OCEAN DRILLING
AND
TECTONIC FRAMES OF REFERENCE

REPORT OF A WORKSHOP
HELD AT
TEXAS A&M UNIVERSITY
ON
APRIL 30 AND MAY 1, 1988

Sponsored by: JOI/USSAC

Convened By: Richard Carlson
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Table of Contents

Summary of Recommendations
I. Introduction
II. Frames of Reference Overview
    Paleomagnetic Field
    Hotspots
    Relative Motions
    Paleogeographic Indicators
    Relationships Between Reference Frames
III. Paleomagnetic Reference Frame
    Problems with the GAD Hypothesis
    Recording the Paleomagnetic Field
    The Role of Ocean Drilling
    Drilling Sites
    Core Orientation and Shipboard Procedures
IV. Hotspot Reference Frame
    Problems with the Hotspot Hypothesis
    The Hotspot Recorder
    The Role of Ocean Drilling
    Drilling Sites
V. Relative Motions
    The "Circuit Breaker" Problem
    Pacific-Antarctic Boundary
    African-Antarctic Boundary
    M-Sequence South of Kerguelen
    Rigid Plate Hypothesis
    Pacific Cretaceous Quiet Zone
VI. Conclusion

SUMMARY OF RECOMMENDATIONS

Four tectonic frames of reference were considered by the workshop participants: (1) the paleomagnetic field, (2) hotspots, (3) relative plate motions, and (4) paleoenvironmental latitude indicators. Ocean drilling is a tool of primary importance for studying the paleomagnetic field and hotspots. Better relative motion models are also badly needed, but the problem is largely one of obtaining more marine geophysical data (magnetic lineation patterns, fracture zone trends, etc) to document sea floor spreading histories along specific plate boundaries, with drilling as a supplemental tool. Though potentially significant for constraining models based on other frames of reference, environmental indicators of paleolatitude lack sufficient accuracy to justify extensive drilling efforts.

Paleomagnetic studies yield APW paths for lithospheric plates and, subject to the GAD assumption, record paleolatitudes. These data are useful for estimating latitudinal motions relative to the earth's spin axis and for constraining, or testing, relative motion and hotspot models.

There are two primary problems related to the paleomagnetic reference frame: establishing or improving APW paths for purely oceanic plates, and resolving the non-dipole (i.e. non-GAD) components of the field. The workshop produced recommendations relating to drilling targets and to equipment, policies and procedures.

Paleomagnetic Target Areas:

Few sites are likely to be drilled specifically to acquire paleomagnetic data, but so little data of high quality exists that much can be learned from sites selected for other reasons.

-Sites which hold potential for particularly good paleomagnetic studies should receive extra attention in this regard.

-Widely separated sites will be particularly useful for constraining APW paths.

-Sites in the southern oceans are particularly important because these regions have been so sparsely sampled in the past.

-The Pacific basin is an important region because it contains most of the world's purely oceanic plates.

-Sites having thick sediment accumulations are potentially important because they offer long, datable paleomagnetic records. However, reliable data from such sections can be acquired only if cores can be accurately oriented (see below).

-Basement re-entry sites are preferred for their magnetic properties, but subject to the caveat that they sample long enough time intervals to average out secular variation. For this reason, sites on the flanks of seamounts or other edifices are desirable.

-Sites on Pacific seamounts are also needed to check the validity of paleomagnetic poles estimated from marine magnetic survey data and to study the motions of hotspots in the paleomagnetic frame of reference.

Policies, Equipment and Procedures:

In the past, ODP (and DSDP) paleomagnetic studies have suffered from contamination, magnetic overprinting, lack of core orientation, and lack of sufficient sample material.

