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Polar Wander Analysis from Paleomagnetic Data

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Abstract. Utilizing marine magnetic anomalies and paleomagnetic pole positions, paleogeographic maps have been constructed for three time intervals back to the Early Cretaceous. From the maps lithospheric plate motions have been calculated and these global displacement fields have been analyzed to determine best-fitting rigid rotations , which then could be ascribed to true polar wander. The values so obtained are no larger than a few degrees and are within the magnitude of the uncertainties involved.

Introduction

Paleomagnetic pole positions determined for a given continental unit can be connected in a temporal sequence; the result is called an apparent polar wander path for that continent. Assuming the ancient paleomagnetic field to have been, on average, dipolar, co-axial, and roughly geocentric, the apparent polar wander paths describe the movement of the pole with respect to the continent held fixed. In reality, the apparent polar wander paths may be due to either or both of two causes: (i) the motion of the plate relative to a fixed rotation axis or (ii) the motion of the rotation axis relative to the lithosphere as a whole. It is commonly accepted that at least some of the differences in the apparent polar wander paths of different continents are due to the relative motions of the continents; on the other hand, it has been suggested a long time ago (Creer et al.,1957) that the comparable length of the apparent polar wander paths of the individual continents imply a common cause, true polar wander.

Jurdy and Van der Voo (1974, 1975a, 1975b) have discussed previous attempts to separate the effects of continental drift (plate motions) from true polar wander and have proposed a new method to achieve this. I will briefly summarize their method here and present the results of their analysis.

Paleogeographic Maps and Paleomagnetic Poles

Maps have been constructed showing the estimated positions of the continents and plate boundaries for the Early Tertiary, the Late Cretaceous, and the Early Cretaceous. Two of these maps are shown here (Figures 1 and 2). The relative positions of the plates have been determined from marine magnetic anomalies, using published data (referenced in Jurdy and Van der Voo, 1974, 1975). All paleomagnetic pole determinations which passed minimum reliability criteria (such as a significant number of samples, demagnetization experiments, well-determined ages, etc.) have been used by combining them in approximate time intervals of 30 million years for each map (e.g., Early Tertiary: 40 to 70 my BP; Early Cretaceous: 100 to 130 my BP). Since the continents were rotated in order to obtain relative ancient positions, the paleomagnetic poles were rotated with

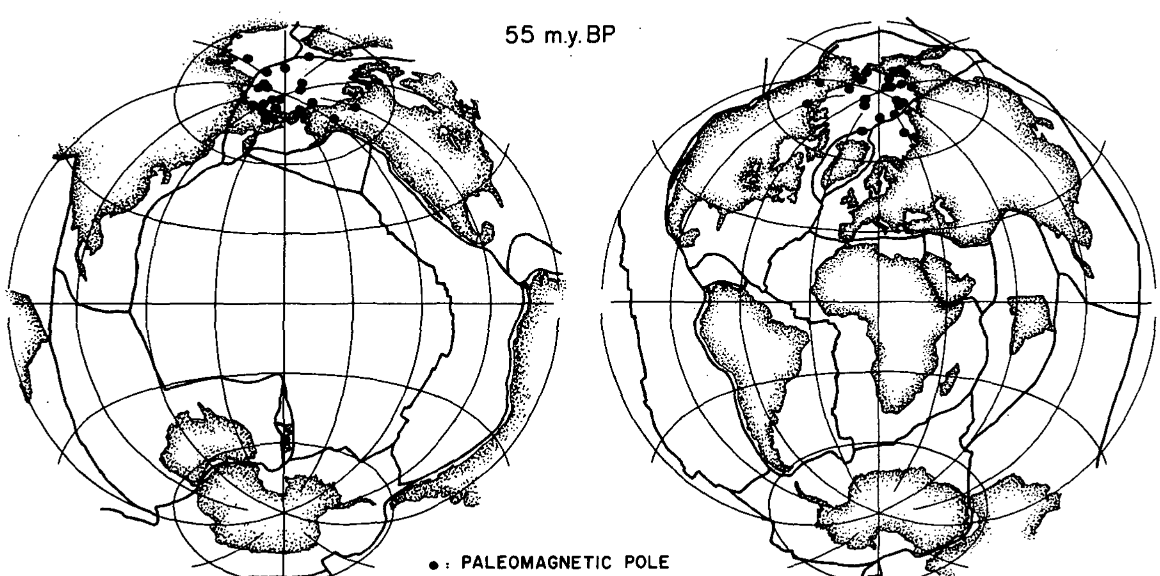

Fig.1. Paleogeographic map of the plates and plate boundaries for the Early Tertiary. The paleomagnetic poles used for the determination of the mean are plotted. The longitudes are arbitrary.

