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PALAEOMAGNETISM AND GEOLOGY

by

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SUMMARY

A brief description is given of the physical basis of rock magnetism and of the various ways in which rocks become magnetised. There follow sections with diagrams showing the variation of the geomagnetic field relative to Australia, and mentioning several applications of rock magnetism to the solution of geological problems.

1. INTRODUCTION

Palaeomagnetism has now developed to the stage at which it is possible for it to be used in helping to solve geological and geophysical problems. This brief review is intended to draw attention to some of the ways in which rock magnetism can be applied. A short account of the physics involved is followed by a section on palaeomagnetic geochronology and a section dealing with some geological problems on tectonic movements and the origin of orebodies. A general reference to these subjects is Nagata (1961).

2. THE MAGNETISATION OF ROCKS

Rock magnetism is an important branch of geophysics, but unfortunately many of the results have to be treated empirically because the theory of the physical processes involved is not always well understood. The remanent magnetisation in rocks is nearly always due to minerals having a composition within the magnetite-haematite-ilmenite-ulvospinel complex of the FeO-TiO_2-Fe_2O_3 ternary system (Plate 1). The magnetite-ulvospinel and magnetite-ilmenite series are the most important because more is known about their magnetic properties and because their behaviour is more predictable. They are cubic minerals having an inverse spinel structure; technically, they are 'ferrimagnetic' substances, but it is common to call them 'ferromagnetic'.

At present, there are thought to be five types of magnetism:

(a) Diamagnetism. This does not concern us because it cannot give rise to remanent magnetism.

(b) Paramagnetism. This occurs when each atom or molecule behaves as an independent elementary magnet, randomly oriented except when in an applied magnetic field. It does not give rise to remanent magnetism, but may be regarded as a special case of ferrimagnetism.

(c) Ferromagnetism. This occurs when, below the Curie point, the elementary magnets (atoms, molecules, or ions) within a region of the crystal known as a 'domain' are aligned parallel to each other, creating a spontaneous magnetisation even when there is no applied field.

(d) Antiferromagnetism. This is similar to ferromagnetism except that two sets of equal elimentary magnets order themselves antiparallel.

(e) Ferrimagnetism. This is a variant of antiferromagnetism, in which the different sub-lattices have elementary magnets of unequal size, so that in the ordered configuration their magnetic moments do not compensate, but create a residual magnetic moment.

The magnetisation of a piece of rock is due to grains of magnetic minerals embedded within an essentially non-magnetic matrix (some minerals containing iron are often strongly paramagnetic, but these do not affect the remanence). The magnetic grains usually constitute from less than 1% to as much as 10% of the rock by volume. The intensity of magnetisation within these grains is much greater than the measured overall magnetisation, and each of the grains is itself split up into magnetic domains (the linear dimensions of a domain are of the order of 10^{-2} microns), inside which the magnetisation is even stronger. Neighbouring domains are magnetised in opposite directions, or form some other 'closed' structure.

The direction of magnetisation of each domain is mainly controlled by crystal structure, and the nett magnetisation of each grain is controlled by its shape; very rarely will the direction of remanent magnetisation of an individual grain be that of the magnetic field that produced it. In the case of rocks isotropic on a macroscopic scale, the vectorial addition of the several hundreds or thousands of magnetic grains in a rock specimen produces a nett magnetisation parallel to the ambient field. If this is not the case, the remanent magnetisation is not necessarily parallel to the ambient field in which it was acquired, and the rock is said to be 'magnetically anisotropic'.

The natural remanent magnetisation (NRM) of a rock may be the resultant of several components of magnetisation acquired by natural processes at different times in its history. For an igneous rock, the most important of these components is the thermoremanent magnetisation (TRM), which a rock acquires on cooling from its Curie point temperature in the Earth's magnetic field. It is very stable and generally the largest component of NRM and is, with certain exceptions, always in the direction of the Earth's field at the time of cooling. Isothermal remanent magnetisation (IRM) is acquired by rocks at a constant temperature but, except for rare cases of unusually strong IRM values acquired in the large fields associated with lightning discharges, it is so weak that it can be ignored. Over a long period of time, rocks also acquire a magnetisation, called 'viscous magnetisation', which is proportional to the logarithm of the time. Fortunately this secondary magnetisation is less resistant to demagnetisation than TRM and it is possible to remove this without destroying all of the primary magnetisation, so that the primary direction can be detected and measured. Demagnetisation may be done by applying alternating magnetic fields - 'magnetic cleaning' - or by cooling from an elevated temperature (less than the Curie point) in zero magnetic field - 'thermal cleaning'.

