[American Journal of Science, Vol. 261, February 1963, P. 194-199]

DISCUSSION

POLAR WANDERING—A PHANTOM EVENT?

E. R. DEUTSCH

Imperial Oil Limited, Calgary, Alberta, Canada

ABSTRACT. Some of van Hilten's (1962) remarks on polar wandering are criticized. The claim that crustal slippage over the mantle is necessary as a model of polar wandering is disputed. Continental drift dominates the paleomagnetic evidence, but the concept of polar wandering *concurrent with* drift is either fallaceous or refers to a phenomenon that may occur but cannot be diagnosed from continental observations. Recent theoretical afterthoughts, combined with the absence of firm data, cast doubt on an earlier belief that polar wandering is unavoidable or easy.

SUBJECT OF DISCUSSION

In barely a decade of research, paleomagnetism has confirmed the fiercely argued contention that major displacements of the Earth's axis of rotation with respect to the continents have occurred. Although the possibility of an error in this main thesis is already remote, the nature and relative importance of the likely causative mechanisms, polar wandering and continental drift, remain in dispute. Van Hilten's (1962) article is a welcome contribution, for his sketch of the paleogeography since the Permian—well elucidated by his "isocline" mapping—supports convincingly what several other authors have lately concluded, namely, that the results from rock magnetism make little sense unless one invokes continental drift on a grand scale. Much detail remains in doubt, and van Hilten himself admits that his result "is a probably too simplified picture of actual geological events".

I disagree with the author's treatment of polar wandering but contend that, if the following criticism is borne out, his error resides less in the data than in their interpretation and is a matter not so much of geology than of physics. For this reason I shall assume van Hilten's maps, and the paleomagnetic and geological premises upon which they are based, to be *broadly* correct. My objection centers mainly on the following statements (p. 423, 424) which I have italicized and believe to be false:

(1) In the definition of polar wandering: "change of the position of the Earth's axis of rotation with respect to all continents; *this is necessarily accompanied by a shifting of the entire crust over the interior of the globe.*"

(2) In accounting for the apparent parallel displacement of five land masses: "*These facts are most elegantly explained by a polar wandering in the opposite direction over 50° during the Permo-Triassic.* Only Antarctica and Australia drifted away from the rest of Pangaea over about 25°. *They thus partly accompanied over this distance the wandering Earth's axis, which however, moved twice as far.*" Similarly, in table 1, the summary: "*Polar wandering and* Antarctica, Australia (and India ?) drifting away from Pangaea", for the Permo-Triassic interval.

POLAR WANDERING CONCEPTS

With respect to Statement (1): During its colorful history (see e.g. Munk, 1956), the subject of polar wandering has intrigued some eminent scientists,

one of the first being George Darwin, who described in a classical paper (1877) the pole movement that might result from changes of mass distribution in the crust of various Earth models. However, at the time the planet was still regarded as essentially rigid, and he concluded that polar wandering could not, in fact, have taken place.

Darwin's negative judgment was not appealed until fairly recently, after a number of new mechanisms had been proposed, notably the mathematical model by Milankovitch (1941), and a scheme based on qualitative reasoning by Gold (1955). In most of the serious treatments, back to Darwin's own, the inherent concept has been that polar wandering constitutes a movement of the *entire Earth* with respect to its axis. Gold took his cue from the observed short-period variations of latitude, whose damping he attributed to dissipative deformation of the solid part of the Earth, proceeding essentially by plastic flow. He showed that under these conditions a relatively modest redistribution of matter (such as some geological process might bring about) could instigate polar wandering through wide arcs in as little as 10^5 years.

A mechanism exists, therefore, which is not only theoretically plausible but would make axial displacements within the Earth comparatively easy. Whether significant shifts of this kind (or any other) have actually occurred is, of course, another question, but van Hilten certainly errs in asserting that polar wandering is *necessarily* a matter of crustal slippage.

Turning now to Statement (2), we note that polar wandering and continental drift have been invoked *together*. In reasoning on this basis, van Hilten is preceded by a long line of authors, including Köppen and Wegener (1924), Gutenberg (1951), Ma (1958), and Irving (1958), who made the first serious attempt at reconstruction of the ancient geography through paleomagnetism. Although Statement (2) is a purely geometrical interpretation, incapable of distinguishing between alternative *versions* of polar wandering, a relationship between polar wandering and continental drift is clearly implied.

In what manner, then, are the two hypothetical motions related? Although van Hilten barely alludes to this question, we shall see that the answer, apart from its wider geophysical implications, bears directly upon his argument. Darwin already recognized that the prerequisite for any polar wandering must be an Earth capable of *yielding*—this much it has in common with continental drift. Whether it also shares with drift the actual instigating mechanism—possibly convection currents in the mantle (Runcorn, 1957)—is debatable, but without question Gold-type polar wandering would be *basically different* in its dynamics from drift.

