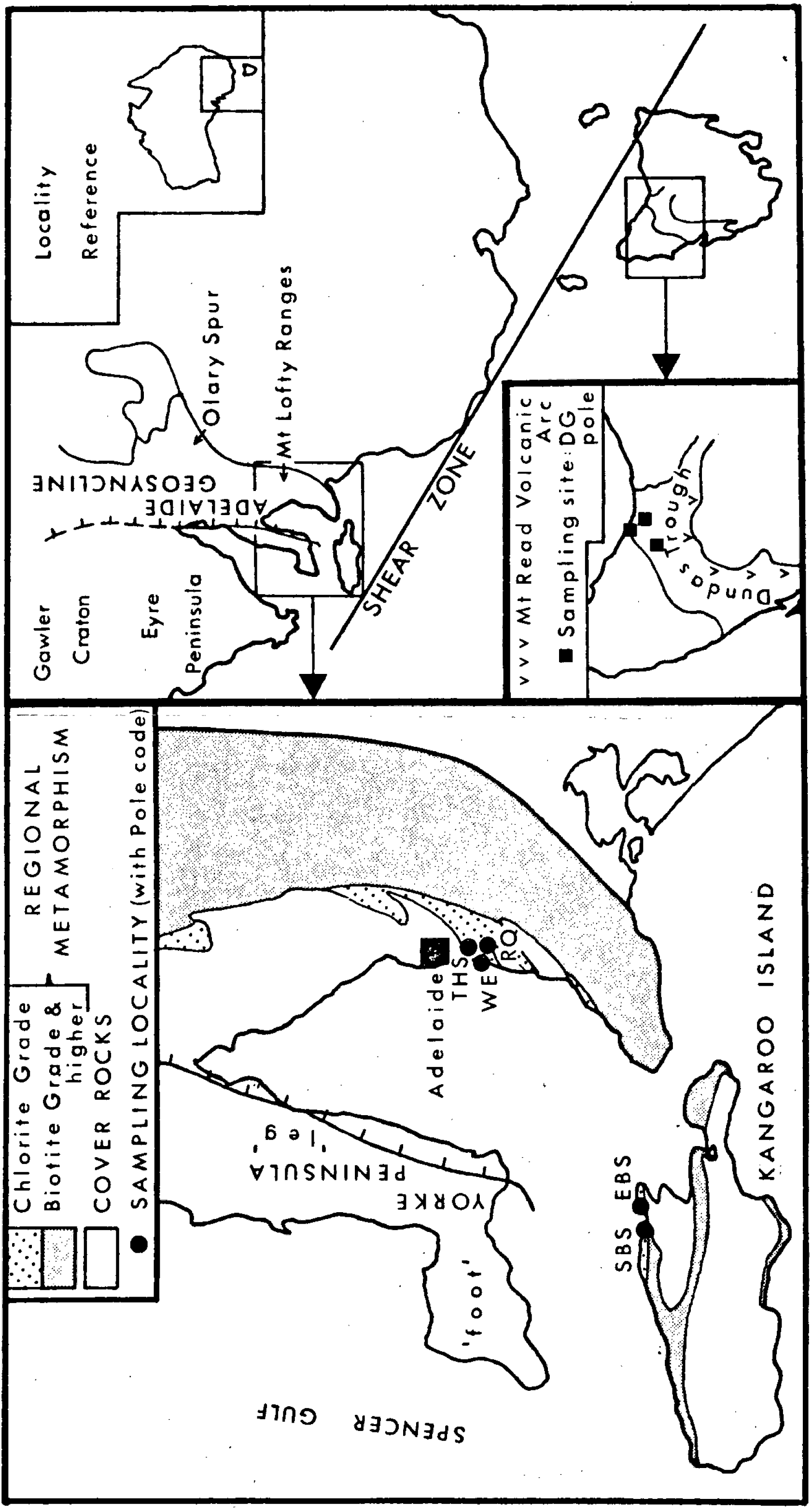

Fig. 1. The principal structural elements in South Australia and Tasmania which according to the Crawford & Campbell (1973*a*) hypothesis initially occupied meridional trends. Sampling localities for the earlier palaeomagnetic investigations are indicated. THS—Tapley Hill Slate, RQ—Marinoan Sandstone (Reynella Quarries), WE—Marinoan Sandstone (Wilmington equivalents), SBS—Stokes Bay Sandstone and Smith Bay Shale, EBS—Emu Bay Sandstone, DG—Dundas Group.

