POLAR WANDER AND PALEOMAGNETIC REFERENCE POLE CONTROVERSIES

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Introduction

The purpose of this paper is to review the progress made over the past four years in studies of Phanerozoic and Precambrian polar wander, with an emphasis on the contributions made by U.S. scientists. We present a summary of these contributions, including the notation that the accuracy of cratonic "reference poles" and therefore of apparent polar wander (APW) paths is not as good as was generally believed four years ago. A renewed interest in research concerning cratonic reference poles is largely the result of paleomagnetic studies in orogenic belts, namely the western Cordillera and Appalachians of North America, the Andes of South America, and elsewhere which seek to document the existence or non-existence of displacements of suspect terranes (i.e., rotation and/or translation) with respect to their presently associated cratons. (Some of the results of this research are reviewed in this volume by Hillhouse and McWilliams.) An important realization of which paleomagnetists have long been aware but which was demonstrated recently by a number of sobering examples for both the Paleozoic and Mesozoic APW paths for North America, is that the reliability of concordance/discordance parameters that define terrane displacement is dependent not only on opinion and analysis of the individual paleomagnetic study, but also on the precision and accuracy of the appropriate cratonic reference pole.

In the previous quadrennial report, McWilliams [1983] accurately predicted that as a future trend (i.e., 1983-1986) "more and better reference data" would be needed "to clarify and refine" APW paths "to provide a more reliable data base for estimating terrane movements." While progress has been made toward this goal, the suggestion is still a valid assessment of future work. The following discussion will briefly review progress in three areas: new paleomagnetic reference poles, analysis and implications of revised APW paths, and true polar wander as analyzed through comparison of paleomagnetic and hot-spot reference frames.

New Reference Poles

The following section covers work over the past 4 years on reference poles from Precambrian and Phanerozoic rocks from cratonic North America as well as other major plates.

Precambrian

Precambrian paleomagnetic research is a daunting enterprise, faced with a tract of time much longer than the Phanerozoic, complex thermal or deformational histories, and the resulting strong possibility of multiple remagnetizations. It is therefore not surprising that progress in this area is slow but the questions are of such fundamental importance (e.g., how far back in the Precambrian was plate tectonics operative?) that new and improved techniques have been actively sought to answer them. Of particular significance has been the continuing application of sophisticated geochronological techniques to document with precision not only the crystallization age of a rock unit, but also the details of its cooling history that are so critical in interpreting the paleomagnetic record. A case in point is the recognition that paleopoles from the Grenville province represent magnetizations acquired during cooling and reheating episodes in post-orogenic time, perhaps as young as the Ordovician [Dunlop and Stirling, 1985]. On the other hand, the use of 40Ar/39Ar thermochronometric calibration of magnetization ages has enabled Onstott et al. [1984] to more conclusively demonstrate relative motion between the West African and Guayana Shields, and possibly also with the Kalahari Shield, since 1.9-2.0 Ga.

It seems clear that high precision thermochronometric analyses will be an essential adjunct to paleomagnetic work not only in the Precambrian, but in metamorphic/igneous terranes in general.

Examples of other contributions to our understanding of Precambrian paleomagnetism are studies by McCabe and Van der Voo [1983] on late Keweenawan rocks, Geissman et al. [1982, 1983] and Tasillo et al. [1982] on Archean rocks from the Abitibi orogen, and Kodama [1984] on Precambrian basement rocks under Kansas recovered from boreholes.

Phanerozoic of North America

Crossing into the Phanerozoic, we find that the reality of the Cambrian APW loop of Watts et al. [1980] for North America is still highly uncertain and suspicion grows that several key paleopoles are seriously contaminated by later Paleozoic remagnetizations. For example, both Late Paleozoic and Cambrian directions have been found in the Upper Cambrian Bonnette Fm. [Winiowiecki et al., 1983; Dunn and Elmore, 1985] although no results from the Bonnette Fm had previously been used for the Cambrian APW loop. Considering the added possibilities of unrecognized tectonic rotations and inclusion of poles...
based on data of marginal quality, Larson et al. [1985] propose a highly simplified APW path from the Late Precambrian right through to the Triassic, essentially a 20° wide swath that in gross terms encompasses all these uncertainties. Ironically, the path is reminiscent of pole paths drawn in the early stages of paleomagnetic research some 30 years ago. An interesting insight into the different philosophical approaches used in the interpretation of reference poles [Irving and Strong, 1984], and the Cambrian data in particular, can be found in the discussion and reply by Van der Voo [1986] and Larson [1986].