> -ODP should continue the practice of coating the drill pipe with zinc to prevent contamination from pipe scale.
>
> -Cores have been found to be overprinted by magnetized core barrels. ODP should consider fabricating a few core barrels (particularly for the APC) from non-magnetic materials, specifically for use at sites deemed important for paleomagnetic studies.
>
> -Inclination data from sediments are notoriously unreliable. Declination data are thus vitally important. Every effort should be made to establish methods and procedures for obtaining reliable, accurately-oriented APC cores.
>
> -ODP paleomagnetists have, at times, suffered from a lack of sufficient core material for detailed sampling. At sites deemed important for paleomagnetic studies, a second APC hole should be drilled specifically for paleomagnetic studies.

Hotspots record the motions of plates by leaving tracks in the form of seamount chains on the sea floor. Major questions related to hotspots are how much they move relative to one another, and how much they move relative to the earth's spin axis. Though hotspot tracks in the Indian Ocean have now been comparatively well sampled by drilling, data from other ocean basins are not sufficient to address these questions. Dates from numerous hotspot tracks are badly needed.

Hotspot Target Areas:

> -Though the Tertiary history of the Hawaiian-Emperor chain is well documented, the early history of the Emperor segment hinges on data from Suiko Seamount. Detroit Tablemount and a Paleocene seamount in the Emperor chain are high priority sites for hotspot studies.

-Though the Louisville Ridge is recognized as a seamount chain contemporaneous with the Hawaiian chain, its history is poorly known. Dates from the Louisville Ridge will permit comparisons and help to resolve the motions of Pacific hotspots.

-Dates from older linear seamount chains in the Pacific are needed to work out Mesozoic plate/hotspot motions and the evolution of hotspots. Candidates for drilling are the Line chain, the Marshall-Gilbert-Ellis Seamounts, the Mid-Pacific Mountains, the Magellan Seamounts and the Guisha Guyots.

-The New England seamount chain is a prime candidate for study because it is the longest chain in the Atlantic.

-Basement sites on hotspot track seamounts are also excellent for paleomagnetic studies because they tend to sample enough flow units to average out secular variations and because direct comparisons of paleomagnetic and hotspot paleolatitudes can then be made.

Relative Motions are important because they offer the most detailed and precise histories of plate motion, and because relative motion models provide both links between and tests of paleomagnetic and hotspot models. Global relative motion models rely on constructing circuits of plate motions. A problem of primary importance is that some key plate motion histories are so poorly constrained by available data that they constitute "Circuit Breakers". Marine geophysical surveys are badly needed to map magnetic lineations and fracture zones; drilling cannot be used to address these problems directly. However, by providing basement ages at selected sites, drilling can be an important supplementary tool.

"Circuit Breaker" Areas:

-One of the most important motion circuits is Pacific-Antartica-Africa-N.America. Pacific-Antarctic history (region A, Fig.3) is probably the weakest link in the reconstructions because magnetic lineations in this region are so poorly mapped.

-Models of Indian Ocean history strongly depend on the motion of Africa with respect to Antarctica. Additional data related to these motions (region B, Fig. 3) are badly needed.

-Another significant gap in reconstructions is represented by the poorly known M-sequence south of Kerguellen (region C, Fig. 3).

-Finally, the history of spreading in the Pacific during the Cretaceous Quiet Period (KQP) is poorly understood, and possibly quite complex. Sonar surveys of spreading fabric in this important region (D, Figure 3), combined with a transect of three of more holes located on a flow line to establish spreading rates, will do much to clarify the evolution of the Pacific plate during this period.

I. INTRODUCTION

On April 30 and May 1, 1988, 26 geoscientists (Appendix 1) gathered at Texas A&M University to discuss the role of ODP in research on plate tectonic reference frames. Four different reference frames were discussed: (1) the paleomagnetic field, (2) hotspots, (3) relative plate motions, and (4) paleoenvironmental paleolatitude indicators. Realizing that drilling results are important in understanding all of these, the panelists nevertheless agreed that the first two, the paleomagnetic field and hotspots, are those for which drill core studies are most critical.