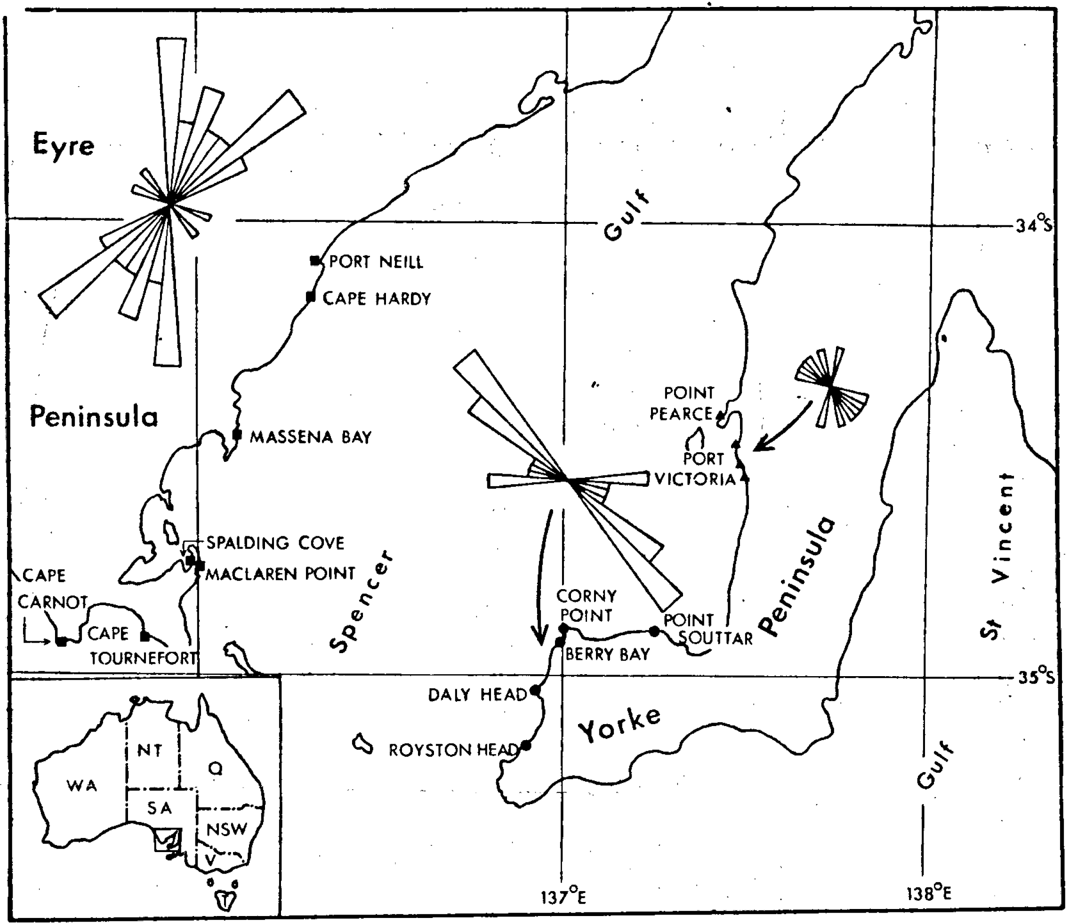

Fig. 2. Precambrian dyke sampling localities in the southeastern region of the Gawler Block. The inset rose diagrams depict measured dyke trends in the principal sampling regions. The shortest unit represents the trend of a single dyke and the longest unit represents four dykes. Each sector covers 10°.

Briden, 1964, 1967*a, b*) were considered inconclusive at the time of publication. A framework therefore now exists within which those data may be reviewed.

## RESULTS FROM THE PRECAMBRIAN DYKES

The remanent magnetism acquired by the dykes has been tested for stability with the alternating field demagnetization technique (As & Zijderveld, 1958). Of the 40 dykes sampled, 34 have retained a proportion of their primary component of magnetic remanence. A full appreciation of the palaeomagnetic results and their interpretation in terms of Precambrian apparent polar wander is being prepared separately for publication. Table I contains the overall mean directions of remanent magnetization of the principal populations of dyke-means from each locality. Dyke-mean directions are plotted stereographically (on a Wulff net) in Figure 3.

(a) *Eyre Peninsula.* Directions of remanent magnetization plot in two distinct groups. The group-means are not antiparallel and probably record successive directions of the geomagnetic field acquired during two separate periods of dyke-intrusion.

(b) *Yorke Peninsula* (the 'foot'). One principal group of directions is apparent; one dyke gave an approximately antiparallel direction. Whether it reflects a geomagnetic field reversal or should strictly be considered a member

TABLE I

*Summary of the palaeomagnetic data from Yorke Peninsula and Eyre Peninsula*

| Sampling Locality | N* | R | D° | I° | $A_{95}$ |
|---|---|---|---|---|---|
| Eyre Peninsula | | | | | |
| (a) positive group | 9 | 8.389 | 270 | +59 | 15° |
| (b) negative group | 10 | 9.665 | 032 | —48 | 9° |
| Yorke Peninsula | | | | | |
| (a) 'leg' | 5 | 4.768 | 275 | +60 | 19° |
| (b) 'foot' | 8 | 7.379 | 275 | +65 | 17° |

* N = number of dykes used to compute the mean, R = resultant of N unit vectors, D° = declination, I° = inclination and $A_{95}$ = semi-angle of the cone of confidence at the 95% probability level (Fisher, 1953).

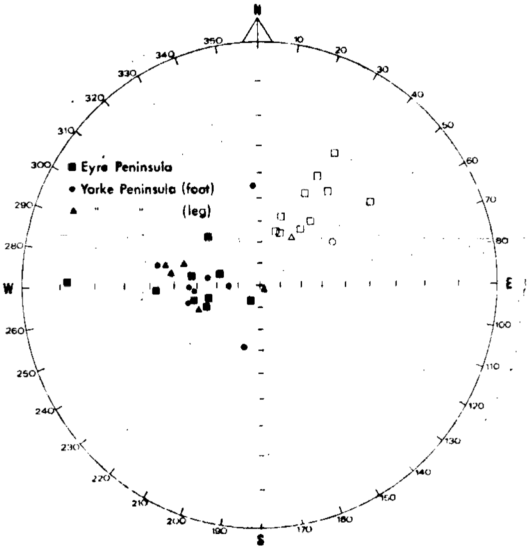

Fig. 3. Dyke-mean directions of primary magnetic remanence. The squares, circles, and triangles correlate with the sampling localities shown in Fig. 2. The positive directions (down-pointing, full symbols) obtained from the 'foot' and the 'leg' of Yorke Peninsula and Eyre Peninsula form a tight homogeneous group.

of the negatively magnetized group defined from Eyre Peninsula is uncertain.