Things become somewhat clearer for the Ordovician and Silurian with the reports of new data from the Lower Ordovician Oneota Dolomite [Jackson and Van der Voo, 1985] and the Middle Silurian Wabash Reef Limestone [McCabe et al., 1985]. The Oneota Dolomite gives a paleolatitude at low latitudes, near to what Larson et al. [1985] would regard as the Early Cambrian segment of their simplified APW path. Obviously this cannot be accounted for by remagnetization of the Oneota, moreover, no paleopoles from rocks younger than Ordovician from North America are known to resemble it. Optimistically, the Oneota can at least be considered to cap the enigma of the Cambrian poles at the Early Ordovician.

The Wabash pole is supported by positive tilt and reversal tests, and coming from the stable interior (Indiana), must be regarded as one of the most reliable Paleozoic reference poles for North America now available. The Wabash gives about the steepest directions found in the Paleozoic of North America, and places the midcontinent in the southern hemisphere 25°S latitude. The paleopole for the C magenetization from the Cordova Gabbro [Dunlop and Stirling, 1985], dated as Late Ordovician (according to geologic time scale of Palmer, 1983) by 40Ar/39Ar plateau ages of 446 Ma [Lopez-Martinez and York, 1983], is however somewhat out of spatial sequence, leap-frogging the Wabash and falling closer to some Late Silurian-Early Devonian poles.

The Devonian and Early Carboniferous poles for North America have undergone major revision in this quadrennial. Roy and Morris [1983] challenged prevailing wisdom that placed North America straddling the paleoequator and suggested on indirect evidence that the Late Devonian-Early Carboniferous cratonic reference poles in fact represent Kiaman (Pertoo-Carbonisland) America straddling the paleoequator and suggested on indirect evidence that the Late Devonian-Early Carboniferous cratonic reference poles in fact represent Kiaman (Perm-Carboniferous) remagnetizations, even though positive fold tests and mixed polarities supported key poles from the Upper Devonian Catskill Fm. [Van der Voo et al., 1979] and the Lower Carboniferous Mauch Chunk Fm. [Knowles and Opdyke, 1968] and the relatively steep directions that pass a fold test in the Lower Carboniferous Deer Lake Group (which overlies Grenville-type basement in western Newfoundland) more directly undermined confidence in the reliability of the middle Paleozoic cratonic reference poles [Irving and Strong, 1984].

Renewed paleomagnetic investigations of the Mauch Chunk [Kent and Opdyke, 1985] and the Catskill Fms. [Miller and Kent, 1986a, b] confirmed that the earlier results were indeed seriously contaminated by Permian remagnetizations. An interesting aspect of the pervasive remagnetiza-
al. [1983], Chen and Schmidt [1984], Horton et al. [1984], McCabe et al. [1984], Stead and Kodama [1984], Elmore et al. [1985], and Kent [1985]. Relevant to the problem of a Pangea reconstruction discussed below, Van der Voo and McCabe [1985] suggest that these more recently determined paleopoles place the North American craton about 50° more northerly in the Permo-Carboniferous than the earlier ones, due to the more complete removal of secondary normal polarity overprints. No new paleopoles from Upper Permian rocks have been published recently and it would be of interest to see if Late Permian poles are similarly affected.

Paleomagnetic results from Triassic rocks of cratonic North America have been published in the past quadrennial period by Herrero-Bervera and Helsey [1983], Shive et al. [1984], and McIntosh et al. [1985]. Both Herrero-Bervera and Helsey and Shive et al. studied the paleomagnetism of the Red Peak Formation of the Chugwater Group in Wyoming. Both studies resulted in paleomagnetic poles which are virtually identical to each other and which help to constrain further the now well known Early Triassic reference pole for North America. These authors suggest that discordance between the Red Peak Chugwater pole and a pole from the Moenkopi Formation on the Colorado Plateau may reflect relative rotation between the Plateau and the basement uplifts of the Wyoming foreland. Gordon et al. [1984] and Steiner [1986], however, discuss age uncertainties and correlation problems of these nonmarine, redbed units and suggest that the respective poles may not be exactly comparable. As will be discussed below, the problem of demonstrating age equivalency between sedimentary rocks on and off of the Colorado Plateau is important for evaluating the suggestion that there has been a small clockwise rotation of the Plateau with respect to other parts of the craton.