As paleomagnetic studies strive to achieve greater detail and accuracy, a major limitation is the geocentric axial dipole (GAD) hypothesis. Another very important problem is the lack of paleomagnetic pole determinations for purely oceanic plates. It has become clear that there are significant nondipole components in the long-term average geomagnetic field. However, the constitution and variations of these components have not been accurately determined mainly because of the inadequate distribution of paleomagnetic data in both time and location. The oceans represent particularly troublesome gaps in the global paleomagnetic data sets. Two contributions from ODP are felt to be essential. First, a reliable core-orientation device must be developed to acquire declination data. Second, holes with wide geographic and sample age distributions must be encouraged; data from these sites can also be used to construct refined Apparent

Polar Wander Paths.

There is disagreement over the utility of hotspots as a reference frame because of apparent relative motions between individual hotspots or between groups of hotspots. If these relative motions are larger than about 10 mm/a, hotspots may not provide a useful frame of reference. A major limitation on hotspot studies is the scarcity of age and paleolatitude data on many widely-distributed hotspot traces. Hotspot studies in the oceans are important because the oceans contain the clearest record of hotspot volcanism, usually in the form of seamount chains. In particular, the Pacific poses a problem because its pre-Tertiary motion relative to hotspots is not well-constrained and because investigators have been unable to make reliable ties between Pacific hotspots and those in other oceans via plate circuits. By providing a larger age and paleolatitude data-base for hotspots (as well as other related geologic data), ODP can improve our knowledge of this reference frame.

Though relative plate motions and paleoenvironmental indicators were discussed, it was felt that neither deserves the priority for drilling that should be reserved for the other frames. The former must be addressed by marine geophysical rather than drilling studies. The latter appears to lack sufficient accuracy to give more than a gross consistency check of the other frames. Nevertheless, ODP results can provide information useful for studying both of these reference frames and should therefore be encouraged.

One particular region of the earth, the Pacific Ocean, is deemed critical for studies of all four reference frames. Covered with oceanic plates, the Pacific basin represents the largest geographic gap in paleomagnetic data sets. It also contains perhaps the clearest record of hotspot volcanism. Moreover, some important boundaries of the Pacific plate are "circuit breakers"; such boundaries pose problems in piecing together relative plate motion circuits because their histories of motion are poorly constrained by available data. Additionally, having little land area to perturb weather patterns and currents, the Pacific contains an excellent record of paleoenvironmental latitude indicators.

II. FRAMES OF REFERENCE OVERVIEW

A plate tectonic reference frame is a self-consistent coordinate system that can be used to estimate present-day plate motions or to reconstruct the past motions of plates. The workshop discussions focused on four different types of reference frames: (1) the paleomagnetic field, (2) hotspots , (3) the system of relative motions, and (4) paleoenvironmental latitude indicators. The workshop participants also recognized the importance of relationships between tectonic frames of references.

Paleomagnetic Field

The paleomagnetic field provides an axially symmetric geographic coordinate system (i.e., without longitudinal constraint) in which a site can be located relative to the Earth's spin axis. The basic paleomagnetic measurements are of the inclination (dip) and declination (deflection from geographic north) of the ancient magnetic field, and geologic age. From these quantities, the paleolatitude (i.e., distance from the geographic pole) and the direction from the site to the paleopole can be estimated. The basic premise is that the long-term average geomagnetic field closely approximates the field due to a dipole located at the center of the Earth and aligned along the spin axis; this is the geocentric axial dipole, or GAD, hypothesis (Figure 1). Subject to the GAD assumption, paleomagnetic poles derived from geologic formations of different ages on a single plate define the motion of the earth's spin axis relative to the plate, i.e. the Apparent Polar Wander Path (APWP; Figure 1d), which is fixed with respect to the plate. Its major features are generally ascribed to the motion of the plate (Figure 2). Thus, paleomagnetic data are valuable for defining plate motions.

