Late Cretaceous True Polar Wander: Not So Fast

Using recalculated paleopoles from seamount anomaly modeling (SAM), Sager and Koppers (1) proposed an episode of rapid Late Cretaceous true polar wander (TPW). A critical review of the data used, however, suggests that Sager and Koppers have underestimated the effects that errors and data selection have on inferences of TPW and that they may not have adequately taken into account alternative explanations consistent with error sources, modeling uncertainties, and the geology of the Pacific Ocean basin. Further, their TPW hypothesis fails a test based on paleomagnetic data from a well-studied, highly regarded pelagic sedimentary section of the same age.

In framing their TPW hypothesis, Sager and Koppers (1) implicitly challenged a basic tenet of paleomagnetic research: to be considered reliable indicators of the ancient field, magnetizations from rocks of indistinguishable age should yield well-grouped directions. They considerably revised previously published SAM-based pole solutions (2) and selected data to construct an apparent polar wander path (APWP). The result was two new subsets of data from 84 million years ago (Ma)—which Sager and Koppers (1) labeled 84E and 84W—that were indistinguishable in age, yet showed greatly different mean directions (Fig. 1). Sager and Koppers interpreted this pattern not as a reflection of varying data quality but as recording a TPW event. Previous TPW studies (3) have relied on a fixed-hotspot reference frame that has since been seriously questioned (4–6). Tarduno and Gee (4), for example, previously showed that the cumulative 15° to 20° of TPW quoted by Sager and Koppers (1) is an overestimate; TPW may not have exceeded 5° for the last 200 million years (My). Nevertheless, the TPW hypothesis of Sager and Koppers differs from previous studies, in that the proposed event is so fast (3° to 10° per My) that it cannot be resolved with 40Ar/39Ar isotopic age data. This requires that the seamounts that record the TPW inferred by Sager and Koppers formed much more rapidly than the 5 to 7 My that other studies (7, 8) have concluded is typical.

The work of Sager and Koppers (1) was motivated by discrepancies between previously published SAM poles and paleomagnetic data derived from basalts recovered through ocean drilling, especially those from Detroit Seamount (4–5). The latter are standard paleomagnetic analyses, in which induced magnetizations are excluded and secondary magnetizations are removed through exhaustive laboratory work. SAM paleopole data, in contrast, include induced and secondary magnetizations (9) and large model uncertainties (10).

The potential importance of these considerations emerges from a close analysis of key data. For example, Sager and Koppers (1) revised a prior Late Cretaceous (82 Ma) SAM pole (2) to create the new 84E pole, the 95% confidence interval of which does not overlap with that of the previously published pole (2, 11). If, as Sager and Koppers claim, large biases in the data are unlikely, then we should expect only small, random changes in individual SAM paleopoles. Instead, the changes are mainly to the north, closer to the paleolatitude constraint from Detroit Seamount (5) (Fig. 1C). That tendency suggests either that the modeling in (1) was parameterized to favor solutions close to those provided by the ocean basalt core paleomagnetic analyses (in which case the SAM paleopoles are not independent measures of Pacific apparent polar wander), or that the SAM data themselves contain systematic errors that bias the final paleopoles.

Fig. 1. Late Cretaceous paleopoles (triangles) based on SAM. Sidebars indicate seamounts used. Blank denotes a previously identified paleopole deleted in a subsequent calculation; dagger (†) denotes a pole position modified from a previous analysis. N: normal polarity; R: reversed polarity. (A) 81 ± 2 Ma pole of Gordon (11) with 95% confidence interval. (B) 82.4 ± 0.7 Ma pole of Sager and Pringle (2) with 95% confidence interval. (C) 84E (83.4 ± 1.6) and 84W (84.0 ± 1.8) poles of Sager and Koppers (1) with 95% confidence intervals. Arrow indicates change in pole position calculated by Sager and Koppers (1). Also shown are data from paleomagnetic analyses of basalt samples recovered by ocean drilling: 81.2 ± 1.3 Ma colatitude value from Detroit seamount (solid line) with 99% confidence interval (dotted lines) (5).
Another example of potential reliability problems in SAM paleopoles lies in three such paleopoles used in prior analyses that were not used in (1). Sager and Koppers excluded these paleopoles not because of questions about their reliability, but because no new 40Ar/39Ar data were available. The reversed polarity of these paleopoles, however, suggests that they should fall on the post-84 Ma APWP, which they do not. These SAM paleopoles probably deviate so greatly from the oceanic-core paleomagnetic data because their reversed magnetizations are heavily contaminated by viscous and induced magnetizations [see, e.g., (9)].