The work of McIntosh et al. [1985] concerns Late Triassic and Early Jurassic Newark Basin rocks from the Eastern United States. These authors studied redbeds, from which they describe a polarity stratigraphy, as well as the Watchung basaltic rocks which, as described by previous workers, are of entirely normal polarity. McIntosh et al. [1985] conclude that the redbed results are complicated by unremoved secondary magnetizations (i.e., they fail a reversal test), and that the Watchung results may fail to average secular variation. Therefore, no results from this study can be used to constrain Late Triassic–Early Jurassic APW. Van Fossen et al. [1986] have also reported results from Early Jurassic redbeds and basalts exposed in the Newark Basin. Failure of the fold test is interpreted by these workers to reflect possible local block rotation along the western limb of the Watchung Syncline although no field evidence could be found to demonstrate the existence of the predicted structures.

Two new reference poles have been obtained from Middle and Late Jurassic volcanic rocks in southeast Arizona. The welded tuffs in the Patagonia Mountains studied by May et al. [1986] (172 Ma) and the welded tuffs in the Canelo Hills studied by Kluth et al. [1982] (151 Ma) represent parts of an autochthonous segment of the Cordilleran Jurassic magnetic arc. The magnetic properties of these rocks are relatively simple and yield well-determined poles. Jurassic rocks on the Laramide margin of the North American craton were also studied by McCabe et al. [1982] and Schwartz and Van der Voo [1984]. Samples for these studies, however, were collected from structural allochthons and can well represent rotations within the Idaho–Wyoming overthrust belt. For this and other reasons discussed more fully by May and Butler [1986], the Twin Creek [McCabe et al., 1982] and Stump Formation [Schwartz and Van der Voo, 1984] poles are probably not reliable cratonic reference poles. Nevertheless, these and other studies [Eldredge and Van der Voo, 1987] illustrate an interesting and very useful application of paleomagnetism for understanding the buttressing effects of foreland blocks, and the associated rotation history of thrust sheets, within fold and thrust belts.

Our understanding of Early Tertiary North American APW has been improved by the work of Diehl et al. [1983]. These authors studied Paleocene and Eocene volcanic and intrusive rocks in north-central Montana and report two new reference poles which are consistent with previous Early Tertiary results. These poles were interpreted to document an Early Tertiary APW stillstand following a period of rapid APW in the Late Cretaceous. Gordon [1984] calculated an alternative Paleocene reference pole based on a technique which allows declination-only data from other studies to be included in the calculation of a mean pole. His Paleocene pole for North America is a few degrees more southerly than the Diehl et al. [1983] pole, indicating slightly more APW in the Early Tertiary.

Eurasia

For Hercynian Europe, new data for the Ordovician [Perroud et al., 1983; Perroud and Van der Voo, 1985] and Late Precambrian–Cambrian [Perigo et al., 1983] further document the Gondwana–affinities of the Armorica plate [Perroud et al., 1984]. Similarly high paleolatitudes have also been found for the Late Precambrian–Early Paleozoic of Avalon [Irving and Strong, 1985; Johnson and Van der Voo, 1985, 1986; Van der Voo and Johnson, 1985; Wu et al., 1985; Rao et al., 1986], suggesting that the Avalonian terrane in the Appalachians was part of Armorica and Gondwana during this time.

The difference in Siluro–Devonian poles between Baltica and Britain has long been problematical, explained by either remagnetization affecting the Baltica poles or a paleolatitudinal separation between these regions. A renewed paleomagnetic investigation of the Lower Devonian Ringerike Sandstone in Norway reports dual polarity characteristic directions which pass a fold test [Douglass and Kent, 1986]. These results strengthen the case for a separation between Baltica and Britain, approximately along the Tornquist, prior to the Middle to Late Devonian.

The scarcity of Jurassic reference poles for Europe was addressed by Johnson et al. [1984] who report on the paleomagnetism of Oxfordian limestones from the Jura Mountains. The only other Late Jurassic paleopole for western Europe [Beller, 1977] is from similar limestones in
southern Germany, however, the pole positions of
these two studies lie some 10° apart. All but
two of the "stable" sites reported by Johnson et
al. are of normal polarity, yet the limestones
sampled are believed to span the Oxfordian, at
least the latter part of which is apparently a
time interval of numerous polarity reversals
[Kent and Gradstein, 1985]. Either the magneti-
zation, although pre-folding and in magnetite, is
a somewhat later remagnetization, or that the
Oxfordian is actually mostly of normal polarity.
These problems illustrate the need for further
work on the Mesozoic APW path for Europe.