The ability of a rock to retain a direction of magnetisation, especially TRM, over millions of years cannot be proved by laboratory experiments, but there is field evidence that even some Precambrian rocks have primary magnetisation which still exists at the present time (Irving, 1959; Blackett, Clegg, & Stubbs, 1960; Collinson & Runcorn, 1960).

Less is known about the magnetism of sedimentary rocks. At this stage it seems probable that, in many cases, the remanent magnetisation is due to chemical magnetisation (CRM) of haematite in the 'cement' and this raises the question of when the magnetisation occurred. There is little or no direct information on this, but palaeomagnetic results from all parts of the world and from rocks of all ages, indicate that it took place soon after deposition. Magnetic anisotropy is more common in sedimentary rocks and must be measured before any reliance can be placed on the palaeomagnetic results obtained, but this does not necessarily affect the usefulness of these results as long as the degree of anisotropy is known and allowed for in the calculations.

The interpretation of palaeomagnetic results from different parts of the world is most often based on the 'geocentric axial dipole' hypothesis for the origin of the geomagnetic field, which assumes that the main field, i.e. the actual field averaged over 10^3 - 10^4 years, is nearly the same as that due to a dipole at the centre of the earth, parallel to the axis of rotation. This is known to be true for the last 10,000 or 100,000 years and currents in the liquid core of the earth, which are the most probable cause of the main field, are likely to have axial symmetry because of forces arising from the rotation of the earth. In many of the cases mentioned below, this is not an essential assumption, but it is a convenient working hypothesis and there is no evidence that it is not true.

The direction of magnetisation is described as 'normal' or 'reversed'. 'Normal' refers to the present-day sense. For earlier times, when the results are interpreted as pole positions, 'normal' means that the ancient boreal and austral poles were in the present-day northern and southern hemispheres respectively. (There are exceptions to this rule in Precambrian times). The normal (or present day) sense of the geomagnetic field is said to have negative polarity. This may seem rather paradoxical, (like electrons and electric currents), but it is a convention only, and is chosen because the poles of the earth are opposite to what is commonly called 'north' and 'south' poles - that is, the boreal magnetic pole is of the same sign as the south-seeking pole of a compass needle.

3. THE 'PALAEOMAGNETIC STRATIGRAPHIC COLUMN'

Just as palaeontology has established a chronology based on fossil evidence, palaeomagnetism is beginning to establish a chronology based on rock magnetism. The 'palaeomagnetic stratigraphic column' is skeletal at the moment, but it will become more complete as work progresses; even now it is possible to give useful results for some geological periods. Because it is often easier to obtain reliable results from volcanic rocks, palaeomagnetism is complementary to palaeontology, being useful where fossil evidence does not exist.

For the purpose of palaeomagnetic chronology within one continent it is not necessary to consider the meaning of the magnetic results in terms of continental drift, earth history generally, or the physics of rock magnetism. In this section we are concerned with the fact that for certain periods of geologic time, consistent directions of magnetisation are found in many kinds of rock scattered over thousands of miles in Australia, and that from late Palaeozoic times to the present the results form a pattern which can be interpreted as the history of the geomagnetic field relative to Australia. With one exception, results from other parts of the world are irrelevant; the exception concerns one of the more important practical applications and is discussed first.