(c) *Yorke Peninsula* (the 'leg'). Six dykes, 5 of which are positively magnetized and 1 negatively magnetized, form a group coincident with dyke-mean directions from Eyre Peninsula and the 'foot' of Yorke Peninsula.

Crawford & Campbell (1973*a*) report that lineations thought to be bedding foliation in the basement gneisses of the 'foot' of Yorke Peninsula diverge by up to 90° from lineations measured in the 'leg' and in the basement gneisses of Eyre Peninsula—following work by Crawford (1965).

Where the outcrops permitted, the structural trends of the dykes sampled for palaeomagnetism were measured. The compass rose diagrams, inset in Figure 2, show quite clearly that the dykes which intrude the basement gneisses of Yorke Peninsula conform to a unimodal distribution. Those intruding the 'foot' vary in strike from about 270° to 320° and intruding the 'leg' vary from 290° to 340°, with one dyke trending approximately north-south. On the other hand dyke trends on Yorke Peninsula are different from those on Eyre Peninsula. As seen in Figure 2, dykes on Eyre Peninsula generally trend between 0° and about 50°.

## APPRAISAL OF PREVIOUS ~~SEDIMENTS~~ INVESTIGATIONS OF LATE PRECAMBRIAN-CAMBRIAN SEDIMENTS

Palaeomagnetic results have been described by Briden (1964) from the Upper Glacial and Interglacial beds of the late Precambrian Umberatana Group sampled south of Adelaide (Fig. 1), and from red-beds of Early and Middle Cambrian age sampled on Kangaroo Island. Much of the material studied was considered '. . . remagnetized, not in recent times, but as long ago as the Early Tertiary' (Briden, 1964, p. 98). This conclusion was reached for two principal reasons: (i) the uncleaned directions of magnetization were considered steeper than the present field direction and clustered around the Early Tertiary field direction—as it was then defined (Irving, 1964); and (ii) the postulated reheating effect of basalts, at that time thought to be of Early Tertiary age, which outcrop on low hills above the Cambrian outcrops on Kangaroo Island. To influence the thermal regime on Fleurieu Peninsula, the basalts would have to have been much more extensive. We now know from potassium-argon geochronology (Wellman, 1971) that the Kangaroo Island basalts are significantly older—about 170 m.y.—than was previously thought. An Early Tertiary remagnetization of the late Precambrian and Cambrian sediments therefore loses credence. Briden reported the results in meticulous detail because he acknowledged that '. . . some of these results will become more intelligible when further work is carried out on rocks of these ages in Australia' (Briden, 1964, p. 99).

The analysis was undertaken initially because our current research program involved the investigation of unmetamorphosed Cambrian and late Precambrian sediments from the northern Flinders Ranges (Embleton & Giddings, 1974). Our study of the palaeomagnetism of the Pound Quartzite indicated that it was necessary to follow very closely the response of individual specimens to thermal cleaning. Since specimens cut from a sample often covered the stability spectrum, analysis of the data obtained at the sample level produced a confused pattern. Luck (1972) also encountered similar problems during his investigations of Lower Palaeozoic formations from northern Australia. Aware that remagnetization and the acquisition of viscous remanent magnetization may take place inhomogeneously we scrutinized the earlier results and tentatively identified specimens which after partial thermal demagnetization appeared to contain a stable component of magnetization oblique to the present field axis. The formations which yielded the data are the Tapley Hill Slates (older than the Marinoan glacials), Marinoan Sandstones from the Fleurieu Peninsula (as old as or older than the glacials) and the Emu Bay Sandstone, the Stokes Bay Sandstone, and the Smith Bay Shale of Early-Middle Cambrian age from Kangaroo Island. However, the directions of magnetic remanence obtained by Briden (1964), although scattered, were not unlike those obtained from Cambro-Ordovician formations described by Embleton (1972*b*), Luck (1972), and Embleton & Giddings (1974). It appears that the formations in the southern part of the Adelaide Orogen may well have suffered remagnetization, but it was a Cambro-Ordovician rather than a Tertiary event. Regional metamorphism and intrusion of granitic bodies in the southern Mount Lofty Ranges and Kangaroo Island occurred during the Delamerian Orogeny in the Late Cambrian and Early Ordovician (Offler & Fleming, 1968; Thomson, 1969). The localities Briden sampled for his investigation are situated within the chlorite zone of the greenschist facies. We believe that the regional metamorphism created an environment suitable for remagnetization.

## IMPLICATIONS FOR LARGE-SCALE HORIZONTAL DISPLACEMENTS IN SOUTHERN AUSTRALIA

We interpret the directions of magnetization measured in the dykes as records of the ambient geomagnetic field direction at the time of dyke intrusion. Alternatively those dykes which constitute the positive (down-pointing) group of directions (Fig. 3) could be regarded as having been selectively remagnetized after the postulated rotation took place, i.e. after Early Ordovician. This interpretation is considered untenable; (a) the direction of magnetization is unlike any field direction yet measured from post-Ordovician rocks in Australia, (b) the bimodal distribution of directions has been retained, which would be extremely unlikely after remagnetization. Therefore, results from the southeastern region of the Gawler Block are inconsistent with a structural model involving local rotation in Yorke Peninsula (viz. the 'foot' with respect to the 'leg') and rotation of the entire Peninsula relative to Eyre Peninsula. Indeed, the consistency of the palaeomagnetic data may be considered particularly good and indicates that the region has maintained its physical integrity at least since the time of dyke intrusion. Furthermore, the trends of the dykes in the 'foot' and the 'leg' of Yorke Peninsula lend no support to the rotation hypothesis.