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the continents. It must be noted that the grouping of the poles is significantly better for all periods for the paleo-configurations than for the present-day positions of the plates.

The Polar Wander Analysis

Knowing the plate positions at the present and at these earlier times, Jurdy and Van der Voo constructed for each of the three time intervals, a displacement field which describes the plate motions during an interval. True polar wander has been defined (e.g., Munk and MacDonald, 1960) as a bodily shift of the earth relative to its spin axis and, if it had occurred, it would appear as a special kind of surface displacement field: a pure rigid rotation about some axis. If no relative motions between plates had occurred but such a rigid rotation of the lithosphere had taken place, it would be observed as true polar wander and the apparent polar wander paths of all continents would coincide. If, on the other hand, no true polar wander but only plate motions relative to each other had occurred, the apparent polar wander paths of different plates would diverge in the geological past. The method of Jurdy and Van der Voo can therefore be best summarized as finding a best-fitting rotation of the entire lithosphere, and it is this rotation that must be attributed to true polar wander. It is crucial for an understanding of the method to realize that in the case of no true polar wander a summation or integration of the displacements of all the plates over the entire surface of the earth would yield a zero global average. In more mathematical terms, such plate motions do not contribute to a first-degree displacement field (a rotation of the entire lithosphere) but instead make up the higher-degree displacement fields such as hemispherical twists or zonal rotations in which the motions are opposite to each other.

The plate configurations were evaluated in a coordinate framework fixed by the paleomagnetic data of the reassembled plates. The mean magnetic poles were used to fix the earth's polar axis and to define a Cartesian coordinate system in which latitudes but not longitudes can be determined. The axes lying in the equatorial plane thus must be positioned arbitrarily, and we chose to hold the longitudinal coordinates of North America more or less fixed. This arbitrary positioning of the equatorial axes implies an indeterminancy in the longitudinal displacements and indeed allows a rigid rotation of the entire lithosphere. However, this is a rotation precisely about the polar axis and such a rotation is irrelevant for true polar wander, since it leaves the position of the magnetic polar axis relative to the lithosphere as a whole unchanged. Consequently, if one decomposes a rigid rotation about a geocentric axis cutting a sphere at arbitrary latitude and longitude, into three component rotations about each of the coordinate axes, respectively, one finds that only rotations about the two equatorial axes will contribute to true polar wander and that the sum of the squares of these rotations is independent of the arbitrary positioning of the equatorial axes.

The plate reconstructions gave Jurdy and Van der Voo (1974, 1975a) three time intervals over which the displacement field could be evaluated. They developed a mathematical method to find the rigid rotation which best-fitted in a least-squares sense a set of observed displacements on a sphere. Denoting the observed displacement field by ($\bar{F}$) and a rigid rotation, corresponding to true polar wander, by a displacement field

