PALAEOMAGNETISM AS A MEANS OF DATING GEOLOGICAL EVENTS

L. W. Morley and A. Larochelle

ABSTRACT

In principle there are three distinct aspects of the palaeomagnetic method that may be considered in attempting to date geological events: the palaeomagnetic evidence for polar wandering allows geological dating on a coarse time-scale; the numerous polarity reversals observed in rocks suggest that it may become possible to date their magnetization with an accuracy of the order of one million years; the scatter in magnetization directions observed in penecontemporaneous rocks resulting from secular field variations might allow, in future, the dating of geological events to about the nearest thousand years.

In practice many difficulties are encountered in attempting to follow any of these approaches for dating rocks or geological events. The inaccuracy and incompleteness of the existing polar wandering curves are pointed out as the main shortcoming in the first case. A brief analysis of the existing North American polar wandering curves reveals that considerable work has yet to be done before the potentialities of this method can be estimated. Similarly, a complete and accurate survey of the earth's field reversals in the past will be required before rocks can be dated with a relatively high precision on the basis of their polarity. A method of estimating the time span between successive reversals is suggested. The possibilities of using the scatter in the magnetization direction of penecontemporaneous rocks, although attractive, do not seem to be very hopeful for rocks older than several thousand years.

THE SCIENCE of palaeomagnetism evolved from studies of rock magnetism when two facts became evident. The first is that certain igneous and sedimentary rocks are found to be permanently magnetized in the direction of the ambient earth's magnetic field at the time of their formation; the second is that this direction is commonly different from that of the earth's field now, and that in general the older the rock is, the greater is this difference. Further investigations revealed that accompanying this so-called polar wandering was another characteristic of the earth's field: it appears to have reversed its polarity several times in the geological past. Furthermore, from compass measurements over the past 500 years or so, the magnetic north pole appears to be circling about the geographic pole with a radius of about 25 degrees, giving rise to the phenomenon known as secular variation. Thus the earth's magnetic field seems to have varied its direction throughout geological history in three distinct ways: first by secular variation, secondly by reversal of polarity, believed to have a period of the order of about one million years, and thirdly by polar wandering at an estimated average rate of 0.3 degree per million years.

The Use of the Palaeomagnetic Polar Wandering Curve

For the geochronologist the polar wandering aspect of the earth's field seems to hold the most promise. Assuming that the earth's field in geological history approximated, as it does at present, that of a dipole at the centre of the earth, it is possible from the measurement of the palaeomagnetic inclination and declination, in a suitable rock sample at any known latitude and longtitude, to calculate the location of the pole at the time the rock was formed. If, in this way, the palaeomagnetic poles are calculated for undisturbed rocks of various known ages, it is possible to plot what is termed a "polar wandering" curve. After such a curve has been established reliably, it should then be possible to determine the ages of other rocks by locating their palaeomagnetic poles on the calibrated polar wandering curve. In essence this is the method of age determination by the palaeomagnetic pole wandering technique. It should be pointed out, however, that in the process of constructing a polar wandering curve and later in determining ages of unknown rocks from this, it is necessary to use rocks from the same continent. This has been found necessary because polar wandering curves of rocks from different continents, although having the same general shape, are nevertheless displaced by great distances. It was the discovery of this fact that led to the revival of the continental drift theory.

Reliability of Poles and Polar Wandering Curves

The basis of comparison being the polar wandering curve, the method cannot be more reliable than the curve itself. For this reason, it is imperative to evaluate the validity of the existing polar wandering curves and to examine the possibility of improving them.

The reliability of an existing polar wandering curve can best be evaluated by comparison with what might be considered the ideal. Such a curve would be based on a very large number of points representing rocks suitable for palaeomagnetic purposes and of many ages. Furthermore, these ages should be known indisputably. Obviously, the hope of obtaining even a sufficient number of points from each geological period, especially the older, is probably Utopian.

In an article written in July 1960, Irving (1961) stated: "since the beginning of 1959 about seventeen papers have appeared containing 54 pole determinations, and in only 16 of these determinations is any direct evidence of stability presented." If this statement alone is enough to put in doubt the validity of the polar wandering curves now in existence, there are other reasons that may be added to confirm these doubts. Some of these reasons are mentioned in the next few paragraphs.

It is not sufficient that the rocks dealt with in palaeomagnetic studies be magnetically stable. The fundamental question is this: Does the direction of magnetization arrived at in the laboratory actually reflect the attitude of the ambient geomagnetic field at the time the rock was first polarized magnetically? For the answer to this question to be confidently in the affirmative, it must be shown that the rock is free from secondary foliation, or schistosity. Similarly, rocks containing both primary and secondary ferromagnetic minerals must be eliminated from palaeomagnetic studies for the obvious reason that part or all of their polarization has probably been acquired under the influence of a geomagnetic field whose orientation was completely different from that of the field prevailing at the time the rock was first consolidated. Secondary minerals are most commonly encountered in rocks that have been exposed to elevated temperatures and pressures, and, for this reason, metamorphic rocks must be rejected systematically from consideration.

Many pole positions may have erroneously been regarded as reliable because neither their magnetic stability nor their suitability in terms of their petrologic character can be challenged although their age or position in the biostratigraphic column has never been established reliably.

Proper choice of sampling sites and rock types is most important. It has been estimated, for example, that 82 per cent of all the North American pole positions were derived from sedimentary rocks—mostly from red beds. There is no denial that red beds are probably suitable for this type of work as far as their stability and fossil-bearing character are concerned, but their deposition and magnetization may not have been contemporaneous.

Many points on the existing polar wandering curves are probably inaccurate because they are based on inadequate or insufficient sampling. The use of an orienting device other than the ordinary magnetic needle compass may not be required for collecting samples of many rock types, but for strongly magnetic rocks, such as certain volcanic types, a serious error in orienting the sample can be introduced unless the latter is oriented directly with respect to a geographic meridian, by means of a solar compass for instance. It is also important in such rocks to take a sufficiently large number of samples to average out the effect of local anomalies. A large number of samples (not less than about 30) is also important in order to eliminate the effect of secular variation. In a formation which may have taken more than 500 years to cool, the effect of secular variation could conceivably account for a spread as much as 30 degrees in the individual determinations.