The result, acknowledged by Crawford & Campbell (1973*b*), only indicates that the southeastern margin of the Gawler Craton has remained structurally intact. The data cannot be extrapolated to disprove bending of the southern Mount Lofty Ranges since they constitute a distinct tectonic unit. Unfortunately, Briden's (1964) data are inconclusive in this context. If the beds were remagnetized, as we believe, then the magnetic remanence would have been acquired syntectonically. Unknown variables in attempting to elucidate this problem include the time relationships of folding and metamorphism (Offler & Fleming, 1968), the degree of remagnetization, and whether secondary components of magnetization were completely removed by cleaning the samples in the laboratory at only 400°C.

The few palaeomagnetic data available for the Late Cambrian Dundas Group of Tasmania (Briden, 1967*b*; Embleton & Giddings, 1974) are free of the inherent problems which complicate the South Australian data. The pole position is based on results from sedimentary and igneous rock types. The stability of the remanent magnetism was demonstrated by thermal and A.F. cleaning techniques, the presence of reversed polarities and the reduced scatter of directions after applying the fold test (Graham, 1949 and McElhinny, 1964). The pole at 23°S, 13°E ($A_{95} = 11.5°$) agrees with poles of equivalent age from the rest of Australia. Early Ordovician fault drag or some other mechanism was therefore not responsible for bending the Dundas Trough and the east-west portion of the Mount Reed volcanic arc from their supposed primary meridional trends.

## CONCLUSIONS

We have concerned ourselves principally with the structural implications of large-scale horizontal displacements in southern Australia. The palaeomagnetic data presented bring into dispute that the effects of shearing produced rotations on the scale envisaged. We do not, however, dispute the geological evidence for activity along a structural lineament as described in the hypothesis. A relatively simple linear displacement of a few hundred kilometres would probably not be resolved palaeomagnetically.

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# Palaeomagnetic results and late Precambrian glaciations

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*A combined late Precambrian to early Palaeozoic polar wander path, which differs from that previously proposed for Africa and South America, is derived for Gondwanaland. It suggests that Gondwanaland existed at least 750 Myr ago. The widespread distribution of late Precambrian glaciations can be explained in terms of this polar migration. It is predicted that the late Precambrian and Cambrian part of the North American polar wander path may be more complicated than previously supposed.*

Piper *et al.*[1] have tested whether the concepts of modern plate tectonic theory, as applied to several Phanerozoic orogenic belts[2–6], can be applied to all ancient orogenic belts. Their analysis shows that all palaeomagnetic pole positions for Africa between 2,200 Myr ago and about 450 Myr ago (close of the Ordovician) lie on a single apparent polar wander path, irrespective of cratonic region. This suggests that the major cratonic areas were approximately in their present relative positions and orientations as early as 2,200 Myr ago. The younger intervening orogenic belts did not, therefore, result from plate accretion and subduction processes during an episode of major ocean closure which culminated in a continent–continent collision[7,8]. Rather, the data support the view that these belts formed *in situ*, the stable cratonic nuclei remaining in place while the intervening belts themselves were being reactivated[9,10]. Present data cannot, however, preclude the possibility that the belts resulted from the successive opening and closing of small intercratonic oceans.

Comparing with American Precambrian data, Piper *et al.*[1] further suggest that South America and, until about 1,000 Myr ago, North America may have been joined to Africa, and the concentration of all continental crust in one large mass until that time remains as a possibility. A further consequence of their interpretation is that if any of the Precambrian glaciations which affected south-west, central and north-west Africa, and parts of South America, originated between 900 and about 650 Myr ago, then they were formed in low latitudes[11,12].

New results from late Precambrian and early Palaeozoic formations in Australia (ref. 13 and J. W. Giddings and B. J. J. Embleton, unpublished information) and India[14,15] allow us to extend the comparisons of Piper *et al.*[1] to include the whole of Gondwanaland. Our results lead to a different interpretation of the late Precambrian to early Palaeozoic apparent polar wander path. A consequence of this is that late Precambrian glaciations are restricted to high latitudes, as may be expected. Our interpretation does not, however, affect the general conclusions of Piper *et al.*[1], but leads to some predictions concerning the apparent polar wander path for North America.

## Gondwanic palaeomagnetism

Palaeozoic and Mesozoic palaeomagnetic results, when referred to the reconstruction of Smith and Hallam[16], suggest that a common apparent polar wander path can be applied to the supercontinent from some time in the early Palaeozoic until its break up in the Mesozoic[17]. Interpretation of the early Palaeozoic section of the path has been uncertain because the poles tend to form rather a loose group in the region off north-west Africa. Stratigraphic sequences have been studied in both northern Australia and the Amadeus Basin of central Australia[13,18]. The studied strata range in age from Precambrian–Cambrian through to the Ordovician. In each of these unrelated sequences a very large polar shift of 50°–60° of arc is observed during the earliest Cambrian, and in the Amadeus Basin[18] the total shift during the early-Palaeozoic is about 90°. Figure 1 compares the Australian results on the reconstruction of Gondwanaland, with the corresponding late Precambrian and early Palaeozoic path for Africa and South America[1]. It can be seen that the two Cambrian sections of the curves do not agree, and in fact have polar shifts in opposite directions.