Hotspots

Though their exact nature is debated, at least some hotspots appear to be deep-seated mantle magma sources. Hotspots leave trails of extinct volcanoes, such as the archetypical Hawaiian-Emperor chain, which thus record the relative motion between the hot spot and the plate (Figure 2). The similarities of various hotspot chain trends suggest that hotspots might serve as a "mantle" reference frame to which plate motions can be tied. The essential assumption that makes the hotspots useful as a reference frame is that their relative motions are much smaller than those of the plates. The basic measurements of the hotspot reference frame are the locations and geologic ages of the volcanoes in the chain (Figure 2b). The hotspot reference frame is particularly useful because it offers comparatively high spatial resolution and because it yields constraints on longitudinal motions that the paleomagnetic reference frame does not.

Relative Motions

Relative plate motions, though not generally considered to be an "absolute" reference frame, are essential to understanding other reference frames. Moreover, when examined globally they provide the basis of the "mean-lithosphere" reference frame in which plate motions are decomposed into two parts: a single rigid rotation of the entire lithosphere and random motions. The primary measurements that yield relative motions are those that decipher the record of seafloor spreading, usually marine magnetic anomalies, fracture zone trends and earthquake slip vectors (for present-day motions). Assuming rigid plates, seafloor spreading histories can be used to establish rotation "circuits" from which the relative positions or motions of the plates can be reconstructed.

Paleogeographic Indicators

Paleogeographic latitude indicators have also been used to estimate paleolatitudes of plates. To be useful, these geologic markers must be restricted to narrow bands of latitude. Examples are the equatorial high-productivity zone, which has produced a distinctive suite of sediments on the Pacific seafloor, and the temperature-induced transition between coral-algal and bryzoan-algal facies in carbonate sediments that occurs at about 25° latitude. Though paleogeographic latitude indicators have not been developed as a reference frame as vigorously as those mentioned above, they are nonetheless useful as an independent check of the other frames.

Relationships Between Reference Frames

Relationships between reference frames are also important because none of those described above will stand alone. Paleomagnetic models suffer from doubts about the GAD assumption (Figure 1), from lack of longitudinal control, and from relatively poor resolution of most APW paths. Hotspot models suffer from motions between hotspots (or groups of hotspots) and between hotspots in general and the earth's spin axis (Figure 2). Relative motion models suffer from poor resolution along some important boundaries ("circuit breakers" Figure 3) and from the fact that relative motions, per se, offer both longitudinal and latitudinal control, but only in arbitrary frames of reference. On the other hand, both paleomagnetic and hotspot models predict paleolatitude; discrepancies suggest drift of hotspots or true polar wander or both (Figure 2). Relative motions constitute an important bridge between paleomagnetic and hotspot models because, given either an APW path or a hotspot trace on one plate, a well-known relative motion model can be used to predict APW paths and/or hotspot traces on another. This procedure can and has been used to test various paleomagnetic, hotspot and relative motion models. Conversely, any useful "absolute" motion model must be consistent, not only with paleomagnetic, hotspot and relative motion models, but with systematic discrepancies between them as well. Hence, it is important to pursue refinements in all of these frames of reference simultaneously.

III. PALEOMAGNETIC REFERENCE FRAME

Because it is the most widely studied and best understood reference frame, the paleomagnetic field plays a particularly important role in reference frame studies. Central to the use of paleomagnetism as a reference frame is the assumption that the time-average geomagnetic field has the properties of a geocentric axial dipole (GAD) (Figure 1). Such a field is symmetric about the spin axis and varies in intensity and inclination with the tangent of the latitude. Typically, paleomagnetic measurements yield the inclination and declination of the geomagnetic field recorded by samples at the time they formed. These directions are used to compute the distance and direction from the sample site to the ancient geographic (mean magnetic) pole.

Paleomagnetic poles from the same plate are combined to give the apparent displacement with time of ancient poles relative to the present pole. Such a curve is known as an apparent polar wander path (APWP) and is often used to infer plate motions.