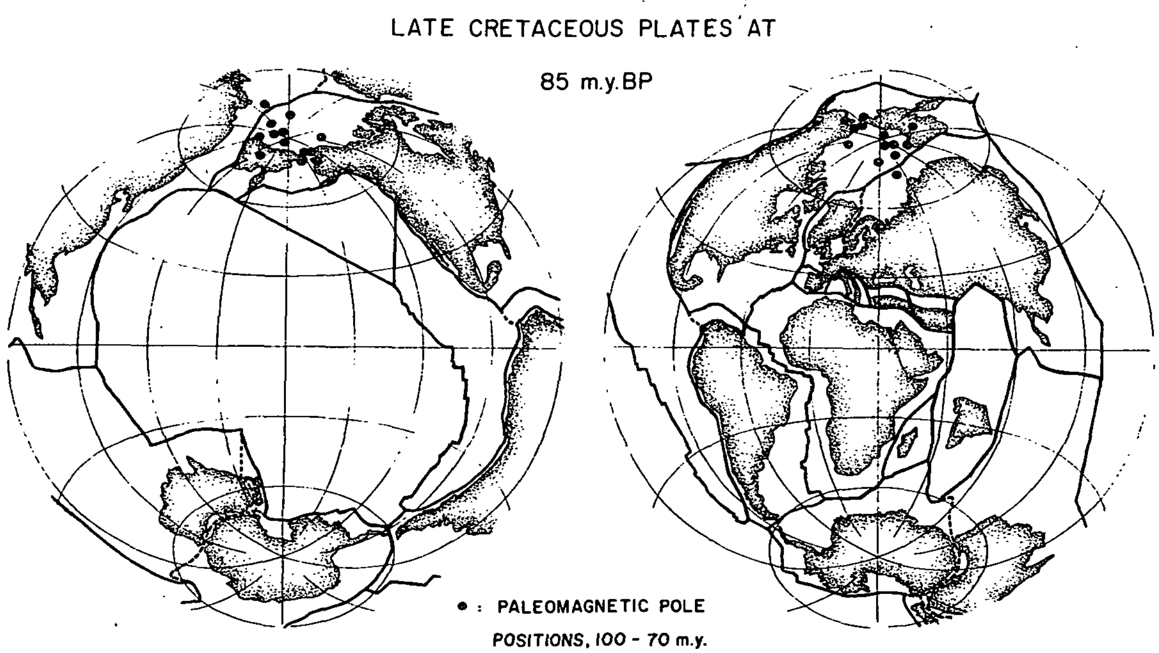

Fig.2. Paleogeographic map of the plates and plate boundaries for the Late Cretaceous. The paleomagnetic poles used for the determination of the mean are plotted. The longitudes are arbitrary.

($\bar{G}$), one can determine how much of the observed field $\bar{F}$ can be accounted for by a rigid rotation of the lithosphere $\bar{G}$, by minimizing the integral

$$\int (\bar{F} - \bar{G})^2 ds$$

where ds is an element of surface, and the integration is done over the entire surface of the earth. Further mathematical details have been presented by Jurdy and Van der Voo (1974).

The analysis of the displacement fields for the three time intervals considered yielded very small rigid rotations $\bar{G}$, an indication of little or no true polar wander. The calculated values are presented in Table 1, where the amount of true polar wander is the length of arc along which the pole moves relative to whole lithosphere or vice versa. The cumulative polar wander, found by adding the motion over longer time is given in Table 2, along with the uncertainty (α_{95}, Fisher, 1953) in the mean paleomagnetic pole used for the plate reconstructions.

The resultant polar wander is quite small, even for the entire time interval from the present to the Early Cretaceous. This is due to the differences in the direction of movement (Table 1) over the three time intervals. The calculated amounts of true polar wander were generally within the uncertainty of the mean paleomagnetic pole and thus must be considered insignificant. Only for the earliest time interval (Early Cretaceous) did the amount of true polar wander exceed the value of the associated α_{95}, but just for this early period additional uncertainties exist in the relative positioning of the plates. Since a primary requirement of the method is a reliable displacement field all over the earth, including the oceans, poor constraints on some Early Cretaceous plate positions (e.g., East and West Antarctica, the southern part of the Pacific ocean etc.) result in large uncertainties of the polar wander analysis (see also Jurdy, 1978). When better Mesozoic sea-floor spreading data become available, it is conceivable that more reliable determinations can also be carried out for the earlier Mesozoic periods.

TABLE 1. Calculated amounts of polar wander

Time interval	Amount of polar wander	Direction relative to North America longitudes
Present to 55 my	2.0°	142°W
55 to 85 my BP	3.2°	177°W
85 to 115 my BP	7.7°	11°W

TABLE 2. Cumulative amounts of polar wander

Time interval	Amount of polar wander	Direction relative to North America longitudes	α_{95}
Present to 55my	2.0°	142°W	4.1°
Present to 85my	5.0°	164°W	5.0°
Present to 115my	4.9°	50°W	4.7°

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