There are two possible explanations of this disagreement. First, is that the earliest Cambrian sections of the two paths could refer to separate plates which collided to form Gond-

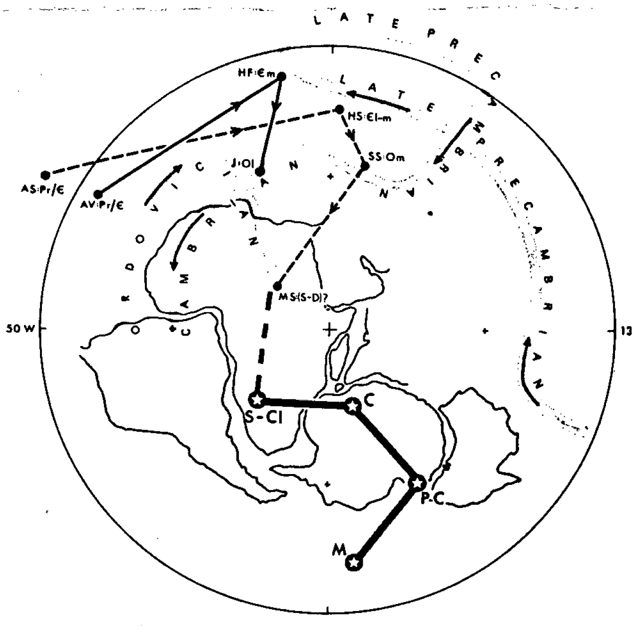

Fig. 1 Late Precambrian to early Palaeozoic apparent polar wander path for Africa and South America suggested by Piper *et al.*[1] (stippled path), plotted against the reconstruction of Smith and Hallam[16] with Africa in its present day position. The large Cambrian polar shift observed in two stratigraphic sequences in northern Australia (solid line) and central Australia (dashed line) are shown for comparison. The pole designations are as listed in Table 1. Note that the path of Piper *et al.* places Africa in equatorial latitudes during the latest Precambrian. The solid black line connecting the mean Silurian–Lower Carboniferous (S–Cl), Carboniferous (C), Permo–Carboniferous (P–C) and Mesozoic (M) poles is the common path for this time interval[13,17].

TABLE 1 Gondwanic continents: late Precambrian–early Palaeozoic pole positions

| Rock unit | Symbol | Age (Myr) | Palaeomagnetic Pole coordinates | |
|---|---|---|---|---|
| **Africa** | | | | |
| Bukoban Sandstone | BS | Pr(~1000) | 40°N | 317°E |
| Kigonero Flags | KF | Pr(>890) | 12°N | 273°E |
| Kleinkaras Dykes | KK | Pr(878 ± 41) | 20°N | 294°E |
| Gagwe Lavas | G | Pr(813 ± 30) | 29°S | 293°E |
| Bukoban Intrusives | BI | Pr(806 ± 30) | 11°S | 281°E |
| Mbozi Complex | M | Pr(743 ± 30) | 72°S | 248°E |
| Lower Buanji Series | LB | (<1,350) | 87°S | 83°E |
| Pre-Nama Dykes | ND | Pr(653 ± 70) | 85°S | 48°E |
| Plateau Series, Zambia (i) | PZA | (<1,000) | 71°S | 353°E |
| Plateau Series, Zambia (ii) | PZB | (<1,000) | 60°N | 25°E |
| Sijarira Group | SG | Pr/€ | 2°N | 352°E |
| Ntonya Ring Structure | N | Pr(630 ± 24) | 28°N | 345°E |
| Klipheuvel Formation | K | Pr/€l | 16°N | 316°E |
| Ouarzazate Volcanics | OV | Pr/€ | 30°N | 237°E |
| Amouslek Tuffs | AT | €1 | 41°N | 250°E |
| Sabaloka Ring Structure | SR | (>540) | 83°N | 339°E |
| Fish River Series | FR | €l | 55°S | 317°E |
| Moroccan Lavas | ML | €m | 53°N | 34°E |
| Table Mountain Series | TM | 0 | 50°N | 349°E |
| Hook Intrusives | HI | 01(500 ± 17) | 14°N | 336°E |
| Plateau Series, Zambia (iii) | PZC | Lr.Pal | 10°S | 352°E |
| Plateau Series, Zambia (iv) | PZD | Lr.Pal | 22°N | 19°E |
| **Antarctica** | | | | |
| Charnockites | C | €u-01 | 2°S | 20°E |
| Sør Rondane Intrusives | SRI | 01-m(485 ± 25) | 28°S | 10°E |
| **Australia** | | | | |
| Precambrian Dykes, B Group | B | Pr(750)* | 24°S | 282°E |
| Pound Quartzite | PQ | Latest Pr | 60°S | 6°E |
| Antrim Plateau Volcanics | AV | Pr/€1 | 9°S | 340°E |
| Arumbera Sandstone | AS | Pr/€1 | 8°N | 325°E |
| Aroona Dam Sediments | AD | >€1 | 36°S | 33°E |
| Hugh River Shale | HS | €1-m | 11°N | 37°E |
| Hudson Formation | HF | €m | 18°N | 19°E |
| Lower Lake Frome Group (Flinders Ranges) | FRS | €m | 8°S | 25°E |
| Upper Lake Frome Group (Balcoracana Creek) | BC | €u | 38°S | 26°E |
| Jinduckin Formation | J | 01 | 13°S | 25°E |
| Stairway Sandstone | SS | Om | 2°S | 50°E |
| Mereenie Sandstone | MS | (S-D)? | 41°S | 40°E |
| **India** | | | | |
| Malani Rhyolites | MR | Pr(745 ± 10) | 42°S | 115°E |
| Bhander Sandstone | BH | Pr/€ | 49°S | 33°E |
| Upper Rewa Sandstone | UR | Pr/€ | 35°S | 42°E |
| Upper Bhander Sandstone | UB | Pr/€ | 32°S | 19°E |
| Purple Sandstone | PS | €1 | 28°S | 32°E |
| Salt Pseudomorph Beds | SP | €m | 27°S | 33°E |
| **South America** | | | | |
| Purmamarca Village | PV | € | 61°N | 293°E |
| South Tilcara | ST | € | 52°N | 27°E |
| North Tilcara | NT | € | 49°N | 24°E |
| Purmamarca | P | € | 5°N | 39°E |
| Abra de Cajas | AC | € | 2°N | 28°E |
| Salta and Jujuy | SJ | €-0 | 12°N | 329°E |
| Salta | S | 0 | 31°N | 13°E |
| Sediments, Bolivia | SB | 0 | 4°N | 302°E |
| Urucum Formation | UF | 0-S | 17°N | 347°E |