A number of points on the existing polar wandering curves are based on samples of unconsolidated deposits, such as varved clays. There seems to be little doubt that these deposits acquired their present magnetization at the time of deposition, but the alignment of magnetization in the direction of the ambient geomagnetic field is not so certain. Experiments carried out a few years ago by King (1955) have shown that in the process of settling of magnetic sand in a tank, the magnetic axes of the particles have a tendency to orient themselves along the meridian of the ambient field but, because of the geometric form of the grains, at a shallower inclination than that of the field. It is therefore clear that points on the polar wandering curve that are based on samples that have acquired their magnetization during a settling process may be misleading.

Many rocks intrusive into metamorphic terrain of complex structure are surprisingly fresh and seem to meet all the requirements in regard to magnetic stability. However, because of the absence of sedimentary rocks in the vicinity, their attitude with reference to the "palaeohorizontal plane" is not defined, and hence pole positions calculated from such rocks should be regarded with suspicion.

The scope of the present paper does not allow a systematic review of all the palaeomagnetic measurements used so far for building up the polar wandering curves for all the continents of the world. Accordingly, we shall restrict ourselves to a brief analysis of the North American polar wandering

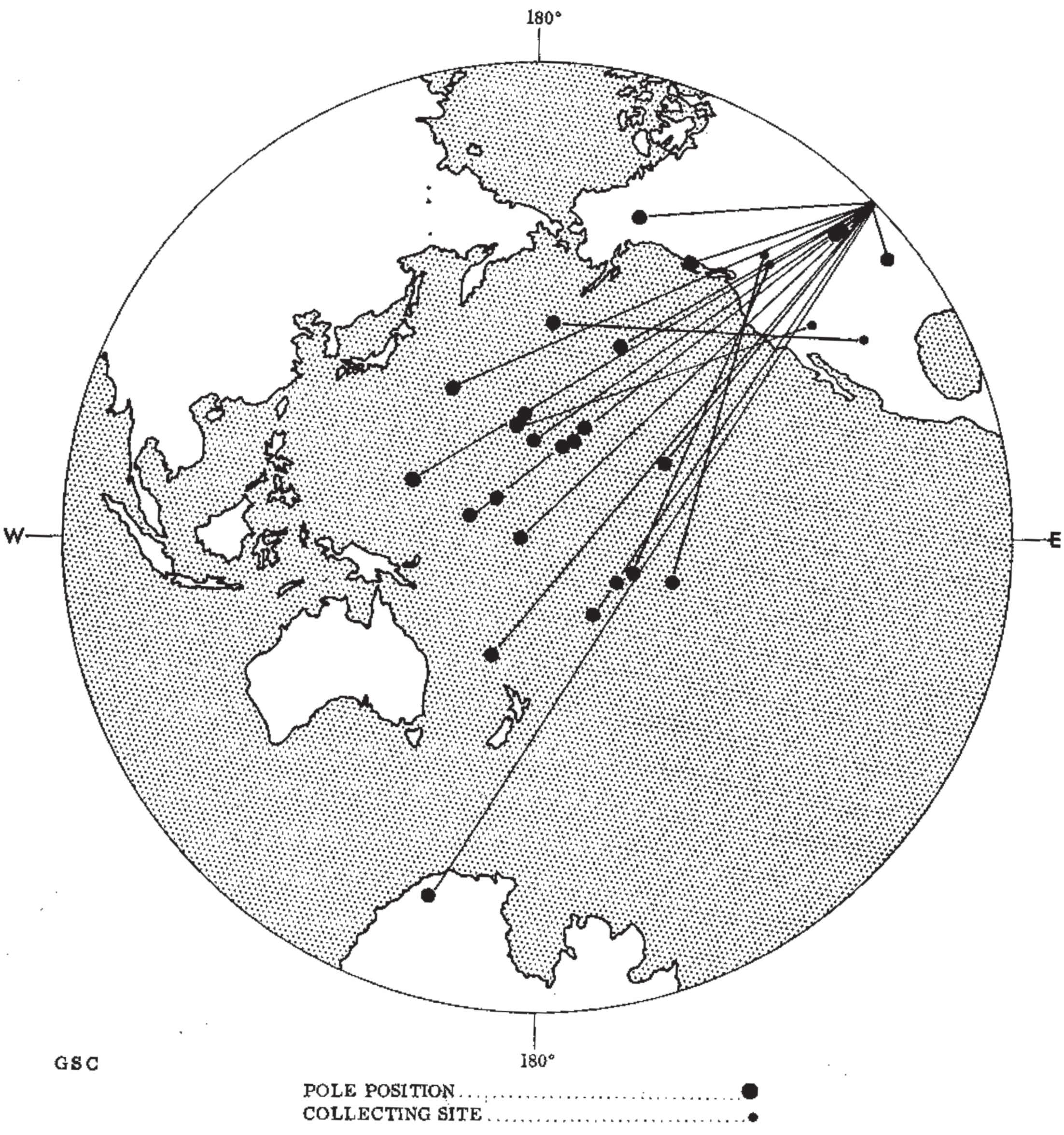

FIGURE 1. Proterozoic pole positions as derived from North American rocks.

curves as a means of evaluating the potentialities of palaeomagnetism as a method of geochronology in North America.

In Figures 1 to 8, North American poles that have appeared in the literature, which was reviewed by Cox and Doell (1960), are plotted for geological periods or groups of periods together with the corresponding locations of the sampling sites.