Permo-Triassic boundary

The study of rock magnetism has established the fact that the geomagnetic field reverses from time to time (the experimental basis for this statement will not be discussed, but there is a large volume of literature on the subject). Rocks from most geological periods in all parts of the world show both 'normal' and 'reversed' polarities. However, all known Permian rocks show reversed magnetisation and there is a sharp transition to the normal direction at the very end of the Permian period. The position of this transition has been determined to the east of the Russian platform, in the Kazan-Perm region, in the Permian 'type-section' (Khramov, 1958) and in Australia, in the Sydney Basin. There is no reason to doubt that, where this transition can be fixed, it records an epoch which is simultaneous in time (within the order of 10^3 years) over the whole earth. It is particularly important because it establishes a precise datum at a time for which there is poor palaeontological correlation between the Gondwana and the northern continents.

At Perm, the transition occurs at the base of the Tartarian; in the Sydney Basin, it occurs in the 'Chocolate Shales', the horizon being known to within 200 ft. As more measurements are made, this exact correlation between rocks all over the world will become more important, but already it has obvious potential uses in the separate Permian basins in Australia.

Australian 'geomagnetic chronology'

Irving and Green (1958) published results showing the direction of the geomagnetic field in Australia from Precambrian times. Since then, much work has been done and, in particular, there is now evidence of magnetic stability for most of the rock formations, younger than Devonian, that have been used for dating, i.e. the results are now more reliable. There is no great change from the earlier paper, but the latest available results are shown in Plates 2 and 3 using the Kulp (1961) time scale. The results are shown in Plate 2 as southern hemisphere pole positions on an equal-area, stereographic projection (the circumference represents the equator and the present south geographic pole is at the centre); for any point, the expected value of the palaeomagnetic inclination (I), can be found from the relation

$$\cot \psi = \tfrac{1}{2} \tan I,$$

where ψ is the ancient colatitude; the declination (D) can be found by calculation or graphically. An alternative presentation in Plate 3 shows the palaeolatitude of Alice Springs, representing the centre of Australia. Although shown in these ways for convenience, it is emphasised that the Australian results can be used for dating without necessarily accepting the polar wandering and continental drift implied in the plates; the drawings can be considered merely as a convenient geometric representation of the ancient magnetic field.

The relatively slow change in the direction of magnetisation since the Carboniferous may sometimes make it hard to distinguish between adjacent periods using directions of magnetisation alone, but the rapid change from the Devonian to the Carboniferous is a distinctive feature. For earlier times the magnetic data is very scanty. In favourable circumstances, rock magnetism may prove useful, but more data have to be collected before the method is of general use.

Stratigraphic correlation

A detailed study of the magnetisation of a formation in which there was continuous deposition or only relatively short breaks in deposition (such as a sequence of lava flows) may reveal a pattern of directions of magnetisation. This makes it possible to correlate between holes drilled in a sedimentary basin, for example, without necessarily fitting the magnetic results into the general context of palaeomagnetism (Khramov, 1958). It is much simpler to apply this technique if reversals of the geomagnetic field occurred during the period being investigated. Once the pattern is established, the method provides precisely contemporaneous levels at different places.

An important level is that corresponding to the time when the last reversal of the Earth's magnetic field occurred. At the moment, the utility of this datum is lessened by the disagreement of stratigraphers, but, roughly, it can be taken as the Pliocene-Pleistocene boundary; the level is certainly within the range of numerous estimates regarding the position of this boundary; whatever the outcome, there is no doubt that a precise world-wide datum exists, which may be as useful as the Permo-Triassic level. It may well be that, in the absence of stratigraphical unanimity, the Pliocene-Pleistocene boundary could eventually be defined as the time of this last reversal.

A recent example of geological correlation of intrusive igneous rocks in S.E. Quebec is given by Larochelle (1961).

4. GEOLOGICAL PROBLEMS

Rock magnetism is used to help in the solving of geological and other problems in a similar way to petrology, palaeontology, or the various other geophysical techniques. Some of these are mentioned below.

(a) An early application was to delineate the boundary between scree and solid rock (McDougall & Green, 1958). The Tasmanian Hydro-Electric Commission was concerned about unconsolidated rock encountered at the ends of aqueducts driven for the Great Lake/Poatina project, in the Western Tiers of Tasmania. Attempts to discover the lower boundary of scree slopes using seismic methods were not a complete success. Knowing the direction and dispersion of directions of the magnetisation of the Tasmanian dolerite (Irving, 1956), McDougall and Green showed that the magnetisation of cores from vertical holes could be used to discover whether or not the rock was in its original position.