To derive their new 84W paleopole, Sager and Koppers used four seamounts, in two complex areas of crust, for which no new age information is reported. The authors reported that the difference between the 84W and 84E SAM poles had been attributed in previous studies "to microplate rotations in the Musicians and South Hawaiian seamounts" (1). But the proposed microplates (12) do not contain the seamounts used to define the new 84W paleopole; instead, these seamount data had been excluded from previous studies because they were thought to be unreliable (2) or to differ in age. In our view, both possibilities remain viable. One seamount (Kapsi-totwa) is in the Line Islands, the archetypal Pacific volcanic chain formed by multiple volcanic events (13, 14). The other seamounts are from a relatively small area within or immediately adjacent to a large fracture zone in which tectonic or volcanic complexity would not be surprising.

Sager and Koppers (1) cite data from North America, rotated into a hotspot reference frame (15), to support their hypothesis, but the TPW prediction and North American pole data differ by more than 60°. In addition, some of the North American data used have declination uncertainties (16) that are an important consideration in the comparison presented by Sager and Koppers (1). The North American data cited (1), however, lack the temporal resolution to test the hypothesis.

Paleomagnetic data from sedimentary sections, by virtue of their near-continuous records, should show evidence for the proposed rapid TPW event. Arguably the most highly regarded such data from the Late Cre-taceous come from pelagic limestones of the Umbrian Apennines (17). The magnetostratigraphic record from these rocks, and their exact match with the marine magnetic anomaly record, constitute a cornerstone of the geomagnetic time scale. Continued work (18) has confirmed the fidelity of the paleomagnetic directions reported in the original, classic studies (17). The TPW rotation of Sager and Koppers (1) predicts a paleoinclination change of ~18° in the Umbrian region (Fig. 2). The paleomagnetic data from Umbrian rocks fail to show this predicted motion, however, and the rapid-TPW hypothesis fails to explain these data even when Late Cretaceous to early Tertiary hotspot motion (5) is considered. In light of this finding and the preceding discussion, we conclude that the TPW event of Sager and Koppers (1) is an artifact of spurious SAM data.

Response: Cottrell and Tarduno criticize our interpretation of rapid polar wander (1) and maintain that our hypothesized 84 Ma polar shift in Pacific SAM data results from an unrecognized error. They argue that SAM data are inadequate because of overprint magnetizations, tectonic complexities, and long seamount eruptive histories. They also claim that the proposed shift is not seen in sedimentary paleomagnetic data from a limestone section in Italy. Finally, they suggest that we have violated basic paleomagnetic practice and biased the selection of data to achieve our result.

SAM data are not of the same quality as paleomagnetic data from oriented rock samples, but high-quality rock sample data from the Pacific are too few to define a detailed APWP by themselves. In light of the paucity of better data, SAM paleomagnetic poles are useful, if employed with proper caution. When using SAM data to define the Pacific APWP, we found two 84 Ma mean poles separated by a large distance that is not readily explained by the observed scatter in SAM poles, and that we interpreted as evidence of an 84 Ma polar shift (Fig. 1). As we discussed (1), the polar shift does not reflect magnetic overprints (induced or viscous), because these would bias SAM poles perpendicular to the observed motion. Tectonic complexities should cause random errors in SAM pole locations and thus do not explain the grouping of poles. Furthermore, the prolonged, 5- to 7-Mb time span that Cottrell and Tarduno cite for seamount formation does not necessarily apply here, because it is inferred from studies of complex, large-volume volcanoes such as Hawaii, and because it includes the low-volume post-erosional volcanic stage. It is reasonable to

**References and Notes**

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**TECHNICAL COMMENTS**

**Fig. 2.** (A) TPW event following methods of Sager and Koppers (1). North America and Africa (black outline) are rotated to position as of 84 Ma, using rotation poles of (15). Dashed lines: predicted rotations around TPW pole (filled triangle) of Sager and Koppers (1). The rotation predicts a southward shift of the Umbrian Apennines on the Adriatic promontory of Italy (red), which is nearly the exact match with the marine magnetic anomaly record, constitute a cornerstone of the geomagnetic time scale. Continued work (18) has confirmed the fidelity of the paleomagnetic directions reported in the original, classic studies (17). The TPW rotation of Sager and Koppers (1) predicts a paleoinclination change of ~18° in the Umbrian region (Fig. 2). The paleomagnetic data from Umbrian rocks fail to show this predicted motion, however, and the rapid-TPW hypothesis fails to explain these data even when Late Cretaceous to early Tertiary hotspot motion (5) is considered. In light of this finding and the preceding discussion, we conclude that the TPW event of Sager and Koppers (1) is an artifact of spurious SAM data.