Statement (1), on the other hand, is consistent with the idea (though it may have been absent from the author's mind) that polar wandering and continental drift are *basically similar*. I suspect that this is a widely entertained notion, for all too often in the literature the siamese-twin approach has been used in describing the two phenomena; a notable exception is Wegener (1920), who cautioned some of his contemporaries against the pitfalls of lumping together these separate hypotheses. I think the similarity-concept would become plausible only if one could conceive of some high-mobility layer beneath the crust, extensive enough to coordinate the random drift of crustal

fragments into gliding of the "entire crust over the interior". Some writers accept crustal slippage with facility (e.g. Ma, 1958, who combines drift with the "sudden total displacement of the solid earth shell"), but Munk and Macdonald (1960), on the basis of calculation assuming a "shell" 100 km thick and a thin lubricating layer underneath, reject this as a reasonable model for polar wandering.

FALLACY OF THE "SIAMESE-TWIN" APPROACH

Let us now examine van Hilten's interpretation when crustal slippage is *assumed* to prevail. Polar wandering may then be regarded as a special case of continental drift, and from this it is a natural step to suggest that the two mechanisms conspired to produce certain data.

Such reasoning can lead straight into a fallacy: the first sentence in Statement (2) invokes polar wandering during the Permo-Triassic, whereas the remainder tells us that at least two fragments (Antarctica and Australia) drifted away from the original supercontinent in the same time interval. But according to Statement (1), polar wandering is a shift of the Earth's axis with respect to "all" continents, or of the "entire crust" over the interior. Concurrency of such a movement with continental drift is clearly a contradiction in terms, since the phrase "entire crust" in the definition becomes meaningless whilst the crust suffers disruption. It follows that the evidence in the case cited is real only with respect to continental drift, but not polar wandering.

To show that more than a quibble about semantics is involved, I have schematized some of the pertinent movements (fig. 1). The crustal-slippage scheme is Case IIA. If we now accept the alternative model (IIB), coincidence of polar wandering and continental drift is admittedly no longer absurd, but only if we specify that axial shifts now relate to the portion of the globe *below* the crust—in other words, any superimposed crustal displacements are taken as negligible for the purpose of defining polar wandering. For that reason, however, it is impossible to *infer* polar wandering from continental data, regardless of the kind and volume of evidence used, if crustal blocks have drifted at the same time. This is illustrated in the example in figure 1 (IV), where the land masses have moved through distances different from those in Case III ("pure" continental drift); additional polar wandering has been just sufficient to make the final geographical pattern identical to the one resulting from drift alone.

It might be objected that my argument still fails to rule out polar wandering, inasmuch as this could occur in *alternation* with continental drift. Irving (1958) has suggested that drift may have been interrupted by quiet periods during which polar wandering proceeded alone; knowledge of such a sequence could enable one to reduce the alternatives for continental rearrangement to a finite or even small number. In van Hilten's interpretation the apparent parallelism of five continental routes might then signify polar wandering after all, for example, if this had been a rapid event near the start of the Permian period, to be *followed* by continental drift of Australia and Antarctica.

This, of course, is perfectly feasible, since fast axial shifts are still beyond the resolving power of paleomagnetism and could easily have been missed in