Proterozoic (Fig. 1). A relatively large number of pole positions have been derived from Proterozoic rocks collected at widely separated localities in North America. It is doubtful whether a complete polar wandering curve for the Precambrian will ever be compiled because comparatively little of the bedrock is left in its original state. Also it is believed that the Precambrian lasted some three billion years so it is probable that the polar wandering curve crossed over itself several times at one or more points on the globe during that interval. Nevertheless, important uninterrupted

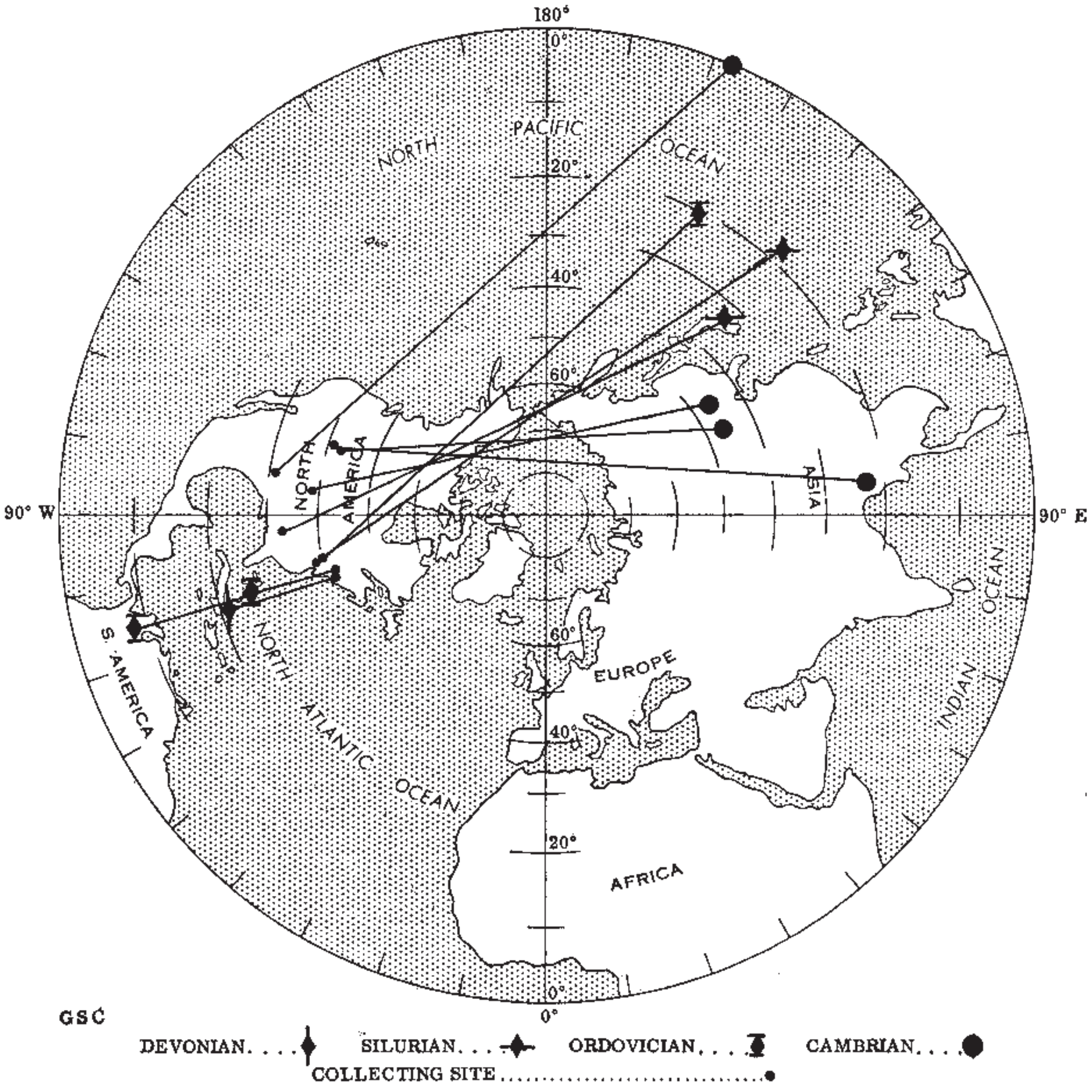

FIGURE 2. Pre-Carboniferous Palaeozoic pole positions as derived from North American rocks.

sections of this period have been or could be studied from cratons overlain by relatively undisturbed and unmetamorphosed Proterozoic rocks. A better opportunity perhaps lies in the sampling of the ubiquitous diabase dykes many of which have apparently not been disturbed since their emplacement. Since present indications show, through the use of isotopic methods, that these dykes span the Proterozoic in time, it should become possible to trace the polar wandering curve for much of this geological era.

Pre-Carboniferous Palaeozoic (Fig. 2). The scatter displayed by the few available data for the Cambrian poles would be enough to discourage any effort to use palaeomagnetism as a means of dating early Palaeozoic rocks were it not for the questionable validity of some of these poles. Less scatter characterizes the group of published Ordovician poles, although it is to be noted that these poles are based exclusively on sedimentary rocks, some of which are strongly suspected of having acquired their magnetization long after deposition. Only two Silurian North American poles have been

