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POLAR WANDERING AND CONTINENTAL DRIFT: EVIDENCE FROM PALEOMAGNETIC OBSERVATIONS IN THE UNITED STATES

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ABSTRACT

Further studies of the paleomagnetic directions of red sandstones and siltstones of various geological ages in the United States are described. Usually the directions of magnetization of samples from a formation at one site are grouped symmetrically about a mean direction. From such a mean direction the position of the pole for that geological age can be calculated. There are, however, magnetically unstable formations in which the directions of magnetization are distributed approximately in the plane containing the present dipole field at the site and the original direction of the magnetic field. This planar distribution is the result of a superposition of a secondary magnetization on the original one. The former is thought to be a viscous or chemical magnetization acquired in the last 1,000–1,000,000 years.

Pole positions calculated from mean directions at different sites are consistent for the same formation and for different formations of the same geological age.

The study confirms the general trend of the polar-wandering curve for North America obtained by Runcorn (1956a), which lies around the northern Pacific Ocean: the pole being in the central tropical Pacific in late Precambrian time, moving across to the tropical western Pacific in the early Paleozoic and to Asia in the late Paleozoic and early Mesozoic. The data also show that the polar-wandering curve for North America is displaced westward relative to that for Europe, as Runcorn (1956b) showed, and provide an estimate for the amount of drift between the two continents since Mesozoic time, which is of the order of 30° in longitude.

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INTRODUCTION

In this paper we describe paleomagnetic observations on red beds of various geological ages in North America. This is an extension of the paleomagnetic survey described by Runcorn (1956a), in which it was established, by observations on rocks from Arizona and Utah, that the axis of the mean geomagnetic dipole (with which the axis of rotation is thought to coincide) has moved since the late Precambrian, along a roughly circular path around the northern half of the present Pacific Ocean at a rate of about ⅓° per million years. Runcorn (1956b) showed that there is a systematic difference between the polar-wandering paths inferred from American and British results, which is best interpreted by assuming that continental drift of North America westward relative to Europe took place in post-Triassic time. The considerably extended paleomagnetic survey reported in this paper supports these conclusions.

Samples of well-bedded, fine-grained red sandstones and siltstones were collected, mainly on the Colorado Plateau where no severe tectonic movements have occurred since the deposition of the sandstones. Apart from samples which fragmented during cutting or which were too weakly magnetized to be measured, the directions of magnetization of all the samples are recorded in the figures and tables of this paper. No experiments on modifying the observed magnetizations, *e.g.*, by demagnetization, are reported here, and the only correction made to the observations is that for the local geological dip at the site—the usual assumptions being made that the bedding planes were initially horizontal and that tectonic movements caused inappreciable rotation of the beds about the vertical. The measurements were carried out by the method described by Collinson, Creer, Irving and Runcorn (1957). With the astatic magnetometer used at Newcastle it has been possible to determine directions of magnetization of 10-cc specimens to accuracies within 1°–3° for intensities of magnetization as low as 3.10^{-7} emu/cc. Only about 30 discs from the whole collection had intensities too weak to be measured.

The theory of the sampling technique has been described by Runcorn (1957) and by Watson and Irving (1957), who show that a sufficiently accurate mean direction of magnetization of a rock formation (and therefore an accurate pole position) can be obtained by measurements on a comparatively small number of rock samples (10 to 20) provided these are well distributed stratigraphically. Consequently the normal procedure followed in making the collections was to sample at random intervals through the full thickness of a particular formation at one or more localities. The observed scatter of the directions of magnetization of a set of samples spanning a small fraction of a geological period is not usually greater than that to be expected from the geomagnetic secular variation (up to about 30° from the mean). Thus the random deviations between the directions of the field at the times of deposition and the present directions of magnetization of the corresponding samples may be assumed to be smaller, *i.e.*, only a few degrees. If the time spanned is of the order of a geological period, however, it is possible that superposed on the scatter due to the secular variation is that due to the movement of the axis of rotation, which may not be, over a span of a few million years, the smooth path inferred from the overall survey of the geological column. The scatter due to this cause could be of the order of 20°.