(b) Blundell (1961) has described the application of rock magnetism to several problems. The age of the Lundy dyke swarm and the correlation of a series of lava flows were determined, using methods similar to those described in Section 3 of this Record. The investigation of possible movement after formation of intrusive igneous bodies in Aberdeenshire is an application of the 'scree slope' problem on a larger scale.

(c) An example showing the application of rock magnetism to the question of the origin of haematite iron ore, in a Precambrian banded iron formation, has been given by Gross and Strangway (1961). They studied orebodies in Mauretania, near Fort Gouraud (12° west, 23° north). The F'Derik ore is of hard haematite (up to 65% total iron) enclosed in Precambrian banded iron formations. Folding has produced ".... an elongated S-shaped structure, which plunges north and which, in the horizontal plane, has an angle of about 37° between the two limbs." The limbs dip at about 90° east and 65° east.

The magnetic directions are consistent within each limb, but with a different direction in each, relative to the present horizontal. 'Unfolding' brings the directions together and is evidence that the magnetism is stable, and that its direction was fixed before folding took place. The interpretation is either that the ore is syngenetic or that it was formed by leaching when the beds were still flat. In either case, exploration should be directed to finding the same stratigraphic level, rather than directed along faults or similar features, which in different circumstances would be the first choice.

The neighbouring Rouessa West orebody is thought to be recent on magnetic evidence, formed perhaps by leaching in the moister Pleistocene climate.

In recent articles about Australian orebodies (not only iron ore but others with associated iron oxides), there seems to be some controversy on their origin, and magnetic studies may provide helpful information.

(d) It is possible that some evidence on the 'granite problem' may come from rock magnetism. Intrusions of 'hot' magma remagnetise the contact rocks and this magnetisation can sometimes be detected. If a granite body reached its present position 'cold', remagnetisation would be absent or only partial. This might be detected by magnetic measurements. Some work on this is in progress at the Australian National University.

In this way also we can distinguish between intrusive sills and lava flows. An intrusion bakes and remagnetises the country rock above and below; a flow bakes only the underlying rock. Many baked contacts are detectable magnetically whereas other alteration effects are slight and undetectable otherwise (Everitt, 1960).

(e) Magnetic anisotropy (see page 2) can indicate directions of lineation and planes of lamination, and distinguish between them (Stacey, Joplin, & Lindsay, 1960). The amount of elongation and 'stringing' (Stacey, 1960) of the magnetic particles can be related to the degree of magnetic anisotropy. The sensitivity of the method is orders of magnitude greater than that of other methods (e.g. optical) and is sufficient for the detection of lineation or foliation otherwise unnoticeable. (See also Balsley & Buddington, 1960; Howell, Martinez, & Statham, 1958; Girdler, 1961.)

To digress a little, similar results can arise from measurments of dielectric anisotropy. A tentative start has been made on investigations (Stacey, 1961).

(f) Magnetic anomalies are caused by bodies that, in general, have both remanent and induced magnetisation (a rough generalisation is that these components are about equal) and the anomaly produced depends on the direction of remanence. However, although the problem is recognized, most published results have been calculated on the assumption that all the magnetisation is induced in the direction of the local geomagnetic field. More attention should be paid to NRM, as well as to susceptibility (Nagata, 1961, ch 10; Smellie, 1956; Green, 1960; Girdler & Peter, 1960).

(g) Archaeomagnetism has produced useful age data from the magnetisation of baked pots, kilns, etc. This method is particularly applicable in Australia, for instance to undisturbed aboriginal hearth-stones.