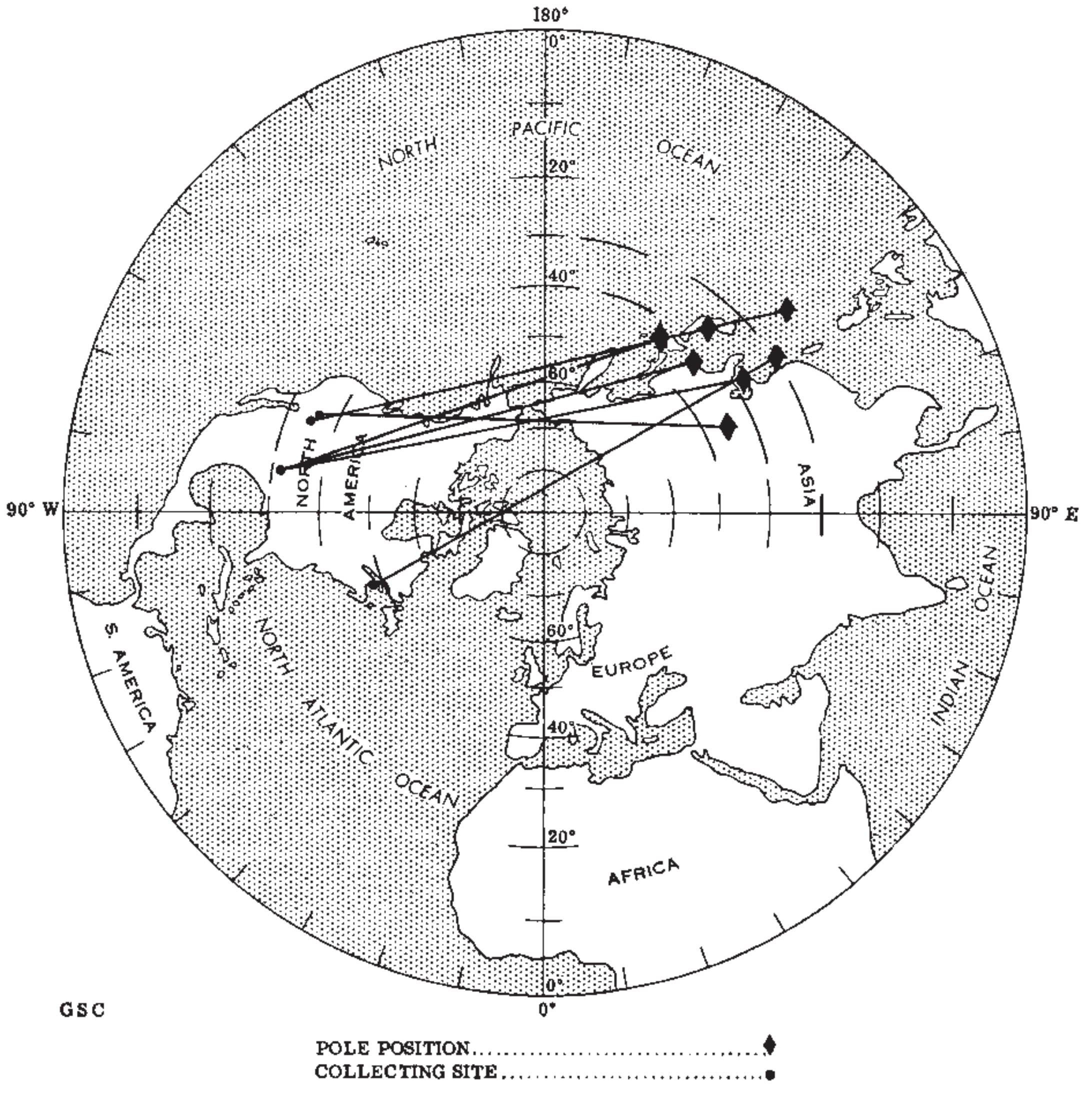

FIGURE 3. Carboniferous pole positions as derived from North American rocks.

published, and, despite their relatively good coincidence, the contemporaneity of their magnetization and deposition is in serious doubt. Finally, the only North American Devonian pole available in the literature is based on rocks for which the origin and age of the magnetization are uncertain. Thus the scarcity of results available for Early Palaeozoic North American rocks does not allow us to determine the age of the rocks on the basis of their palaeomagnetism. However, many well-dated formations of Early Palaeozoic age are known throughout Canada, and these could be sampled to redefine the polar wandering curve.

Carboniferous (Fig. 3). In contrast to the Early Palaeozoic poles, the Carboniferous poles derived from North American rocks are relatively closely grouped. It must be recognized, however, that these poles have all been derived from sedimentary rocks, and measurements on volcanic rocks are still needed to confirm their validity.

Permian (Fig. 4). Particular attention has been given to the palaeomagnetism of the Supai Formation whose deposition transgresses the Permo-