Problems with the GAD Hypothesis

As tectonic studies have evolved toward ever-increasing resolution, problems with the GAD hypothesis have become apparent. Evidently, a few percent of the time-averaged geomagnetic field consists of non-GAD components. The most significant of these seems to be the axial quadrupole, sometimes modeled as an axial dipole offset from the earth's center. Available data suggest that other low-order zonal field harmonics, and perhaps some low-order nonzonal harmonics, may also be important (Figure 1). All of these non-GAD components may fluctuate in magnitude with time. In addition, the non-GAD field may not reverse with the main field and may assume a greater importance during polarity transitions.

If GAD formulas are used to determine paleomagnetic pole positions, as they typically are, but significant non-GAD components are present, the calculated pole will be erroneous (Figure 1 b,c). Results from the literature suggest that these errors may be as much as 5^{o}. Corrections for non-GAD fields can be made in principle; however, the magnitudes of these fields are poorly known. The primary problem is the distribution of paleomagnetic data. Most sampling sites are on land, and the majority of these are concentrated in North America and Europe. Consequently, large portions of the globe are not represented by data. This is particularly true of the oceans. Moreover, as one proceeds backward in time, the scarcity of reliable, well-dated paleomagnetic data becomes even more of a problem. As a result, non-GAD components for times before the Late Miocene are very uncertain.

Problems in determining non-GAD fields also arise from uncertainties in other reference frames. To put Miocene and older paleomagnetic sites into their correct relative positions, plate motions must be considered. Both the motions of the plates relative to the hotspots and motions relative to one another have been used to this end. Unfortunately, the resulting geomagnetic field models are still sensitive to the choice of data sets and plate motion models. More paleomagnetic data and better plate motion models are needed.

Recording the Paleomagnetic Field

An important element of studying the paleomagnetic field is understanding the limitations of the paleomagnetic field recorder. Oceanic paleomagnetic samples are typically sediments, sedimentary rocks, or basalts. Sediments and sedimentary rocks have the advantage that they are usually easier to drill and date. However, some sediments are affected by inclination errors, a shallowing of the measured geomagnetic inclination, probably resulting largely from compaction and de-watering.

Though this effect has been observed mostly in redeposited turbidite material, it is poorly understood and has been found in enough diverse settings to make it difficult to predict its occurrence. Thus, caution is often in order when interpreting paleoinclination results from sediments and sedimentary rocks.

Most paleomagnetists would agree that basalts are superior to sediments as recorders of the magnetic field; however, samples from cores made up of these rocks also present problems in paleomagnetic interpretation. Azimuthal orientation is currently impossible for ODP basalt cores, so no declination data can be obtained. Furthermore, oceanic basalt flows are typically several meters in thickness, so a deep hole through basalt is needed to sample enough independent flow units to average secular variation properly. Basement holes this deep are rare in the history of DSDP and ODP. Another potential problem with basalt samples is that the oceanic crust is known to be highly fractured at the ridge crest and tectonic tilting is likely. Unfortunately, it is difficult to detect and correct for such bias.

Because both sedimentary and igneous paleomagnetic samples have associated problems, a balanced approach is necessary. Paleomagnetic studies and intercomparisons of results obtained from both types of samples must be encouraged.

The Role of Ocean Drilling

Ocean drilling can play an important role in addressing the paleomagnetic field as a reference frame. The primary contribution is new paleomagnetic data. Because they are from the oceans, these data help fill gaps in global paleomagnetic data sets. They are usually precisely dated, either by biostratigraphic or radiometric methods. Furthermore, they provide constraints on the usually-uncertain APWP and motions of the oceanic plates.

Other information garnered by ocean drilling also helps in understanding and deciphering the behavior of the geomagnetic field. Dates for basement rocks and sediments adjacent to basement provide additional constraints for plate motion models and reconstructions. These dates, along with magnetostratigraphic studies, aid in calibrating the geomagnetic polarity reversal time scale which is used to provide a time framework for plate reconstructions. Additionally, rock magnetic studies usually done in conjunction with tectonic paleomagnetic studies are helpful because they yield a better understanding of the fidelity of oceanic crustal materials as recorders of the paleomagnetic field.