Across the continent in eastern Asia, it has
been evident that China is made up of a number
of cratonic elements, principally the North China
(NCB) and South China (SCB) or Yangtze blocks,
but very little was known about their relative
motion history until fairly recently. Modern
paleomagnetic work in China was initiated by
McElhinney et al. [1981] who showed that the NCB
and SCB plus other Asian blocks had not yet
docked by the Late Permian. The paper by Lin et
al. [1985] reports work on extensive collections
of Phanerozoic rocks from throughout China and
lays out in broad outline the APW paths for both
the NCB and SCB. Unfortunately, few details of
the paleomagnetic survey work are described in
the paper but rapid progress is being made to
document and refine these preliminary APW curves,
especially from the SCB. Chan et al. [1984]
report results from Upper Permian, Lower Triassic
and Middle to Upper Triassic rocks that show low
paleolatitudes for SCB in Permo-Triassic time.
More extensive studies of Triassic rocks from
South China by Opdyke et al. [1986a] also
indicate low paleolatitudes and support the
argument that the final suturing of SCB with
mainland Asia occurred sometime after the
Triassic. A Late Cretaceous paleopole from the
northeastern part of South China agrees well with
Eurasian reference poles [Kent et al., 1986a].
However preliminary results from Cretaceous sedi-
ments from more southerly parts of South China
are anomalous and may reflect deformation of Asia
associated with the impingement of India in the
Tertiary [Kent et al., 1986a; Chan and Zich,
1986].

Pervasive remagnetization has also been
reported in paleomagnetic studies in both South
and North China [Kent et al., 1986b; Zhao and
Coe, 1985] but in contrast to the Kiaman
(Permian) age of remagnetization in the Appala-
chians, the magnetizations of many of the
Paleozoic formations in China, especially the
carbonates, appear to have been reset in Late
Mesozoic and Cenozoic times. More ancient remag-
netizations may also be involved, for example,
Cambrian directions reported by Lin et al. [1985]
from South China are now seen to closely resemble
Silurian directions that pass a fold test [Opdyke
et al., 1986b].

Gondwana

Paleomagnetic work on the Gondwana continents
has received renewed attention in this quadren-
niual but the new Paleozoic data are problematical
to say the least. The long-known salient feature
of APW for an assembled Gondwana is that the
(South) pole must traverse somehow from a posi-
tion in the vicinity of northern Africa in the
Early Paleozoic (corresponding for example to
Ordovician glacial deposits in the Sahara), to a
position around southern Africa by the Late
Paleozoic (corresponding to the Gondwana glacia-
tions). A pole from Lower to Middle Devonian
redbeds in Mauritiutna falls off southern Africa
[Kent et al., 1984] and disagrees with the only
other then reported Devonian pole from Africa
(Msissi norite, cited as Late Devonian; Bailwood,
1974) which plots in northern Africa. Hurley and
Van der Voo [1986a] determined a Late Devonian
pole from the Canning Basin of western Australia
which agrees closely with the Msissi pole in a
conventional Gondwana fit. A plausible interpre-
tation of the Devonian data is that the Mauri-
tania pole represents a Carboniferous or younger
remagnetization. However, the Msissi has
recently been dated radiometrically as 135 Ma
(late Jurassic or early Cretaceous) and the mag-
etizations were found to be very complex [Salmon
et al., 1986]. Although the agreement of the
Canning Basin pole with the old Msissi pole must
now be seen as fortuitous, the Canning Basin
results which include a positive fold test and a
magnetostratigraphy [Hurley and Van der
Voo, 1986b] still argue that the pole did not get
to southern Africa until after the Devonian. But
then there are the paleomagnetic directions from
ring-dikes in Niger, radiometrically dated as
400-440 Ma (nominally Silurian), which give a
pole off southern Africa [Margraves et al.,
1986]. How all these and other Paleozoic paleo-
poles from Gondwana fit into a coherent scheme
of apparent polar wander is still far from clear.
Current paleomagnetic work on the Paleozoic Cape
Supergroup, South Africa, may shed some light on
the dilemma [Bachtadse et al., 1986].