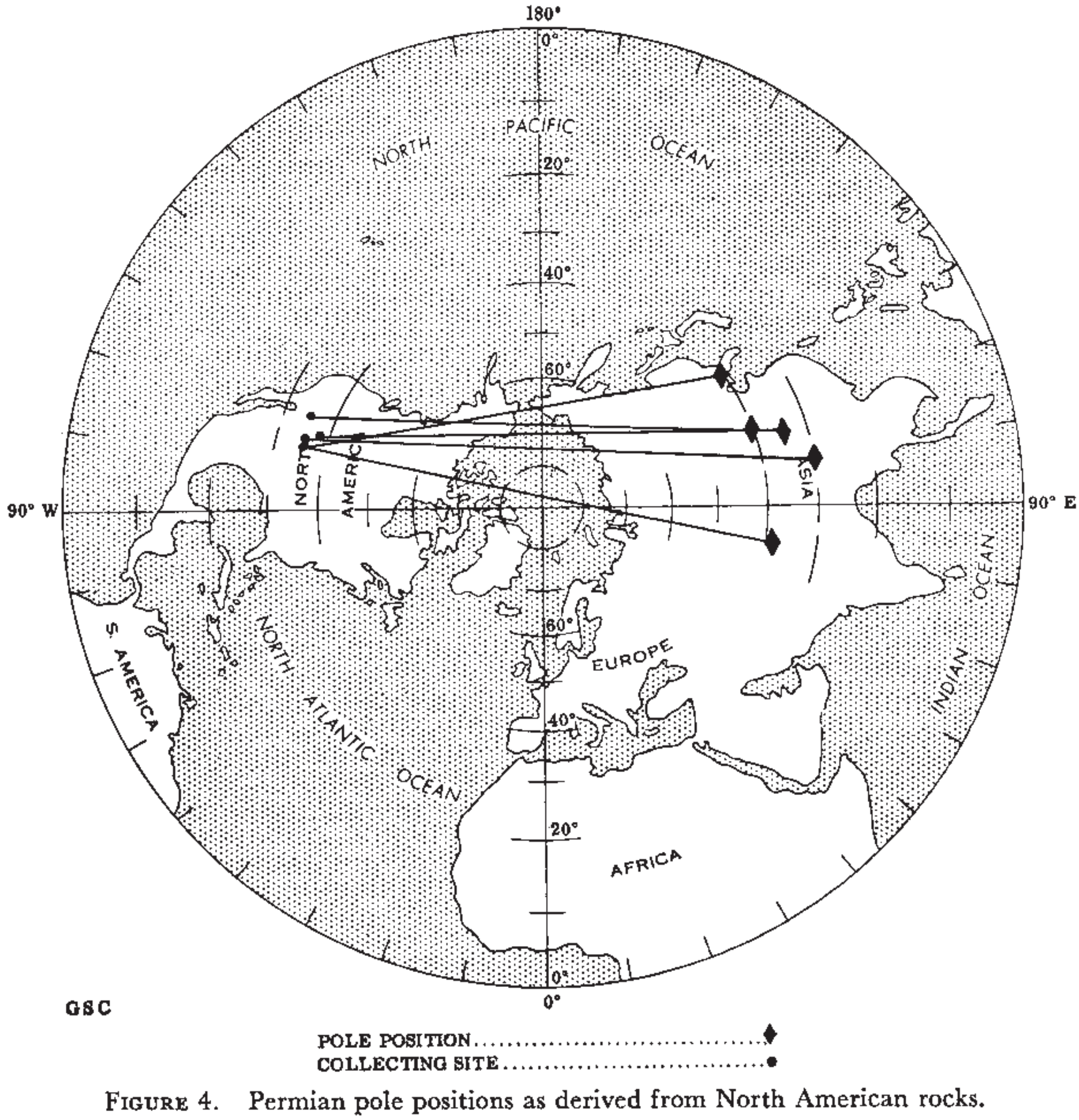

FIGURE 4. Permian pole positions as derived from North American rocks.

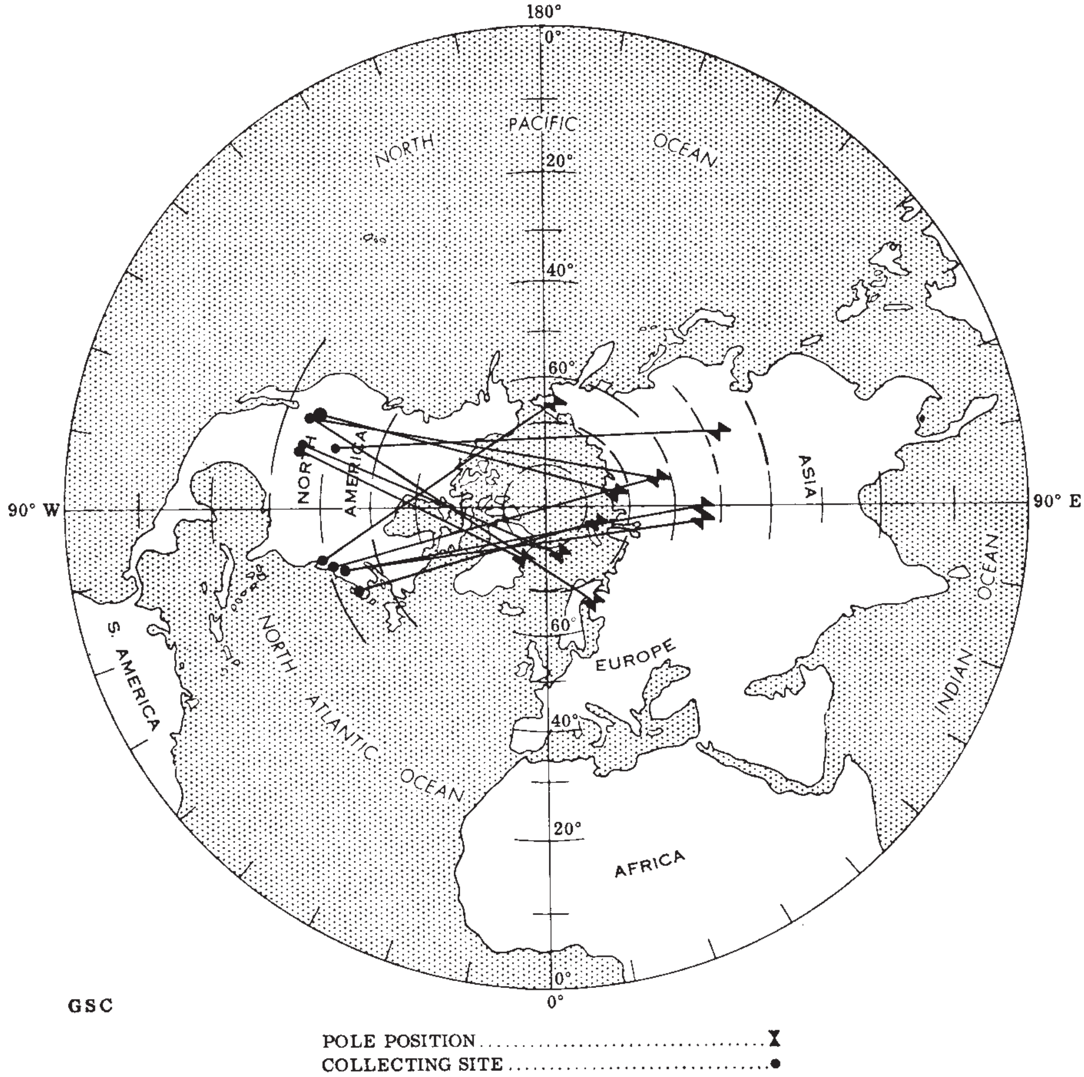

FIGURE 5. Triassic pole positions as derived from North American rocks.