To have the maximum impact, paleomagnetic data from the Ocean Drilling Program should be from oriented samples. With the azimuthally-unoriented data that usually results from drilling, it is difficult to construct an APWP. Typically, a mean paleomagnetic pole determined from this sort of data is well-constrained in one direction, but ill-constrained in the perpendicular direction. Likewise, without declination measurements, it is impossible to discern tectonic rotations about Euler poles located near the sampling site. Recent research results suggest that microplates have been more prevalent than previously realized and that they sometimes displayed rotations of this kind. Thus, the ability to measure declination changes is important. Furthermore, because the fidelity of inclination data determined from sediments is often in question, declination data assumes much greater importance because it is less likely to be changed by compaction and dewatering.

Drilling Sites

There will probably be few drill sites selected solely on the basis of their paleomagnetic potential. This situation is not necessarily bad; subject to the requirement that interval sampled must be long enough to average out secular variations, almost any drill hole can produce important paleomagnetic results because the oceans represent such enormous gaps in global paleomagnetic data sets. In this respect, holes drilled in areas that have not been sampled previously by DSDP or ODP are particularly important, and sites on seamounts where numerous flow units can be sampled are preferred.

The two regions that are especially important for paleomagnetic studies are the southern oceans in general and the Pacific Ocean in particular. The former are of critical importance because these regions have been so sparsely sampled in the past; the Pacific contains most of the earth's oceanic plates. Few paleomagnetic data are available from these plates and it is difficult to reconstruct their past positions with respect to plates outside the Pacific because of circuit problems described in a following section of this report (see "Relative Motions"). The Pacific is also important because it contains the largest remnant of pre-Cretaceous seafloor, so it is the preferred region for deciphering the Jurassic geomagnetic polarity reversal time scale and Jurassic plate motions. Additionally, sites on Pacific seamounts are needed to judge the validity of paleomagnetic poles calculated from seamounts, a method used extensively in the determination of the Pacific APWP and inferences of the past motions of that plate.

Core Orientation and Shipboard Procedures

The Ocean Drilling Program can have a major impact on studies of tectonic frames of reference by providing high-quality paleomagnetic data. The shipboard laboratory facilities are excellent, and much valuable data can be readily acquired at sites drilled for other purposes. There are, however, several problems which must be addressed to optimize paleomagnetic studies; among them are core orientation, the sampling environment, and sampling policies or procedures.

Accurate core orientation is important because both inclination and declination are needed to calculate APW paths and because declination is the only means of establishing magnetic polarities at low-latitude sites. Core orientation is a problem which has plagued ODP paleomagnetists for a long time. Rotary cores cannot be oriented, and there is no solution in sight. Perhaps the only hope of obtaining oriented cores by "conventional" coring methods is to use multiple core barrels in which the inner barrel does not rotate with the drill string. Methods of this kind are used in the mining industry, and have the additional benefit that recovery is greatly increased. However, it is not clear that such methods can be adapted for use with existing ODP technology, and the multiple core barrels have the disadvantage of reducing the diameter of the core.

The advanced piston corer (APC) is capable of providing oriented cores from the upper 200 to 300 m of the sediment column. The APC is equipped with an anti-spiralling mechanism, which prevents the core barrel from rotating during insertion, and an Eastman-Whipstock multishot tool for recording core orientation. However, the multishot tool is plagued by mechanical problems and only about 30 percent of the cores recovered are reliably oriented. A new, digital tool is being tested on Leg 121, and will perhaps solve the problem. In any case, a reliable and routine method must be found for obtaining oriented cores if the full potential of the shipboard paleomagnetic facility is to be realized.

Paleomagnetic studies rely on careful orientation, handling, and maintenance of a magnetically "clean" environment. These chores can be particularly difficult on a drill ship where several classes of problems can occur: mis-orientation, contamination, and magnetic overprinting.