Runcorn (1956a) and Creer (1957) showed that the observations on red sandstones fall into two broad groups: (1) directions of magnetization symmetrically distributed around their mean, to which the statistical methods by Fisher (1953) may reasonably be applied, and (2) directions of magnetization scattered along a great circle through the direction of the present axial dipole field. This conclusion is again verified by the results reported in this paper. The simplest hypothesis to explain this result is to suppose that the directions of group (1) are coincident, apart from errors discussed in the previous paragraph, with the directions of the field at the time of deposition of the rock samples. It is reasonable to suppose that these rocks have been unaffected by the changing geomagnetic field since their original magnetization; they are therefore termed stable. On the other hand, group (2) appears to consist of rocks the magnetizations of which are the vector resultants of stable magnetizations acquired in the geomagnetic field at the time of deposition and secondary magnetizations acquired in the latter part of Cenozoic time in the present geomagnetic field. They are therefore termed partially stable rocks. Occasionally the effect of this secondary magnetization is so strong relative to the primary magnetization that no estimate of the latter is possible.

The directions of magnetization of lavas are sometimes greatly scattered (Cox, 1957; Creer, 1958) but are still symmetrical about a mean direction, from which it may be inferred that the secondary magnetization acquired by them is randomly directed. For instance, a viscous magnetization acquired during the unoriented storage of specimens between collection and measurement would be a reasonable explanation of the effects. Demagnetization by alternating fields of the order of 100 gauss removes this secondary magnetization, and the directions of magnetization become much more closely grouped. In red sandstones and siltstones no such large but symmetrical dispersion of directions has been observed. The planar distribution must therefore arise from a comparatively stable secondary magnetization lying along the direction of the present dipole field. This could be a viscous magnetization with a longer time constant than that of the lavas—the red sandstones contain hematite grains, while the lavas contain magnetite.

There are, however, other processes by which some samples of the red sandstones might have acquired this secondary magnetization. The samples collected from outcrops will have been exposed at the surface for at least some thousands of years. During this time the following processes might have occurred:

(1) A component of thermo-remanent magnetization might have been acquired through the daily heating and cooling.

(2) Water from desert storms and the heat might have caused some of the hematite grains to form iron hydroxides and carbonates and thus to lose their original magnetization. These unstable compounds might eventually form hematite again, which would then become remagnetized by the process of "chemical magnetization". It is possible that this process could occur also through the circulation of ground water and consequently affect rocks at depth.

It appears that this secondary magnetization is more frequently observed in the Western United States than in Europe (*cf.* results given by Creer, Irving, and Runcorn 1957) and could therefore be the effect of the desert climate on surface outcrops. In any case, the secondary magnetization of the red sandstones must have been acquired when the rocks were *in situ* and since the beginning of the Pleistocene, when the geomagnetic field last acquired its present polarity.

At various times mechanisms have been suggested by which the directions of magnetization of a group of samples from a rock formation could have become systematically different from the corresponding directions of the geomagnetic field at the times of their formation. The preferential settling of elongated or discoidal iron-oxide grains either horizontally or in the direction of water currents is a bias which might be introduced at the time of formation of the rock. Irreversible changes of magnetization by the process of magnetostriction caused by stress due to tectonic activity or deep burial; "chemical magnetization" occurring through the gradual change of maghemite, a common constituent of the red soils which may go to form red beds, to hematite long after deposition of the beds; or a partial thermoremanent magnetization due to the fall of temperature after deep burial are examples of biases which could occur at any time between the formation of the rock and the present. The change in the direction of magnetization resulting from recent fields, which was discussed in the previous paragraph, is the only one of such effects for which clear evidence exists.