Carboniferous boundary. Three groups of workers collected oriented samples at widely separated occurrences of this formation. The pole position that each group arrived at is very close to the mean pole derived from the totality of the samples collected, i.e. at 40° N. and 110° E. Three other Permian formations have been sampled at either one or two sites each. Although the results obtained are in perfect agreement with the indications of the Supai Formation, their validity would be greatly enhanced by more extensive sampling. From the data available at the present time, however, it does seem fairly certain that the north pole migrated from a location centring on Korea in Carboniferous times to one near Central China in Permian times, a distance of approximately 3000 miles. However, more data are required to confirm this section of the path.

Triassic (Fig. 5). Several North American Triassic formations have been sampled extensively at many sites, but the wide scatter of the resulting pole positions is disconcerting. They are spread between latitudes 50° N. and 80° N. around the present geographic pole. It seems that a complete

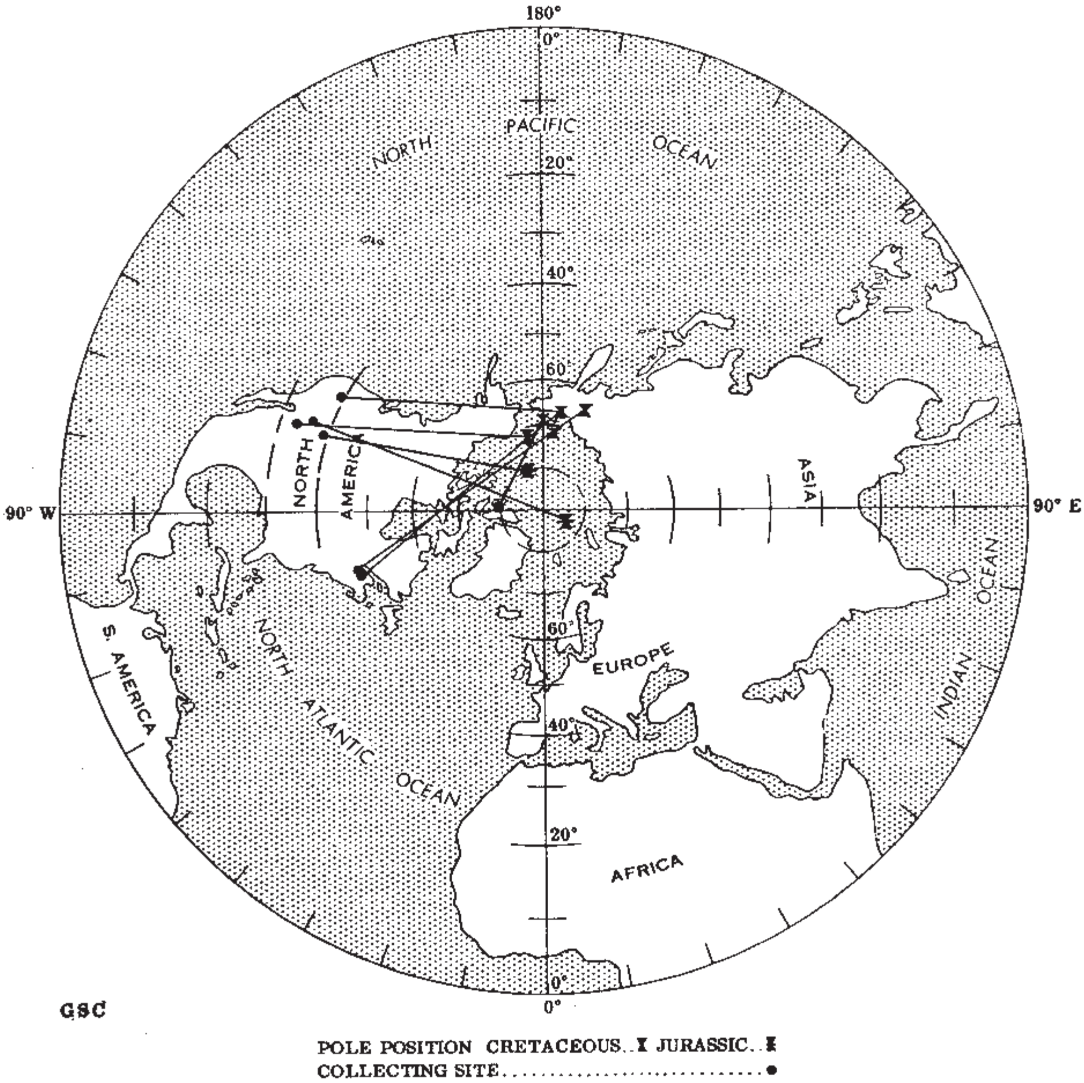

FIGURE 6. Cretaceous and Jurassic pole positions as derived from North American rocks.

re-examination of the existing data is necessary as well as the addition of new data.

Jurassic and Cretaceous (Fig. 6). The Jurassic section of the North American polar wandering curve is very sketchy since it is based on the sampling of only two formations, one of which was sampled at a single site. A better representation is available for the Cretaceous period from the extensive sampling of four widely separated rock units comprising sedimentary, volcanic, and intrusive rocks of both polarities. The available Cretaceous poles are particularly well clustered around their mean.

Tertiary (Fig. 7). The number of poles calculated for different formations of Tertiary and Early Pleistocene age is probably sufficient to leave little doubt that the earth's dipole axis was inclined only slightly to the present geographic axis during this period. The validity of the data is enhanced by the fact that reversed polarites are a common feature in many of the formations of various types.