Orientation is provided by aligning fiducial marks on the core liner and core barrel. After retrieval, the core liner is sectioned and split perpendicular to the orientation mark for sampling. A mistake during deployment or during post-retrieval handling can render the orientation useless. Although handling has not been a notable problem in the past, the potential for errors exists unless a well-considered handling protocol is established. The rig-floor and technical personnel should be familiar with the orientation procedures and committed to carrying them out.

Physical contamination of the cores occurs when pipe scale or other metal fragments fall into the hole and are incorporated into the core material. This problem has reportedly been mitigated by coating the inside of the drill pipe with zinc; this procedure has the added benefit of prolonging the life of the pipe. A more serious problem is magnetic contamination revealed by the cryogenic magnetometer. Cores are sometimes overprinted by magnetization acquired from magnetized core barrels or the drill string. Demagnetizing the core barrels is not an entirely successful remedy because the barrels tend to become remagnetized after a few trips for reasons which are not yet understood. Other sources of overprinting are the drill string itself, which is magnetized during inspections, and stray fields. A particularly strong field is produced by the draworks brake.

These problems are currently under investigation, and steps will be taken to minimize their effects. If the core barrels continue to be a problem, we strongly recommend that ODP consider fabricating some from non-magnetic materials for use on at least those sites deemed important for paleomagnetic studies.

A final problem confronting ODP paleomagnetists is sampling; after the cores are sampled for other purposes, it is often impossible to conduct detailed paleomagnetic studies for lack of sufficient material. We recommend that, at sites which are particularly important for paleomagnetic studies, a second APC hole should be drilled specifically for that purpose.

IV. HOTSPOT REFERENCE FRAME

The nature of hotspots is poorly understood. Even their number is subject to debate. It can be said, however, that hotspots are localized centers of deep-seated volcanism which appear to move slowly relative to one another. The movements of plates with respect to hotspots give rise to hotspot "tracks", usually in the form of linear or arcuate seamount chains, which record the relative motions. Euler poles for finite plate motions relative to hotspots are obtained by fitting small circle segments to the seamount chains, and rates are obtained from the progression of seamount ages (Figure 2b). Instantaneous hot spot poles and rates of motion can be estimated by integrating data from hotspot tracks with instantaneous relative motion models. Hence, the principal measurements required to define plate motions in the hotspot reference frame are geographic locations and absolute geologic ages.

The hotspot reference frame is attractive because it offers comparatively high spacial resolution and because it provides longitudinal control. However, the hotspot reference frame depends on the assumption that hotspots do not move appreciably with respect to one another.

Problems with the Hotspot Hypothesis

Though the similar trends of many hotspot tracks suggest that hotspots can be used as a frame of reference, this frame is fraught with problems. An important, but subtle, problem relates to the nature and origin of hotspots; the notion of a set of widely-separated, persistent volcanic centers, fixed (or even approximately fixed) with respect to one another for long periods of geologic time holds important implications for mantle convection. Some other questions related to the nature and origin of hotspots: Do oceanic plateaus and flood basalts represent the initiation of hotspot volcanism? How do hotspots evolve? Does each hotspot have a unique geochemical signature? If so, do the mantle sources remain the same or do they change with time? While motions between hotspots limit their utility as a frame of reference, what implications do these motions have for mantle convection?

More directly related to tectonic frames of reference are questions pertaining to the motions of hotspots, both with respect to the spin axis and with respect to one another. It is, in general, difficult to reconcile motions in the hotspot reference frame with paleomagnetic data or with reconstructed relative motions (Figures 2c, d). This fact suggests that hotspots do move, albeit slowly. How much hotspots move with respect to one another is unresolved. Detailed analyses of two or more hotspot tracks on a single plate (intraplate hotspot tracks) will reveal the motions between individual hotspots; comparisons of hotspot tracks on different plates, made by using the relative motions of intervening plates, will indicate whether hotspots constitute a useful unified set, or global framework.