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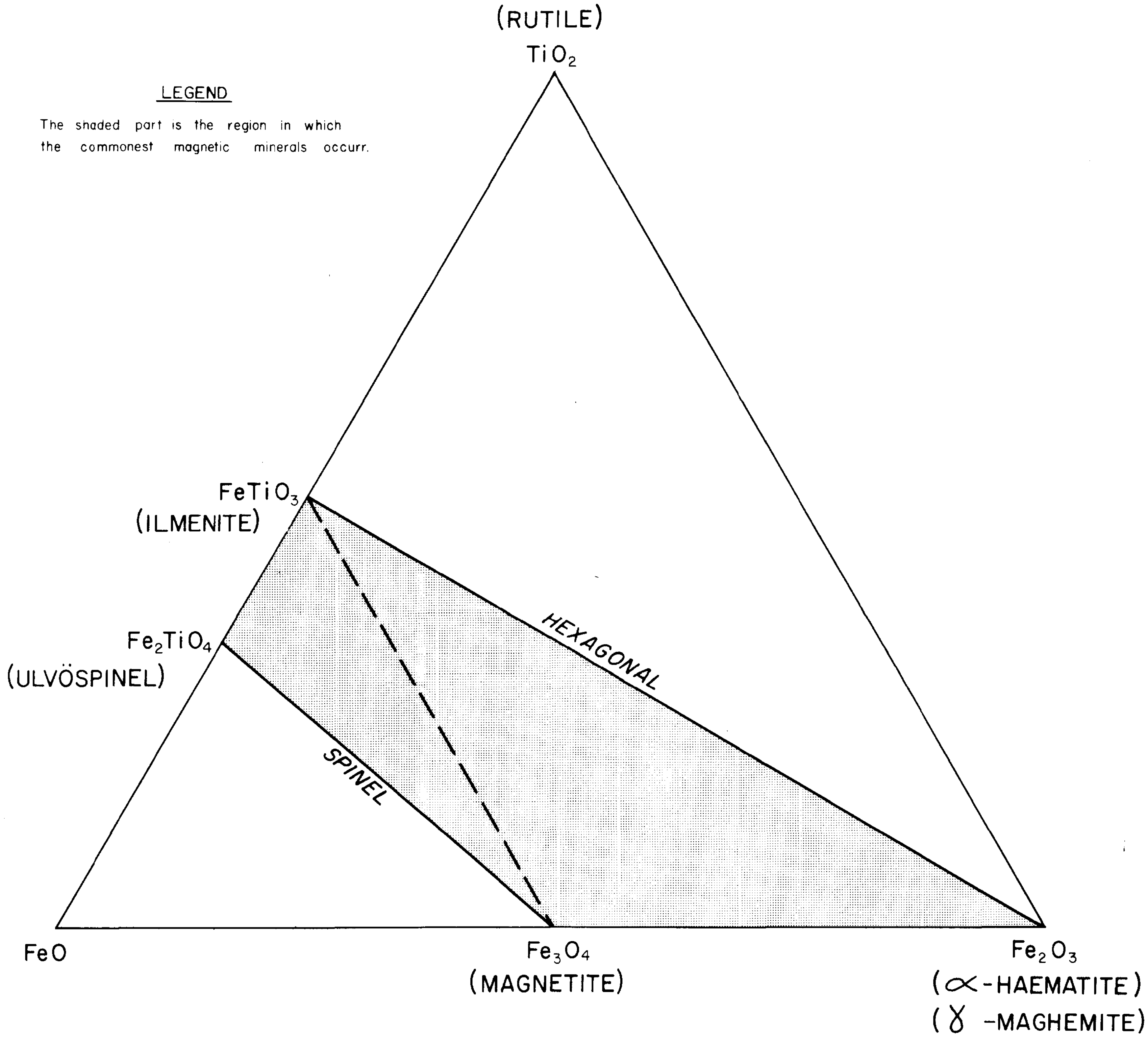
LEGEND

The shaded part is the region in which the commonest magnetic minerals occurr.