Age symbols: *provisional Rb-Sr age; Pr, Precambrian; €, Cambrian; 0, Ordovician; S, Silurian; D, Devonian. Upper, Middle and Lower divisions denoted by u, m and 1 respectively.

References: Africa[1,17,21]; Antarctica[17]; Australia[13], McElhinny, M. W., Giddings, J. W., and Embleton, B. J. J., not yet published; India[14,15,17,19]; South America[17,20].

wanaland during the mid-Cambrian. The timing then corresponds to the peak of the 550 ± 100 Myr pan-African orogeny, which was not the result of plate convergence[1]. It thus seems unlikely that any one of these orogenic belts, such as the Mozambique belt, represents the suture between an eastern and a western Gondwanaland. The alternative is that it may be possible to re-interpret the African and South American data to conform with the Australian results.

## Pole path for Gondwanaland

Table 1 lists all the palaeomagnetic poles for the Gondwanic continents between about 1,000 Myr and about 450 Myr (close of the Ordovician).

All the palaeomagnetic poles of Table 1 have been analysed with respect to the reconstruction of Gondwanaland of Smith and Hallam[16], and are shown in Fig. 2. We have been able to interpret all the data to account for the Cambrian polar shift observed in the stratigraphic sequences in Australia. All the South American poles designated Cambrian by Thompson[20] now fall on the Cambrian section of our combined path. African poles younger than about 700 Myr, but pre-Ordovician, have very poor age control, with the single exception of the 630 ± 24 Myr Ntonya Ring Structure of Malawi. We have been able to incorporate these poles into our combined path by minor rearrangement of their sequence without violating the tolerances on their age control. Significantly, this places the Ntonya pole at a point on the path just before the Precambrian–Cambrian boundary, whereas in the African path proposed by Piper *et al.*[1] it was out of sequence and inferred to have a much younger age.

We have not drawn the path through the two late-

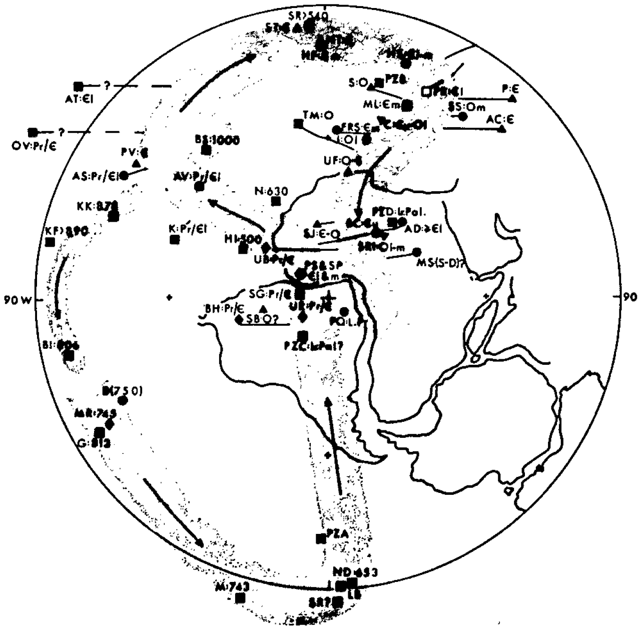

FIG. 2 Revised late Precambrian to early Palaeozoic polar wander path using all the Gondwanic poles listed in Table 1. Bearing in mind the uncertainties in some of the ages and the errors associated with the pole positions, all poles younger than 750–800 Myr are consistent with a common polar wander path when referred to the Smith–Hallam reconstruction[16]. The path is indicated by the broad band drawn through the poles. Before 750–800 Myr the sequence of poles is as yet only defined by African data indicated by the narrower band going back to about 1,000 Myr. ■, Africa; ▼, Antarctica; ●, Australia; ◆, India; ▲, S. America. Labelling as in Table 1.

Precambrian and early Cambrian Moroccan poles[21] because this part of Africa might be a remnant of a Precambrian North America. It would not, however, be difficult to incorporate these into a slightly modified path, and then also identify a large Cambrian shift for North Africa to the pole for the Middle Cambrian Moroccan lavas. Latest Precambrian poles cluster in the region west or south of north-west Africa. The pole from the Cambro–Ordovician Hook Intrusives of Zambia is in this group but its circle of confidence is large enough for it to be associated with the later part of the curve in the region of the Sahara. The Cambrian poles from the Salt Range also seem to be out of sequence. This supports the suggestion of a separate Indus sub-plate[15], but for an entirely different reason to that proposed. Originally the proximity of the Salt Range poles to those from the Bhander and Rewa Series seemed to suggest that they were all of the same age[14]. A more likely late-Precambrian age for the Bhander and Rewa Series now supposes that the structural setting of the Salt Range has caused their poles to be displaced from the Cambrian part of the curve. The pole from the Bolivian sediments of supposed Ordovician age falls in a region which suggests that these sediments may be rather older than supposed.