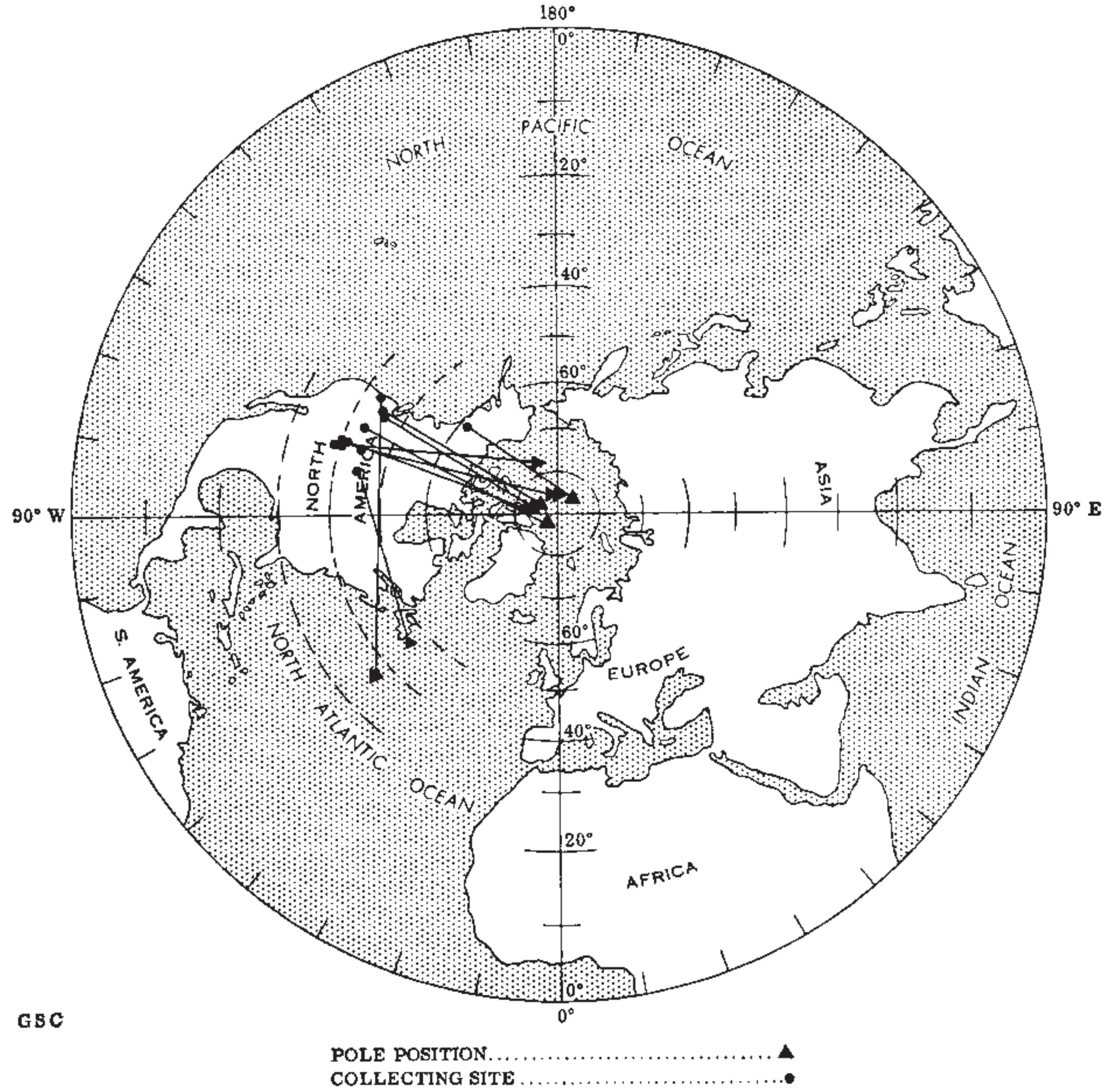

FIGURE 7. Tertiary pole positions as derived from North American rocks.

Recent (Fig. 8). Apart from the observatory records of the last few centuries there are only two pole positions for this period which have been derived from North American rocks. As in other continents, the mean value of these poles coincides closely with the present geographic pole, and their magnetization directions follow the present polarity of the earth's field.

A more extensive review of the North American palaeomagnetic literature is hardly needed to show the necessity for more palaeomagnetic measurements throughout the geological column, as well as improvements, or at least standardization, in the methods of sampling, measuring, and testing, before the polar wandering concept of palaeomagnetism may be considered as a method of geochronology. The most pressing need for new data would appear to be for Proterozoic, pre-Carboniferous Palaeozoic, and Triassic times.