A further factor must be considered: If an appreciable proportion of the magnetized grains are elongated along their direction of magnetization, compaction subsequent to the magnetization process appears capable of reducing the angle of inclination. If the magnetization of the sediment occurred during deposition through the alignment of the magnetized iron-oxide grains by the geomagnetic field, an appreciable error would result only if (1) the degree of compaction were larger than, say, 5 to 10 per cent, which would not be expected in a sandstone, although possibly in a shale; and (2) the iron-oxide particles were sufficiently large to interlock with the other grains. If, on the other hand, the heavy minerals were smaller than the other grains, which is usually true in sandstones, the magnetized particles would be free to rotate, especially if the sediment were water-logged. Thus it would appear that the geomagnetic field will retain the power to orient the magnetized grains until the final stages of compaction. On the other hand chemical magnetization will occur only after the bulk of the water is squeezed out from the pores of the sediment, *i.e.*, after compaction had been substantially completed. To examine whether such effects do, in fact, bias the determinations of the mean field directions, comparisons between different formations of the same age collected in different places is necessary.

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Dr. N. D. Opdyke, except for the Belt series which was sampled in the summer of 1957 with the help of Mr. H. R. Eisenbeis. The preparation of the rock specimens, coring, and cutting into discs was done by W. Rutherford, and the magnetic measurements and computation were made with the able assistance of A. Major, P. Dewell, and W. Rutherford in the Physics Department of King's College, Newcastle upon Tyne. This research was made possible by generous support from the Penrose Bequest of The Geological Society of America, from the Museum of Northern Arizona, Flagstaff, and from the Department of Scientific and Industrial Research, London.

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STATISTICAL TREATMENT OF PALEOMAGNETIC DIRECTIONS

The statistical methods used in this paper follow the treatment of Fisher (1953), who assumes that the population from which a sample of directions of magnetization is drawn is such that the probability of a direction making an angle between θ and $\theta+d\theta$ with the true direction is proportional to exp (κ cos θ).$d\theta$. Fisher shows that if each direction is represented by a unit vector the direction of the vector mean is the best estimate of the true direction. He also shows that a cone of confidence can be described about this mean direction which will contain the true direction at any assigned probability, the semi-angle α of the cone of confidence for a probability of 95 per cent being usually calculated. The parameter κ is a measure of the scatter, termed the precision, which is larger as the directions are more tightly grouped. For large κ the distribution becomes approximately Gaussian with a standard deviation in degrees equal to $88/\kappa^{\frac{1}{2}}$ (Runcorn, 1957).

It has been argued (*e.g.*, Blackett, 1956) that the application of such statistical methods to this subject gives an undue impression of accuracy. This point of view seems to rest on the following grounds: (1) The cone of confidence derived from the scatter of a set of observations does not include systematic errors, and it may be misleading to direct the attention of the reader to the random error in the mean direction when it may be smaller than the systematic error. (2) The analysis is based on the assumption that the directions are distributed with a frequency proportional to exp (κ cos θ), which implies assumptions about the physical cause of the scatter (Wilson, 1959). (3) Where small samples are used the divergence between the actual distribution and the theoretical one for an infinite population will be obvious by inspection.

We think that criticism (1) is mistaken because an exact statistical method is a powerful means of determining a systematic bias if one exists. This is carried out by comparing mean directions taken from two or more sets of results obtained from different localities in the same formation and testing whether the differences could arise from the finite number of samples used. The studies of the Chugwater formation in the different localities and the upper and lower parts of the Supai discussed in this paper are examples of this method of searching for systematic errors.

Objection (2) is not well founded. Runcorn (1956c) shows that if the three rectangular components of the magnetization of a series of rock samples are each distributed according to the Gauss-error function with the same standard deviations, then the directions of magnetization are distributed with a frequency proportional to exp(κ cos θ), assigning unit intensity to each sample. As the Gaussian distribution is approached where the errors are the result of a large number of independent errors, positive or negative, Fisher's distribution would appear to be appropriate to discuss the scatter of magnetization of samples, each containing a very large number of magnetized particles. Because the magnetization of the sample is weak there can be no interaction between the particles—all act independently. Further, as in Gaussian statistics, the calculations made prove to be rather insensitive to the exact form of the probability-distribution function.

Objection (3) might be raised to all modern statistical work which, having been developed largely for use in the nonphysical sciences, allows exactly for the effect of a small sample. There can be no merit in collecting larger and larger numbers of samples unless these are used effectively, *i.e.*, by an exact statistical method, and the size of the sample is simply determined by the accuracy required in the mean direction, which depends on the use to be made of the observations. The sample size used in this paper proves to be adequate in view of the doubt which exists of the age relationships of the rocks examined.