If the African part of the apparent polar wander path is to be extended back from the late Precambrian group it should continue southwards (Fig. 2) to the vicinity of the Mbozi Complex pole. It is at this point that our interpretation differs significantly from that of Piper *et al.*[1]. The early Palaeozoic section of the pole path, as we have drawn it, represents the South Pole path (Fig. 2), but our interpretation obliges us to join up with what Piper *et al.*[1] regard as the North Pole path for about 700 Myr and older (Fig. 4 in ref. 1).

## Unity of Gondwanaland

The 745 Myr Malani rhyolite pole for India plots close to a new Australian pole (J. W. Giddings, and A. R. Crawford, unpublished information) for which a provisional Rb-Sr age of 750 Myr has been estimated. These poles fall on the African curve near poles dated at around 800 Myr. This suggests to us that the consistency of the results for the Smith–Hallam reconstruction[16] defines a single pole path extending back at least 750 Myr. It confirms the conclusion that the Pan-African orogenic belts must have been formed *in situ*[1]. We can now extend the case of the intercratonic belts within Africa to those within Gondwanaland, such as the Mozambique belt and the eastern Ghats belt.

## Late Precambrian glaciations

The occurrence of glacial deposits (tillites) in many late Precambrian formations throughout the world has led to the hypothesis that a widespread glaciation occurred just before Cambrian times[22,23]. An essential point relating to this hypothesis is whether these glaciations occurred successively throughout polar migration or whether they occurred simultaneously and therefore perhaps extended to low latitudes. The interpretation of the late Precambrian to early Palaeozoic apparent polar wander path for Africa is crucial in this context because many of the late Precambrian glacial deposits are located in that continent. The pole path deduced by Piper[11] and Piper *et al.*[1] implies that the glaciated regions essentially occupied low latitudes, and that the glaciation was widespread[12]. Our interpretation of the late-Precambrian to Cambrian pole path leads, however, to the conclusion that the pole migrated across South America (which was then joined to Africa) from south to north, during the late Precambrian. This is consistent with the occurrence of glacial deposits which are successively younger northwards along western Africa (Fig. 3).

In South West Africa two glacial episodes are recorded[24]. Glacial horizons occur in the upper part of both the Damara

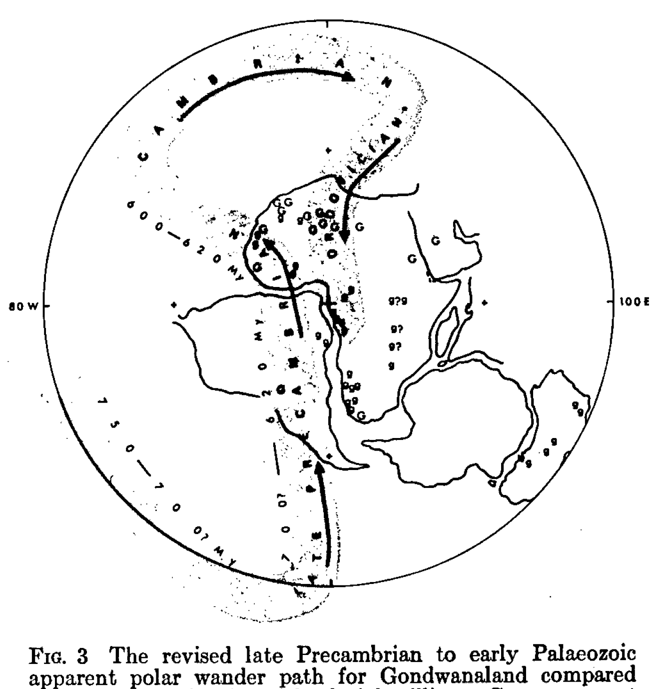

FIG. 3 The revised late Precambrian to early Palaeozoic apparent polar wander path for Gondwanaland compared with the distribution of glacial tillites. G,g, represent Ordovician and late Precambrian occurrences respectively. Glacial deposits in Africa possibly older than about 700 Myr and therefore not related to the drawn path have question marks. Successively younger late Precambrian occurrences along the west coast of Africa are matched by the south–north migration of the pole.

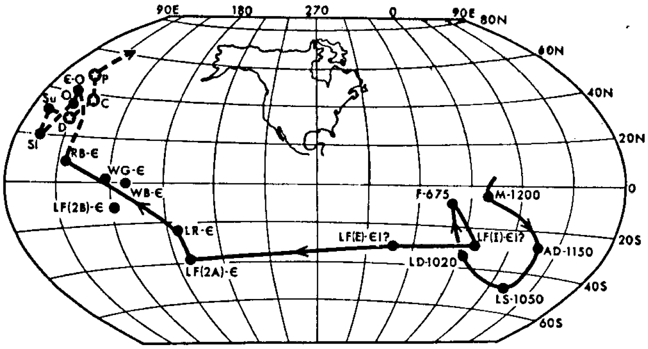

Fig. 4 Suggested revised North Pole apparent polar wander path for North America, which joins the Great Logan Loop[35] (1,200–1,020 Myr) to the Ordovician (O) part of the curve by means of a large Cambrian shift. Cambrian poles from: RB, the Ratcliffe–Brook formation[18]; WG, Wichita granites[18]; WB, Wilberns formation[39]; LR, Lodore formation[18]; LF-I, 2A, 2B and E, Lamotte formation[38]. Anchor points for the Great Logan Loop[35] are shown together with the Franklin pole[35] (F). Post-Cambrian Palaeozoic poles[39] are joined by a dashed line, the stars representing mean Devonian (D), Carboniferous (C) and Permian (P) poles.