While Paleozoic poles for Gondwana have a
direct bearing on the tectonic evolution of the
Appalachian-Caledonide orogen and the formation of
Pangea, precise Mesozoic and Cenozoic
reference poles from the Gondwana continents are
needed to evaluate tectonic rotations and dis-
placements in the Andean Cordillera and Alpine-
Himalayan belt. A significant obstacle to the
interpretation of paleomagnetic data being
obtained from the Andean margin of South America
[Irving et al., 1985; Kent et al., 1985; Sheriff,
1985; Forsythe et al., 1986; May and Butler,
1985; Beck et al., 1986; Janesky et al., 1986] is
the uncertainty concerning the reliability of the
South American reference path. The available
Mesozoic and Cenozoic reference poles, as listed
for example in the compilation of Irving and
Irving [1982], generally cluster close to the
geographic pole and ostensibly show very little
APW over this time. Fortunately, the fit and
subsequent sea-floor spreading history between
South America and at least Africa are well
established so it should be possible to transfer
good quality poles from other continents into
South American coordinates for any selected time
interval. The recent critical analysis of
African Late Mesozoic and Cenozoic poles, with
the additional constraint of paleolatitudes
derived from well-dated Deep Sea Drilling Project
cores from the eastern South Atlantic [Tauxe
et al., 1983], should be useful in this regard. We
should also mention that tectonic conclusions
drawn from current paleomagnetic work on Mesozoic
rocks in West Antarctica [Watts et al., 1984; Grunow et al., 1986, 1987] are also dependent on well-founded reference poles from East Antarctica as well as South America and Africa.

Analysis and Implications of Revised APW

Here we draw attention to developments in syntheses of the paleomagnetic reference pole data sets in terms of APW paths and their paleogeographic and geodynamic implications.

Pre-Carboniferous APW

In a recent and comprehensive summary of Precambrian paleomagnetic data for North America, Roy [1983] observes that even though the data base for this craton is much greater than for any continent it is still difficult to draw a meaningful APW path. He provides an interesting perspective on the problem by noting that over 2000 pole determinations would be required for North America alone (compared to the approximately 350 available at his writing) to obtain a polar path of reliability and definition comparable to the APW path for the last 300 Ma for North America, even assuming that the continent was not an aggregation of separate blocks over the Precambrian. It seems that the testing of specific hypotheses of relative positions of cratons at well-defined times, based on precise thermochronometric dating of magnetizations, is going to be the most practical and fruitful approach to the problem of the Precambrian for the foreseeable future.

As outlined above, there have been significant changes over the past quadrennial in the interpretations of the paleomagnetic reference poles for the Paleozoic of North America, which have necessitated revisions of previously postulated paleocontinental reconstructions and their implications, particularly for the Atlantic-bordering land masses. Convincing paleomagnetic evidence is lacking for the involvement of cratonic North America in an Eocambrian supercontinent [Bond et al., 1984; Van der Voo et al., 1984a] which would make a convenient starting point for Paleozoic (as well as Precambrian) paleocontinental reconstructions and tectonic analysis. But despite the problems in drawing an exact APW path through the Early Paleozoic data, virtually all the available poles place North America near to the paleoequator, with the possible exception of preliminary results from the Cambrian Cardora Sequence in Sonora, Mexico, which would suggest moderate paleolatitudes for the east coast of North America [Barr and Kirschvink, 1986]. In contrast, the Early Paleozoic poles for the Avalon terrane indicate high paleolatitudes and suggest that Avalon was separate from North America and more likely associated with Armorica and Gondwana. Differences still exist in Late Silurian-Early Devonian poles from Baltica, Britain and North America [Van der Voo, 1983] but there are no long-term suggestions for the Late Devonian and Early Carboniferous due to the revisions in the North American cratonic reference poles. In a synthesis of Silurian to Permian tectonic and paleomagnetic data for the Atlantic-bordering continents, Kent and Keppie [1986] therefore suggest that Euramerica, and possibly even Pangea, formed during the Devonian, producing the late Caledonian/Scandian/Acadian/Ligerian orogenic events. The alternative interpretations of the width of the Devonian ocean between Gondwana and Euramerica, due to the large uncertainties in the Gondwana poles, are illustrated in a set of global maps by Scotese [1984]. Briden et al. [1984, 1986] discuss further the paleomagnetic data base related to Paleozoic paleocontinental reconstructions of the Atlantic-bordering continents, including estimates of the width of the Iapetus Ocean and the scale and timing of motion on the Great Glen Fault.