CONVENTIONS USED THROUGHOUT THE PAPER

The directions of magnetization of discs cut from samples collected from a certain section of a rock formation are plotted on a stereographic projection. Points on the lower hemisphere of the projection, *i.e.*, representing directions with positive (downward) angles of inclination, are represented by full dots. Points on the upper hemispheres of the projection, *i.e.*, representing directions with negative (upward) angles of inclination, are represented by open circles. Directions from discs cut from the same core are connected together by a full line, and directions from cores from the same rock sample are connected by a broken line. The samples are numbered from the bottom of the section upward: missing numbers represent samples either too weakly magnetized to be measured or too fragile to be satisfactorily cut to shape.

The direction which the geomagnetic field would have at the site if the earth's field were that of a dipole orientated along the present geographical axis is plotted on each stereographic projection by a square (full for sites in the present northern hemisphere).

For each set of directions at one section, the mean direction is calculated and plotted as a star. From this calculation is omitted the occasional result which is erratically displaced from the main group. The center of the star is a dot if the direction has a positive angle of inclination and an open circle if the direction has a negative angle of inclination. Described around the mean point is the 95 per cent circle or cone of confidence of radius α. Samples from some formations in which the bedding planes were easily recognizable were cored so that the axes of the cores are perpendicular to these bedding planes. The declination and inclination of the magnetization of the discs cut from these cores were thus automatically corrected for tectonic dip. The mean directions of magnetization plotted for these formations therefore can be taken as estimates of the geomagnetic field at the times of deposition. This procedure is indicated by an asterisk in the column in Table 1 headed Geological Dip. In all other cases the points on the projections give the directions of magnetization in space today, *i.e.*, the plane of the projection is the horizontal at the site. The declination and inclination given in Table 1 is corrected for local geological dip, and this corrected mean is indicated on the stereograms by a full or open triangle, according to whether the inclination is positive or negative respectively.

Where secondary magnetization is appreciable, so that the distribution of directions of magnetization is planar, the primary direction must be estimated. A point on the great circle lying near the end of the planar distribution farthest from the present dipole field is indicated by a cross on the stereograms. If the strata are flat lying this is the estimate of the primary direction. Where the rock strata are tilted and the plane of projection is the present horizontal, the planar distribution passes through the present dipole field, and the direction indicated by a cross must be corrected in the usual way for the geological dip. This point, denoted by an open or full triangle, is then the estimated primary direction of magnetization.

In Table 1, S is the number of samples collected, N denotes the number of discs cut, and N' the number used in the statistics, R is the vector sum of these N' directions (each being assigned unit length), κ the precision, and D and I the angles of declination and inclination of the vector mean direction.

Unless otherwise stated the term "pole" is always used to mean the geographical pole or pole of rotation for the geological period under discussion.

Corresponding to the 95 per cent cone of confidence for a mean direction of magnetization is a 95 per cent oval of confidence for the corresponding pole positions. In Table 1 are given the semi axes ($d\psi$, $d\chi$) of this oval along and perpendicular respectively to the great circle joining the site to the pole position.

We now proceed to describe the measurements through the geological column (Table 1).

PRECAMBRIAN FORMATIONS

In the Western United States upper Precambrian (Algonkian) unmetamorphosed red beds, which have been little affected by serious tectonic movements, are prominent in the Grand Canyon series and in the Belt series.

UNKAR GROUP OF THE GRAND CANYON SERIES (ALGONKIAN) (FIGS. 1-3): The lowest formation of this group, exposed in the Canyon of the Colorado River, is the Bass limestone, a brown limestone which proves to have sufficient remanent magnetization for measurement. This formation was sampled near the Kaibab Trail south of the Colorado River.

Lying conformably on the Bass limestone is the Hakatai shale, a series of red shales, which was sampled north of the Colorado River 4.3 miles from Kaibab Bridge, just west of the Kaibab Trail, north of Phantom Ranch.