and Nama Systems which are correlated with one another, and whose lower boundaries are not older than 650 Myr. Immediately underlying the Nama System are the Blaubeker Formation glacials and the Buschmannsklippe tillite. These are correlated with glacials of the Numees Formation which forms the upper part of the Gariep Group. A felsite lava in the Kapok Formation, which corresponds to the lower part of the Gariep Group, has an age of 720 Myr. The Blaubeker–Buschmannsklippe–Numees glacials are therefore very likely to be younger than 700 Myr. In Katanga the Pétit Conglomérate is probably of glacial origin and has a minimum age of 620 Myr (ref. 25). The Grand Conglomérate of Zaire is, however, probably older than 850 Myr (ref. 25) and therefore relates to a very much earlier glacial episode. In north-western Africa the Saharan 'Eocambrian' tillite has been dated at 620–650 Myr (ref. 26), whereas, in Ghana the Oti tillite has an age of 620 Myr (ref. 29). This succession strongly suggests that the centres of glaciation followed the path of the pole in late Precambrian times as it swept from south to north, past southern, western and north-western Africa, between about 700 Myr ago and 620 Myr ago (Fig. 3). It seems significant that the best dated African late-Precambrian pole, the 630 ± 24 Myr Ntonya result, plots just off north-west Africa (Fig. 2) corresponding to the time when this region was extensively glaciated.

During the Cambrian the broad trends of climatic change are perceptible[28]. In North Africa the occurrence of thick successions of Lower Cambrian warm water deposits include also archaeocyathid reefs. Cambrian rocks are frequently brightly coloured, indicating a warm climate, but they give way to more drab Ordovician sequences which culminate in the great, late Ordovician, Saharan glaciation[29]. These broad trends are not only compatible with the Cambrian and Ordovician sections of the pole path, but also resolve a previously puzzling palaeoclimatic anomaly[30]. From near polar conditions in north-west Africa the broad loop taken by the pole during the Cambrian placed North Africa in low latitudes, with a return to intermediate, and finally polar, latitudes during the Ordovician.

It is not clear how the pattern of late Precambrian glaciation in Australia fits into the polar migration proposed in Figs 2 and 3. Dunn *et al.*[31] cite ages of 750 Myr for the Sturtian–Moonlight Valley glaciation, but these are all based upon Rb-Sr measurements on shales. The interpretation of isochrons drawn through such data in terms of age of deposition is very much an open question (W. Compston, personal communication), so that the relationship of these ages to those on our pole path is unclear. We make the general observation, however, that between 750 Myr and 600 Myr a polar migration of at least 180° is proposed with respect to Gondwanaland. Very large polar shifts are observed in almost all continents during the late-Precambrian and Cambrian. It is therefore not surprising that the poles migrated quite rapidly over different parts of the globe leaving records of glaciated regions as they passed over the various continents. In these circumstances it is not necessary to invoke the hypothesis of an extensive synchronous world-wide glaciation that extended to low latitudes (see also ref. 32). The decisive test between the two hypotheses will come from palaeomagnetic measurements on the actual glacial horizons in various places around the world. If these measurements show that many of these deposits were formed in low latitudes then this will support the hypothesis of a synchronous world-wide glaciation.

## Great Logan Loop of North America

There is an impressive correspondence between an extended loop in the African apparent polar wander path and the so-called Great Logan Loop[33] of the North American path[1,11]. Both of these loops cover the time range 1,200–1,000 Myr. Our interpretation of the African polar wander path means that the poles in this time range are now south poles which can only be matched with the presumed North American north poles for the same time. The fit of the two loops is impressive, and so we tentatively suggest that the late Precambrian to early Palaeozoic section of the North American polar wander path may be much more complicated than previously supposed. Irving and Park[34] have already noted the very tentative nature of this section of the North American curve. There is only a single pole (the Franklin pole, 675 Myr) between the end of the Logan loop at about 1,000 Myr, and the Cambrian. During the same period in Africa the polar shift was more than 180° (Fig. 2). During the Cambrian alone the pole shift was about 90°. Furthermore, Cambrian results from the Bohemian massif have previously been interpreted in terms of a large polar shift of about 130° (ref. 35) and a large polar shift is also recorded in the Cambrian of Siberia[17].

The Lamotte formation of Missouri (Cambrian in age, although the fossil evidence is poor) shows four distinct palaeomagnetic poles[36]. Poles from the higher horizons are in two groups (2A and 2B), related to their stratigraphical positions, and suggest a polar migration during the Late(?) Cambrian. Poles from the lower horizons seem to be anomalous. No reason is apparent for group 1 and the other (Locality E) is close to the Carboniferous pole for North America. Carboniferous remagnetisation has been proposed, although no evidence has been given either to suggest how this arose or why it occurred selectively at only one locality. Studies of the Ordovician Trenton Limestone[37] have shown that the hypothesis of widespread late-Palaeozoic remagnetisation of Lower Palaeozoic rocks is no longer tenable. We therefore interpret these poles as representing a polar migration during the Cambrian.

Figure 4 shows how it is possible to join the later Palaeozoic poles for North America through an extended Cambrian path, to the opposite poles of the Logan Loop. These poles become the north pole path for North America with the consequence that the plot of the Logan Loop in the Pacific[33,34] represents the south pole path. It is then readily matched with the African loop (see ref. 1). Our prediction therefore is that extensive studies of late Precambrian and Cambrian rocks of North America (1,000–500 Myr) will reveal a complicated apparent polar wander path with a polar shift through at least 180°.

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