Pangea Problem

A key ingredient in attempts at Phanerozoic paleocontinental reconstructions is a good model for Pangea, the supercontinent whose break-up history started in the Late Triassic. The time of formation of Pangea in the Paleozoic is still uncertain as it depends strongly on the problematic Paleozoic paleomagnetic data from Gondwana [see also Boucot and Gray, 1983], but while there is broad consensus that it had occurred by the Late Carboniferous, there has been ongoing discussion regarding the exact configuration(s) of the supercontinent. There is first the familiar configuration of Wegener, Pangea A, quantitatively fit by Bullard et al. [1965]. There are however disagreements among Carboniferous, Permian and Triassic paleopoles from Euramerica and Gondwana when these continents are assembled in this fashion. To solve the debate regarding the exact configuration(s) of the supercontinent, is going to be the most practical and fruitful approach to the problem of the Precambrian for the foreseeable future.

Irving [1983] reviewed the history of the Pangea fit problem and restated his case for Pangea B prior to the Jurassic. Van der Voo et al. [1984b] reevaluated the paleomagnetic data base for the critical time period from the Late Carboniferous until the earliest Triassic. They conclude that even though the data for the Late Carboniferous and Early Permian are in better agreement with the Pangea A2 fit, the Pangea B fit is also paleomagnetically permissible; for the far fewer paleopoles available for the Late Permian than the earlier intervals examined, Pangea B fits better. Livermore et al. [1986] suggest that the Pangea B and C are less likely alternatives, possibly resulting from inaccuracies of pole ages. They favor a supercontinent resembling Pangea A2 which formed in the Late Devonian and subsequently evolved to the Pangea A configuration by the Late Triassic. More recently, Ballard et al. [1986] have shown that many of the Late Permian-Early Triassic paleomagnetic data from southern Africa that were incorporated in the various Pangea analyses represent post-Triassic remagnetizations. They suggest that the paleomagnetic data for the Late Permian-Early Triassic are insufficient for a valid test of the alternative Pangea reconstructions. In any case, it seems evident that the Pangea supercontinent did not include large parts of eastern
Asia which as mentioned above had yet to dock by the time the circum-Atlantic Pangea began to break up.

**Windows, Cusps, and Data Selectivity**

The lack of a definitive paleomagnetic test of Pangea reconstructions notwithstanding, the Late Carboniferous (ca. 300 Ma) to Recent time interval is certainly represented by the best reference pole data set available, especially for North America. It has therefore been possible to apply more sophisticated analytical techniques to construct APW paths for this time interval.

The sliding time-window technique has proved very useful for illustrating the first-order features in APW and such analyses, especially by Irving and Irving [1982] for all the major continents, have been widely used for reference paths. This method is designed to average out 'noise' contributed from paleopoles that are either more poorly determined or less well dated than others, giving a smoothed, empirical model of APW.

An important contribution to understanding plate motion information contained within APW paths was made by Gordon et al. [1984]. Expanding and quantifying previous models by Francheteau and Sclaté [1969] and Irving and Park [1972], they suggested that APW paths are composed of "tracks" which record long periods of constant direction plate motion. Tracks should therefore follow small-circle segments, each of which defines a paleomagnetic Euler pole (PEP) in the same way as hot-spot tracks and transform faults define line Kline Euler poles. Successive tracks are joined at "cusps" which record plate reorganization events reflected as a change in the direction (and angular velocity) of plate motion.

Gordon et al. [1984] analyzed Carboniferous through Cretaceous poles for North America and recognized a Carboniferous - Late Triassic track, an Early Jurassic cusp, and a Jurassic through Early Cretaceous track. Based on a slightly different data base that also included a new Middle Jurassic reference pole, Butler and May [1985] and May and Butler [1986] recognized the same Early Jurassic cusp which they labeled "J1", but were able to statistically demonstrate a second cusp in the Late Jurassic labeled "J2". Both J1 and J2 cusps correlate temporally with known plate tectonic and intra-plate deformational events.

As was illustrated by Gordon et al. and applied by May and Butler, the angular distance along the best fit small-circle, plotted as a function of age, reflects the angular velocity of a plate about the associated PEP. This type of angular velocity analysis can be interpreted as a test of the PEP corollary that not only do plates undergo rotation about fixed Euler poles for significant periods of time, but they do so with nearly constant angular velocity.

Gordon et al. [1984] found that the rms angular velocities for North America were similar to those calculated by Schult and Gordon [1984] using hot-spot tracks and sea-floor spreading data. May and Butler [1986] also found that the Early to Late Jurassic (J1-J2) and Late Jurassic to mid-Cretaceous (J2-K) APW tracks are well described by simple, unconstrained linear regres-
sions in angular velocity space. Such results argue strongly for the validity of the PEP model and support the suggestion by Gordon et al. [1984] that the best fit model can then be used to generate synthetic reference poles for use in other analyses such as for comparison with data from suspect terranes.