The Shinumo quartzite conformably overlies the Hakatai shale and is a hard compact fine-grained purplish quartzite. It was sampled near the Kaibab Trail south of the Colorado River.

The results show possible slight effects of recent secondary magnetization. Thus the original mean direction of magnetization of the Hakatai shale is likely to have had a more southerly declination and a smaller angle of inclination than the mean of the observed directions.

BONITO CANYON QUARTZITE (PRECAMBRIAN) (FIG. 4): The Bonito Canyon quartzite of Precambrian age was sampled east of Fort Defiance. Assuming it to have been deposited under water the well-marked ripple-marked surface was taken as the original horizontal. The quartzite rests unconformably below the Supai formation, and its age has been discussed recently by Lance (1959), who concludes that it is older than the Grand Canyon series.

BELT SERIES (ALGONKIAN) (FIGS. 5-9): The Belt series consists of a thick series of limestones, red shales, and argillites (Clapp and Deiss, 1931) which crop out mainly in Montana, where the collections reported in this paper were made. An illitic shale from the Siyeh formation of this series has recently been satisfactorily dated at 750 million years by Goldich, Baadsgaard, Edwards, and Weaver (1959).

The lowest group of the Belt series sampled was the Ravalli group in Glacier National Park, in which the Appekunny formation and the overlying Grinnell formation can be sampled easily along the road west from St. Mary's. Above these lies the Siyeh limestone at the top of which is several hundred feet of sandy and shaly beds, mostly red, which are probably correlated with the much thicker Spokane formation of the Piegan group. These were sampled at McDonald Creek. The Spokane is fully exposed in Prickly Pear Canyon, north of Helena, where it was sampled along Highway 91.

The Missoula group, possibly correlating in part with the Piegan group farther east, was sampled near Missoula, where it rests conformably on the Wallace limestone. Lowest in the section is the Miller Peak formation which was sampled in Donovan Creek, off Highway 10, east of Missoula, Montana. Above it, possibly unconformably, lies the Hellgate formation, on which the McNamara formation rests conformably. This was sampled at McNamara's Landing on State Highway 20 in Blackfoot Canyon.

LOWER PALEOZOIC FORMATIONS

Fine-grained and undisturbed red beds of Early Paleozoic age are rare in the Western United States, but the formations sampled are described.

TAPEATS SANDSTONES (CAMBRIAN) (FIG. 10): A few feet of red sandstones was found in the Tapeats sandstones in a creek bed south and west of Peach Springs, Arizona (Wood, 1956, Ph.D. Thesis, Univ. Arizona). The Tapeats sandstone can be traced almost continuously from this area northward along Peach Springs Draw to the Grand Canyon, where McKee (1945) studied the Cambrian rocks. The upper 100 feet of the Tapeats sandstone becomes finer-grained as the base of the overlying Bright Angel formation is approached, cross-bedding becomes less evident or absent, and beds of red or of yellowish-gray shaly siltstone, 6 inches to 2 feet thick, alternate with beds of light-brown to black sandstone of similar thickness. A few of the beds of the shaly siltstone are light greenish gray.

A Cambrian pole position, based on an incomplete preliminary examination of these results, was quoted by Day and Runcorn (1955) but was withdrawn in the survey of British and American paleomagnetic results by Creer, Irving, and Runcorn (1957).

BRIGHT ANGEL SHALE (CAMBRIAN) (FIG. 11): The Bright Angel shale of the Tonto group of Cambrian age of the Grand Canyon region, lying conformably below the Muav limestone and above the normally coarse-grained Tapeats sandstone, has been sampled in the Grand Wash cliffs near the Diamond Bar Ranch, Arizona, where it includes some red sandstones, as described by McKee (1945). Starting from the lower contact with the Tapeats sandstone 260 feet was sampled.

LODORE FORMATION (CAMBRIAN?) (FIG. 12): The Lodore formation was sampled along Highway 44 between Manila and Vernal, Utah, on the north flank of the Uinta Mountains, where the beds dip steeply beneath a massive Madison limestone exposure. Samples 12 and 13 are excluded from the statistical analysis. Although Williams (1953) gives the age of this formation as Cambrian, the basis for this appears to be lithological rather than paleontological.