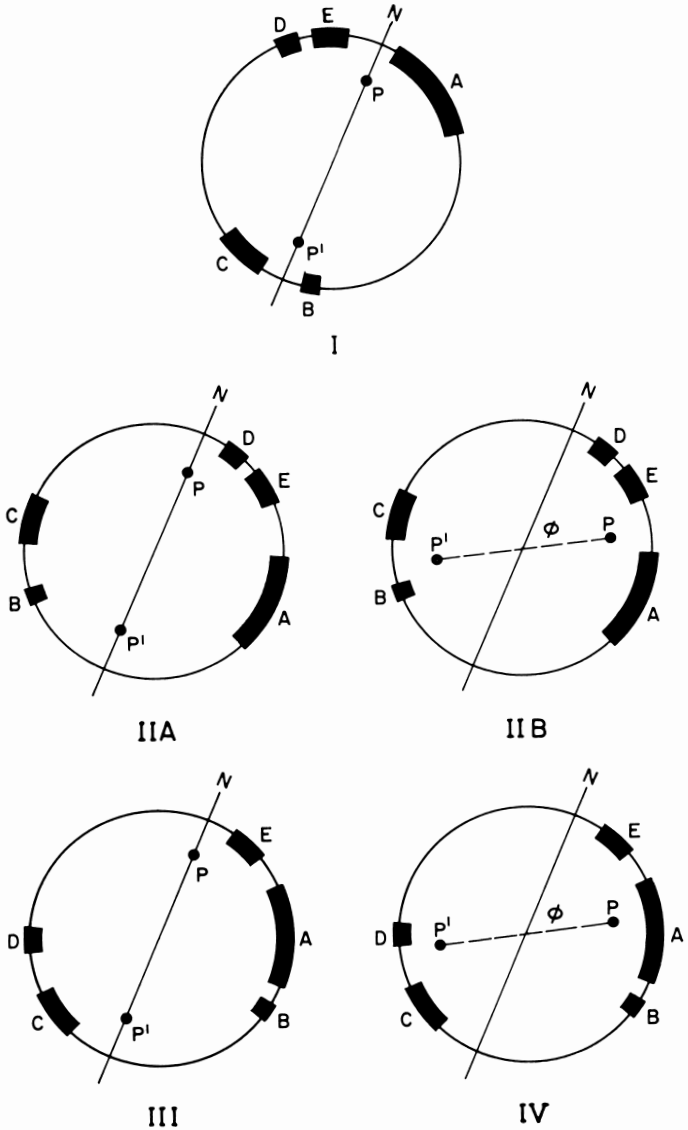

Fig. 1. Schematic view of relative pole movements. I. A meridional cross section of the Earth is considered, with continents A, B, C, D, E, and reference points P, P′ below the crust. The axis of rotation remains fixed in space, with P, P′ initially along this axis. IIA. *Polar wandering through slippage of the crust over the interior.* The continents turn in unison with respect to the axis of rotation, which remains fixed relative to core and mantle, and hence PP′. IIB. *Polar wandering relative to the whole Earth.* The continents and reference axis PP′ turn in unison through the angle Ø. III. *Continental drift.* A . . . E move with respect to each other and to the axis of rotation, which remains fixed relative to core and mantle, and hence PP′. IV. *Polar wandering with continental drift.* In the example chosen, the angles of drift differ by Ø from their magnitude in case III, but the final arrangement of continents relative to the poles is identical. Tests based on continental sampling cannot distinguish between cases III and IV.

the record. It would impose the requirement, however, that the two errant land masses participated in the original polar wandering, at either the start or conclusion of which they would have found themselves situated quite far from their relative "Permian" residences; it follows that a large amount of unrecorded polar wandering (and possibly drift) must be postulated to relocate them on their nonconformist tracks in van Hilten's map (fig. 8), along which they would presumably continue drifting as shown.

Whether such complex motions have, in fact, taken place is still entirely speculation, though information might come forth to prove their reality. Such a possibility does not invalidate my previous criticism to the effect that polar wandering is undiagnosable from the evidence *now* at hand.

DOUBTFUL REALITY OF POLAR WANDERING

Moreover, I find it difficult to justify preference for complicated reconstructions when simpler schemes based on continental drift alone might suffice. Parallelism in the apparent travel paths of land masses is undoubtedly a striking feature but may be amenable to explanations other than polar wandering. The fact that the direction of principal shear zones in the crust predominantly makes small angles with the present meridians has been interpreted as favoring the north-south component of drift (Bederke, 1957). Thus it should not be too difficult to conceive of reconstructions that involve continental drift along roughly parallel tracks without overstepping reasonable premises of geophysics or geology: the hypothetical breakup of Gondwanaland, during some of its stages at least, comes to mind as an example that might qualify.

Even granting his interpretation, van Hilten's maps show clearly that continental drift dominates the evidence. This is surprising, for with removal of earlier theoretical objections polar wandering had seemed by far the more likely of the two mechanisms to occur on a grand scale. Indeed, it was considered so easy that members of a symposium held in 1955 at Cambridge University, at which Gold outlined his polar wandering model, expressed themselves emphatically (even by show of hands!) against the occurrence of any significant continental drift, for (so the argument went), supposing that some part of the crust had in fact begun drifting, the resulting change in its mass distribution would surely at once initiate polar wandering of much larger proportions.

The first publication of paleomagnetic evidence favoring drift seems to have rendered this view untenable almost as soon as it was propounded. Polar wandering also faces objections of a theoretical nature. The justification for calibrating the motion with a constant derived from nutational damping has been questioned (Munk, 1959), and for prolonged stresses the rheological condition of the mantle may be that of a "Bingham" body of finite yield strength, having a relaxation time of 20,000 years or more (Scheidegger, 1958). Polar wandering would then be slowed down by three orders of magnitude compared with typical rates derived from Gold's assumption. On the basis of moment of inertia considerations, I have attempted to show (Deutsch, in preparation) that continental drift, even of major proportions, need not provoke more than modest polar wandering at most.

Finally, recent hypotheses of continental and oceanic differentiation (Dietz, 1961; commentary by Wilson, 1961) bear directly upon the subjects discussed. Dietz accepts earlier proposals (Holmes, 1944) for the existence of large convection currents in the mantle, but considers that the ocean bottom itself is essentially "outcropping mantle" and constitutes an upper surface for the convection cells. In this way, the sea floor is continually rejuvenated through spreading, while at the same time continents may be compelled to drift because of coupling with the upwelling currents.

If this is borne out, terms like "oceanic crust" or "entire crust", not to mention "Earth's shell" or "skin", will lose their traditional meaning. It would do away, once and for all, with the concept of crustal slippage over the mantle, and at the same time remove major objections to continental drift in the "classical" sense, for one would no longer have to explain how continents can bully their way against the resistance of a tough oceanic crust.

Much of the foregoing has been speculative. Perhaps in discussions on polar wandering and continental drift this will be inescapable for some time yet. The best one can hope for while much of the subject remains unavoidably tentative is that it will not be further confounded by arguments that are avoidably mistaken. The 1956 paper by Munk, previously cited, was entitled: "Polar wandering: a marathon of errors". It appears that the runner has yet to reach Athens.

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