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expect that 95 to 98% of a seamount’s volume is emplaced during the shield-building stage, in no more than 0.5 to 1.5 My (2).

The data selection criteria in (1) were simple and unbiased. Because improved age dates and SAM models were available, we used more stringent criteria than in past analyses (3,4). We used only SAM data with $^{40}$Ar/$^{39}$Ar isotopic dates and with model parameters that indicated a close fit of observed and modeled magnetic anomalies [note 13 in (1)]. Cottrell and Tarduno make much of differences in our mean poles compared with the 81- and 82-Ma poles of previous studies (3,4). The new mean poles are different because we used more stringent rejection criteria on a different data set. Only three of nine SAM poles from the previous 82 Ma pole grouping (4) were used in our recent study, simply because the others have no $^{40}$Ar/$^{39}$Ar dates. In addition, the three poles in common have all been reanalyzed with updated modeling techniques [note 12 in (1)].

But how reliable are the two 84 Ma poles? Fig. 1 shows that one cluster of SAM poles, the 84E group, agrees with independent magnetic skewness data from Chron 33n [79 to 83 Ma (5)] and with Ocean Drilling Program (ODP) core data from Detroit Seamount [81 Ma (6)] and Wodejebato Guyot [83 Ma (7)]. SAM poles of the 84W group fall with magnetic poles of slightly older age [91 Ma (1)] and ODP core data from Hole 869B [97 Ma (6)]. Clearly, the two poles agree with other paleomagnetic data and only the timing is in question. The velocity of the shift depends on the dating of the paleomagnetic data. ODP core data can constrain the shift only within about 14 My (Fig. 1), but seamount dates imply a time shorter than about 4 My. We interpreted the data as they appear, suggesting that the 84E and 84W poles are indistinguishable in age, but admitting that the shift might have occurred in several My or more owing to uncertainties in seamount dating.

In criticizing our use of hotspots as a reference frame, Cottrell and Tarduno miss the point of our arguments. We concluded that the polar shift was TPW for two reasons: it was more rapid than can be readily explained by plate motions, and the direction agrees with global compilations of paleomagnetic data in the hotspot reference frame. Whether hotspots are a valid reference frame is immaterial for the first argument—and, if the hotspot reference frame were invalid, we would not see the agreement cited in the second. Our APWP agrees well with global apparent polar wander curves with plate motion relative to the hotspots removed (Fig. 2). Especially interesting is a new study (9), based solely on paleomagnetic studies of igneous rocks from the continents, that shows $\sim 10^°$ rapid polar wander in the same direction at 84 Ma. Although that shift is slightly less than the lowest bound in our most conservative estimate, the confidence limits of the two estimates overlap.

Cottrell and Tarduno finally state that they do not see evidence for the proposed polar wander shift in paleomagnetic data from a well-regarded limestone section in the Umbrian Apennines. These data, highly regarded for magnetic polarity zone studies, are less suitable for pole studies, because sediments can be biased recorders of magnetic inclination (10). The Umbrian data typically show 20$^°$ to 30$^°$ of inclination scatter and larger, spurious shifts in direction. We therefore view the Umbrian data as equivocal. Assuming for the moment that they are adequate, however, we might ask why these data do not clearly show the shift. One possibility is that Cottrell and Tarduno are correct and the shift did not occur; other possibilities are that our estimate of the timing of the shift is off by a few million years or that the location of the proposed polar wander rotation pole is incorrect. In fact, using 95% confidence circle geometry for the 84E and 84W poles, the azimuth of the inferred rotation axis itself has a
95% confidence limit of 48°—an inevitable result of defining a rotation pole with only two paleomagnetic poles with large confidence radii. As figure 2 of the Cottrell and Tarduno comment shows, a westward shift of 48° in the rotation pole location would be consistent with little or no latitudinal motion of the Umbrian site.

In the end, it comes down to whether one is willing to accept SAM data that agree with other data sets. If Cottrell and Tarduno are right, there is an accumulation of errors from different sources that produce a fortuitous agreement with other Pacific paleomagnetic data. The agreement of Pacific data with global paleomagnetic data sets, compared in the hotspot reference frame, must also occur by chance. Occam’s razor favors a different explanation: the data agree because they are accurate, and they show a global tectonic event. We conclude that the test based on data from one site in Italy is inconclusive.

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Editor's Summary

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