It should however be noted that the rather stringent data selection employed in PEP analysis provides a list of reference poles which may differ significantly from those generated with a "sliding-window" averaging technique. The philosophy of the latter allows somewhat less rigor in data selection, relying on the belief that the best estimation of a reference pole is obtained by averaging lots of data. May and Butler [1986] have shown that systematic biases among poles of questionable reliability have tended to displace Late Triassic and Jurassic North American reference poles toward the present geographic axis, thereby predicting anomalously high paleolatitudes for the craton. These differences lead to quite different estimates of the relative latitudinal motion of suspect terranes along the western cordilleras.

**Colorado Plateau Rotation**

A controversial topic involving North American APW which has come to light in the past quadrennial period and of importance to PEP models is the question of whether or not the Colorado Plateau has undergone significant rotation with respect to other parts of cratonic North America [Hamilton, 1981]. Steiner [1986] argues that comparisons of individual poles from rocks of similar age on and off the Plateau indicate about 100 of clockwise rotation in post-Late Triassic time, probably reflecting intraplate deformation during Laramide compression and Rio Grande rifting. It has also been noted, however, by Bryan and Gordon [1986a] that various Permian poles do not show a significant discordance. Bryan and Gordon [1986a] argued that "uncertainties in the precise age of characteristic magnetization and errors in paleomagnetic poles make comparisons of individual poles too inaccurate to discern small rotations". They present an alternative method for simultaneously comparing all available paleomagnetic data from on and off the Plateau which is not dependent on demonstration of exact age equivalency. Their method evaluates the dispersion of data generated by various hypothetical rotation cases with respect to the North American APW model of Gordon et al. [1984]. Bryan and Gordon [1986a] find a value of 3.90 clockwise rotation with a 95% confidence interval of 1.6-6.6. May and Butler [1986] also found that the Early to Late Jurassic (J1-J2) and Late Jurassic to mid-Cretaceous (J2-K) APW tracks are well described by simple, unconstrained linear regres-
sions in angular velocity space. Such results argue strongly for the validity of the PEP model and support the suggestion by Gordon et al. [1984] that the best fit model can then be used to generate synthetic reference poles for use in other analyses such as for comparison with data from suspect terranes.

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**True Polar Wander**

Research concerning true polar wander (TPW) has received continued interest by U.S. scientists. Two reference Frames are commonly
compared to evaluate the possibility of TPW, namely the hot-spot and the time-averaged geomagnetic field. Hotspots are thought to track plate motions with respect to the mantle; the geomagnetic framework as defined for example by Jurdy and Van der Voo [1975] allows tracking of plate motions with respect to the dipole axis (i.e., the core). Since there does not appear to be convincing evidence for net motion of the plates with respect to the core or dipole axis, any differences between the hotspot and paleomagnetic reference frames ascribed to TPW may indicate that only the mantle moves or 'rolls' (e.g., Hargraves and Duncan, 1973).

Harrison and Lindh [1982b] compared the two reference frames using a global "mean" APW path based on paleomagnetic data from a number of plates combined with a relative motion model [Harrison and Lindh, 1982a], and the Morgan [1981] hot-spot model. Their general conclusion was that there has been approximately 200 of relative motion between the two reference frames since 200 million years ago, and that this displacement has varied with time. Harrison and Lindh ascribe this discrepancy to a TPW model wherein the hot-spot generating portion of the Earth's mantle rotates with respect to the spin axis (to which the geomagnetic field is fixed).

Andrews [1985] attempted a similar analysis, using a somewhat different global paleomagnetic data set that excluded the Pacific, and the relative motion and hot-spot models of Morgan [1983]. She concludes that there has been a relative displacement of 22 ± 10° since 180 Ma, including episodes of both relatively rapid and relatively slow motions. Andrews interprets the motion of global mean paleomagnetic poles within a fixed hot-spot reference as TPW, due to a "shifting of the entire Earth in response to a change in the principal axes of the moment of inertia of the mantle."

An alternative TPW model was discussed by Davis and Solomon [1985] who suggest that a net torque on the lithosphere can be exerted both by ridge push and trench pull forces. When oriented properly, these forces are considered potentially significant enough to induce rotation of the global lithosphere with respect to the mantle.