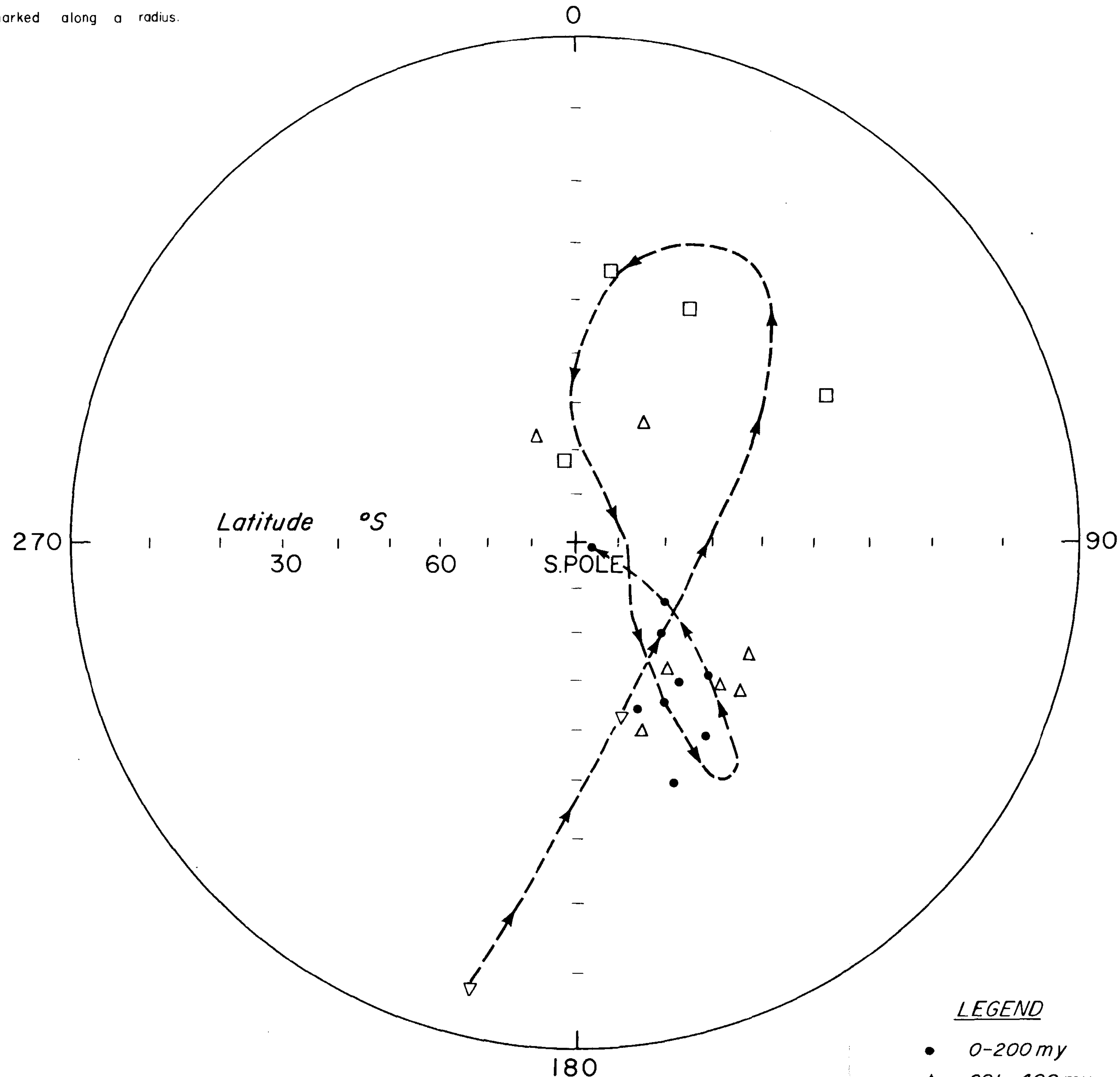
PHASE DIAGRAM OF MAGNETIC MINERALS

TO ACCOMPANY RECORD NO 1964/166

Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics.

LEGEND

This is an equal-angle stereographic projection; the outer circle represents the equator, the south pole (present position) is at centre, and longitude is measured eastwards from 0 to 360°. The latitude is marked along a radius.