These Cambrian results present an interesting example of secondary magnetization.

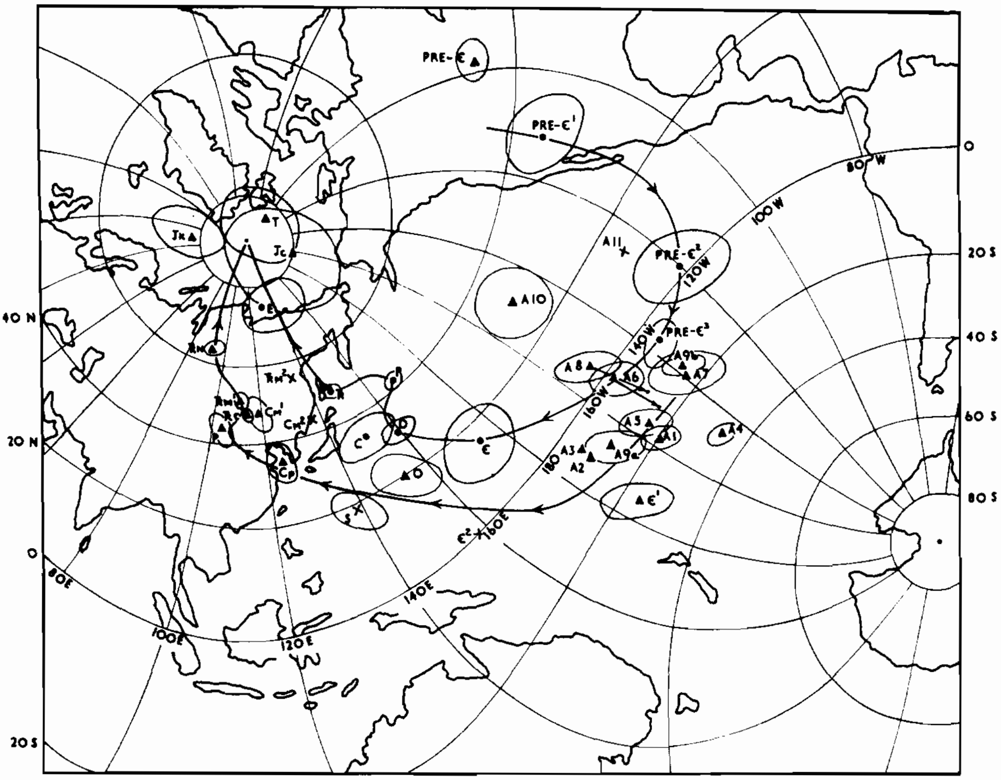

FIGURE 26.—POLE POSITIONS AND PATHS BASED ON BRITISH AND AMERICAN ROCKS

British rocks——●——. American rocks——▲——.

Poles determined from British rocks are those given by Creer, Irving, and Runcorn (1957), but the Triassic and Permian poles are slightly modified on the basis of data by Nairn (1960).

Poles determined from American rocks are as follows:

J_K	mean of Kayenta poles (Jurassic)
J_C	Carmel pole (Jurassic)
ŦRM^1	mean of Moenkopi poles (Triassic)
ŦRM^2	Moenkopi pole (Kintzinger 1957)
ŦRC	mean of Chugwater poles (Triassic)
ŦRN	Newark formation (Upper Triassic)
C_m^1	Deadwood formation (Mississippian?)
C_m^2	Barnett formation (Howell and Martinez, 1957) (Mississippian)
A 10	Hakatai shales (Runcorn, 1956a)
A 11	Hakatai shales (Doell, 1955)
Pre-Є	Michigan dykes (Graham's data quoted by Creer, Irving, and Runcorn, 1957)

Algonkian poles A1–9 and all other poles: as in Table 1 and the figures of this paper.

Projection is oblique Mercator's, with pole at 0° N., 112° E., giving a uniform scale for angular distance near polar-wandering paths.