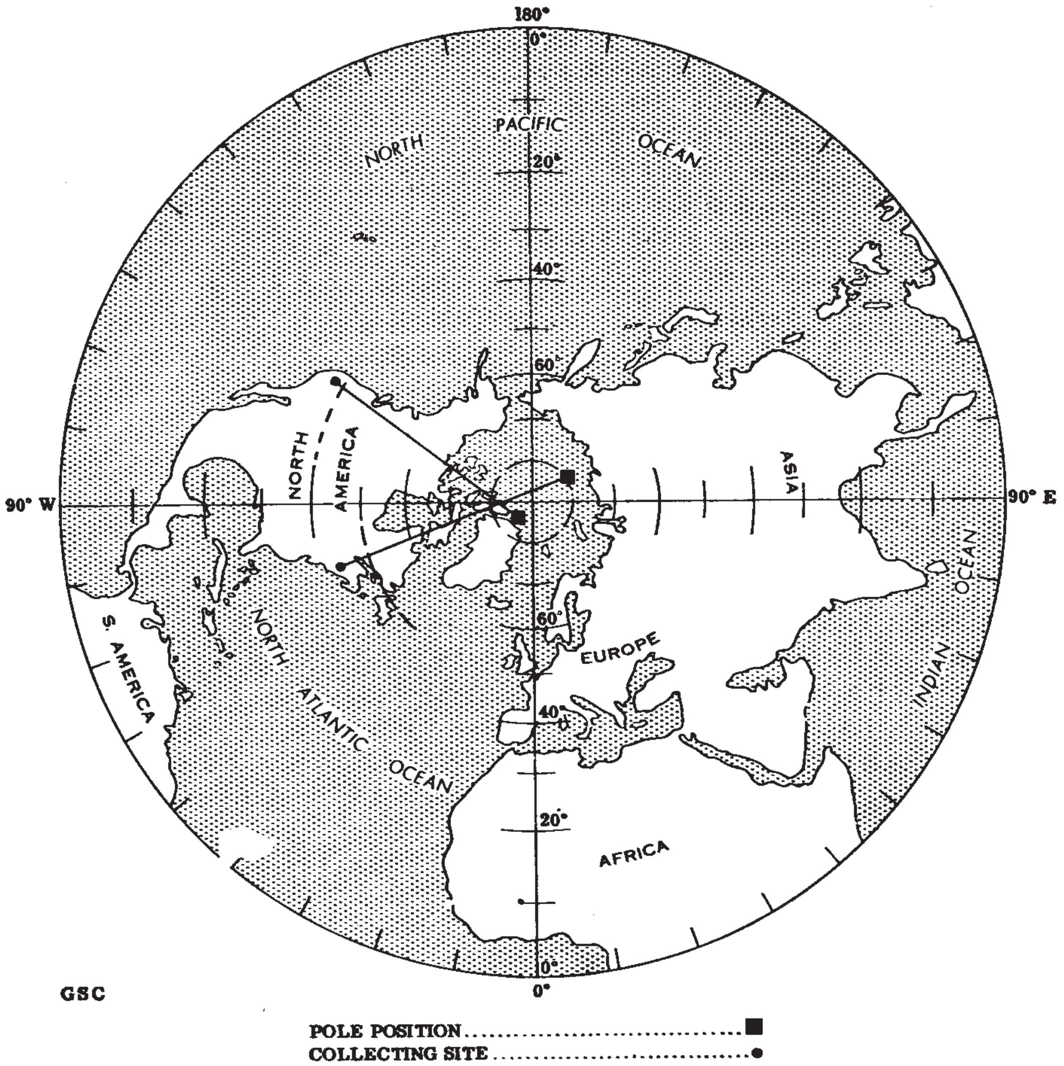

Figure 8. Late Pleistocene and Recent pole positions as derived from North American rocks.

The Use of Reversals as a Means of Geochronology

The fact that the earth's magnetic field has reversed its polarity, perhaps more than a hundred times since the Carboniferous (R. L. Wilson 1962), has been a difficult concept for many to accept. The evidence, however, is now overwhelming, and we do not intend to review it here. Unfortunately, so little is known about the times and exact durations of these reversals that they are of little use as geochronological markers. On the other hand, these palaeomagnetic reversals are found to be of great help in problems of correlation in non-fossiliferous rocks. Examples of this type of work are Einarsson's (1957) Magneto-Correlation in Icelandic lavas. Black (1963) found a large number of reversals in the Belt Series of southwestern Alberta that would be very useful for correlation purposes in these rocks, which are quite devoid of fossils useful for correlation.

The possibility of calibrating the time of these reversals throughout several periods of geological history is remote, especially since absolute age methods are at present not a great deal more definite than to the nearest geological period. However, Morley suggests* that a nearly unbroken record of these reversals may exist in the permanent magnetization of the rocks on the floor of the ocean basins. Mason and Raff (1961) have outlined a wide sequence of long north–south striking magnetic anomalies whose origin is puzzling. If one refers to recent papers of several authors (J. T. Wilson 1963; Vacquier 1962; Dietz 1961) in which the concept of mantle convection currents rising under ocean ridges, travelling horizontally under ocean floors, and sinking at ocean troughs is presented, it stands to reason that the rising rock, as it reaches the Curie point geotherm, will become permanently magnetized in the direction of the earth's field prevailing at the time. As this portion of rock moves upward and then horizontally to make room for the following rising material, and if, in the meantime, the earth's field has reversed and the same process is repeated many times throughout geological history, a linear magnetic anomaly pattern of the type observed would result. The present rate of travel of this mantle convection is believed to be of the order of a few centimeters per year. If this figure could be determined accurately for the various geological periods, it would then be possible, using the data from a magnetometer survey of the ocean basin floors, to reconstruct not only the history of reversals of the earth's field but also the direction and rate of the drift of continents. This time-reversal information could then be applied to problems of geochronology on the continents. Although such thinking is still very speculative, the study of palaeomagnetism and magnetometer surveys in the oceanic islands and ocean basins will no doubt prove or disprove it in the near future.

Geochronology by Palaeomagnetic Secular Variation

From observatory records it appears that the magnetic dip pole wanders within a circle of about 25 degrees radius centred at the geographic pole, so that it may be possible by this method to date material that exhibits stable magnetic remanence. Indeed the method has been used by Thellier and Thellier (1959) for dating ancient pottery made of baked clays. Attempts have also been made with less success to date recent varved clays by this method (Johnson, Murphy, and Torreson, 1948). The possibility of being able to combine such data with age determinations by the carbon-14 method is promising. It does seem quite clear, however, that there will be

*This hypothesis was originally presented at the Annual Meeting of the Royal Society of Canada in Quebec City on June 4, 1963. Since then, a letter by F. J. Vine and D. H. Matthews, Department of Geodesy and Geophysics, University of Cambridge, entitled "Magnetic Anomalies over Oceanic Ridges" has been published in *Nature* (No. 4897, Sept. 7, 1963, pp. 947–9), in which a similar hypothesis is presented. It appears that similar conclusions were arrived at independently.

little possibility of applying this technique to materials older than a few thousand years.

Conclusions

There is no doubt that palaeomagnetism will never supplant any other methods of geochronology in use today, but this is not the ambition of the palaeomagnetist. It is hoped, nevertheless, that some use will be made of a record still preserved in many rocks for filling gaps that cannot be filled by other methods or in supporting one or other of these methods in cases of disagreement.

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