Relatively rapid TPW during the late Neogene is compared by Andrews [1985] to astronomical observations for the last 75 years which document motion of the Earth's rotational axis at a rate of about 10°/m.y. If such a high rate was operative over a long time, then a relationship with processes other than lithospheric plate motion is implied. Schneider and Kent [1986] propose that Andrews [1985] overestimated the rate of Plio-Pleistocene TPW because of the uncompensated effect of long-term non-dipole components. After correcting for these second and third order axisymmetric features of the geomagnetic field within the same data set as used by Andrews, Schneider and Kent find only 1.5° ± 1° of TPW in the last 5 million years (i.e., significantly less than the 4° to 5° suggested by extrapolating recent astronomical data or by the uncorrected Plio-Pleistocene paleomagnetic data).

Gordon [1983] compared paleomagnetic and hot-spot reference frames for Late Cretaceous and Early Tertiary data from the Pacific plate. He found evidence for a rapid shift of the Pacific Ocean basin hot-spots with respect to the geomagnetic field between 90 and 81 Ma. Gordon believed that this shift represented an event of TPW and that the temporal proximity with anomalous geomagnetic field behavior observed at the end of the Cretaceous normal polarity superchron (anomaly 34) might reflect a causal relationship between the motion of the hot-spot reference with respect to the spin axis and the end of the long-lived geomagnetic field configuration. However, Ogg [1986] recently found that a relatively constant rate of latitudinal motion for the Pacific plate is instead in better agreement with the Late Aptian through Early Tertiary paleomagnetic results from DSDP sediment cores. Sager [1983] used paleomagnetic data from DSDP cores on the Pacific plate in conjunction with seamount magnetic anomaly studies and sediment facies data to calculate a Late Eocene data set that excluded the Pacific, and the Pacific plate pole is concordant with a synthetic 40 Ma pole predicted by various hot-spot constrained motion models. Sager concludes that there has been no significant displacement between the Pacific hot-spot and geomagnetic reference frames since the Late Eocene.

One of the assumptions in TPW studies such as those described above is that the hot-spots are relatively fixed with respect to the mantle and with respect to each other. Chase and Sprowl [1984] suggested that groups of hot-spots exhibit relative motion with respect to each other (North Pacific vs. South Pacific in their study) and that this motion may be associated with geoid anomalies which they interpret as related to convective phenomena in the mantle. If they are correct, then discordance between hot-spot and geomagnetic field reference frames need not necessarily reflect TPW. This emphasizes the larger problem with studies of the above type, namely the reliability of pre-anomaly 34 (approx. 84 Ma) hot-spot models, so that what appears as discordance between reference frames may simply reflect inaccuracies of either the pre-Late Cretaceous hot-spot tracks; or paleomagnetic reference poles.

Summary

Research concerning cratonic reference poles, particularly from North America but from other plates as well, has received increased, and some would argue overdue attention in the past quadrennial period. For the Mesozoic and Cenozoic this largely reflects the great interest in using paleomagnetic data to constrain motion histories of suspect terranes, coupled with the understanding that the resolution of tectonic models derived from such data are directly dependent on the reliability of cratonic reference poles. Fundamental problems still exist concerning major-plate reconstructions in the Paleozoic and there are correspondingly greater uncertainties in the paleomagnetic documentation of displacements of more ancient terranes. However, significant advances have been made in generating new high quality reference poles and at the same time in demonstrating the prevalence of remagnetization not fully appreciated in many of the earlier studies. For research concerning
Percambrian APW, sophisticated chronometric techniques in close conjunction with detailed paleomagnetic studies are being successfully used to decipher complex thermal histories and thereby rejuvenating interest in this difficult but important area.

As more paleomagnetic data become available and the demands for higher precision and accuracy increase, the question of data selection, stringent and comprehensive reliability criteria or weighting schemes are being enacted. The current PEP models of APW for North America in particular are predicated on the application of severe data selectivity. A strongly compelling factor is that the PEP conceptual model is predictive, based on the critical assumption that APW should follow small-circle segments, in contrast to the highly empirical nature of conventional APW paths. Nevertheless, the question remains open as to which pole will be of sufficient quality to constitute a realistic test or a basis for refinement of the PEP models. While there does not appear to be any satisfactory scheme of data selection free of subjectivity, we expect that the importance of data quality, indices, based on multiple criteria such as recently applied to the North American paleomagnetic data base by Van der Voo [1987] to increase. Although such efforts at objective pass-fail or graded criteria may not meet with universal approval, they effectively define the quality level of work needed to address the important issues of the nature and significance of true and apparent polar wander that remain outstanding.

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