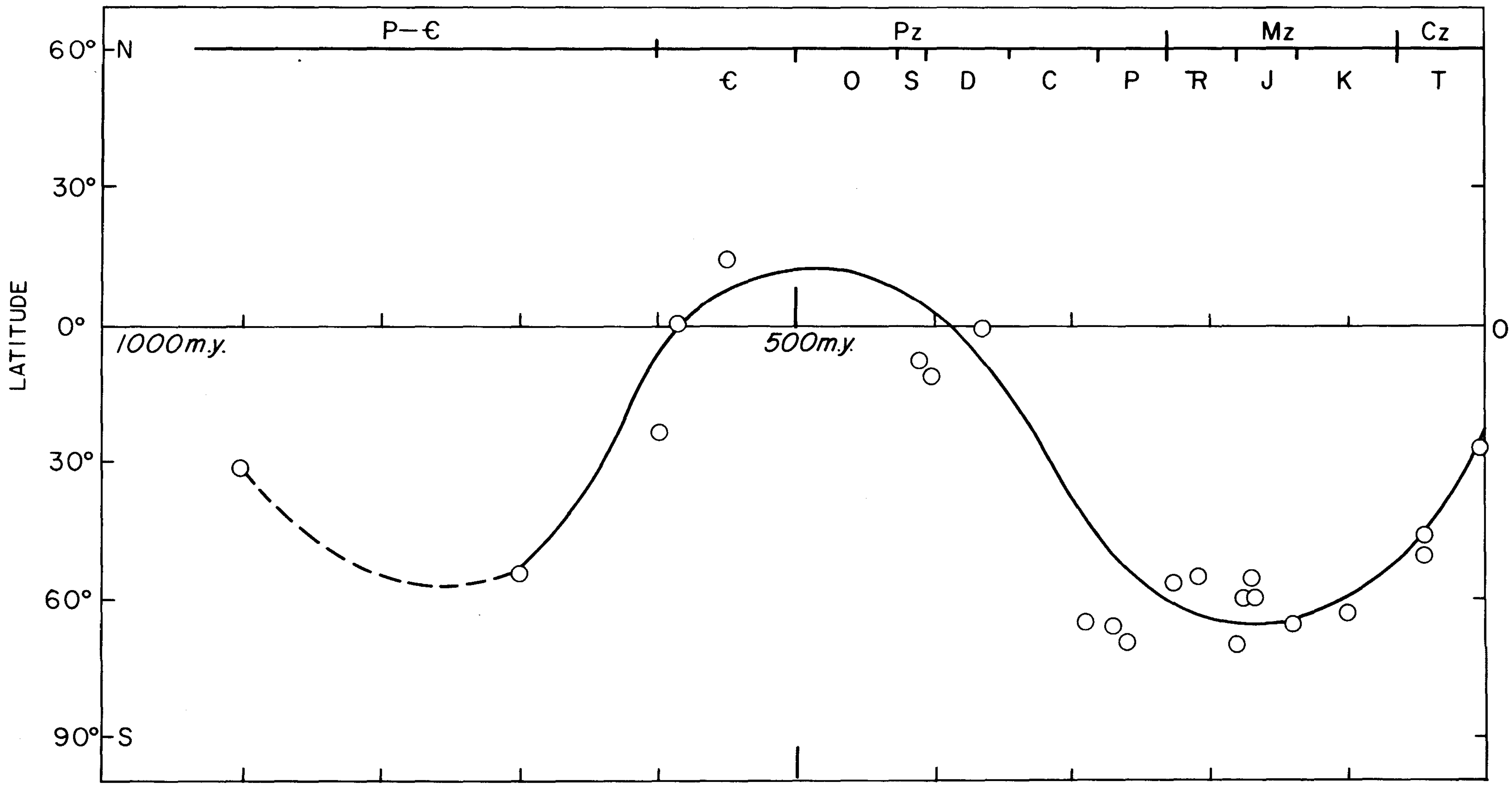


LEGEND

- ● *0-200 my*
- △ *201-400 my*
- □ *401-600 my*
- ▽ *> 601 my*

THE PAST POSITION OF THE SOUTH POLE, RELATIVE TO AUSTRALIA

Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics. 1101



THE PAST LATITUDE OF ALICE SPRINGS
FROM PALAEOMAGNETIC MEASURMENTS

1102

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