The distribution of hotspot tracks and well-dated age progressions severely limits our ability to address the questions cited above. Only four plates contain extensive and spatially well-defined records of hotspot volcanism: Pacific, India, Australia, and Africa. Recent drilling in the Indian Ocean represents a significant increase in hotspot data. In the Pacific only the archetypical Hawaiian-Emperor chain has been extensively studied; the history of the Hawaiian chain (0-40 Ma) is well known, but the early history of the Emperor segment (>40 Ma) is poorly constrained. Data from other hotspot tracks on the Pacific plate are badly needed, both to evaluate Pacific intraplate hotspot motions and for comparison with hotspot data from India, Australia and Africa. Data from other regions are needed to expand the global set.

The Hotspot Recorder

As in the case of the paleomagnetic record, sampling and evaluating the hot spot record requires an understanding of the recording mechanism. In general, hotspot volcanism is localized for a period of time; each edifice is constructed over an interval of several million years and then abandoned in favor of the next site, to form a chain of more-or-less distinct seamounts. This fact gives rise to very good spatial definition of the hotspot track, but can lead to difficulty in dating.

Each location represents several million years of the record, and the history of the seamount can be complicated if erosion and subsidence occurred after volcanic activity ceased. Biostratigraphic dating of the oldest sediments can yield ages significantly younger than the age of the last volcanic activity. Radiometric data for extrusive rocks is therefore preferred, but that too, has pitfalls. The effects of alteration, for example are well known. Argon/argon is the method of choice, and the most reliable results are obtained when samples can be selected from a large suite.

The Role of Ocean Drilling

Problems related to the hotspot reference frame can be addressed most directly by drilling on hotspot tracks; ages are needed to define the progression of volcanism along tracks, and reliable paleomagnetic data (paleolatitudes) obtained from points on hot spot tracks can be directly compared with hotspot paleolatitudes to resolve latitudinal motions of individual hotspots in the paleomagnetic reference frame (Figure 2 c,d). These motions can also be estimated, though less directly, using paleomagnetic data from other sites on the same plate.

The problem of motions between hotspots can be addressed by drilling on two or more hotspot tracks on the same plate. Best-fitting poles and rates of rotation can then be analyzed to determine what significant relative motion between the hotspots has occurred.

Resolving motions between widely separated hotspots or hotspots beneath different lithospheric plates is an important, but more difficult problem. As noted elsewhere, drilling and other data from the Pacific and Indian Oceans suggest several degrees of southward drift of the Hawaii and Reunion hotspots in the paleomagnetic reference frame in early Tertiary time. Data from hotspot tracks on other plates, improved APW paths, and accurate relative motion models are badly needed to resolve these motions, their times of occurrence, and implications.

Drilling Sites

Potentially important drill sites can be grouped in several ways. For example, there are those in the Pacific Ocean and those elsewhere. The Pacific plate figures prominently in drilling strategies for two reasons: (1) it contains many seamount chains of possible hotspot origin and (2) even though the Pacific hotspots appear to be a relatively coherent group, they may be in motion relative to other hotspot groups; it is of critical importance to decipher their motions with respect to one another and with respect to other reference frames.

Hotspot targets in the Pacific and elsewhere can also be roughly divided into two groups by age: those older than about Late Cretaceous and those younger. This grouping arises because plate/hotspot relative motions are generally much better known for younger chains. Consequently, drilling sites on younger hotspot tracks are needed to refine plate/hotspot movement models, whereas those on older hotspot tracks are needed to place gross constraints on plate motion models.

In the former category are sites in the Emperor seamount chain. This chain carries a large amount of weight in calculations of Pacific/hotspot motion because it is spatially well defined, but it also introduces large uncertainties because the age-progression along older portion of the chain is poorly constrained. To remedy this situation a site on Detroit Tablemount has been suggested. Drill sites in the Louisville seamount chain are also recommended to refine Pacific/hotspot relative motion models. This chain is also linear and has recently been found to be contemporaneous with the Hawaiian-Emperor chain. Because of its remoteness, however, its age progression has not been well defined. Nevertheless, its remoteness also makes it extremely important because its separation from other Pacific hotspot chains provides a good constraint on the locations and rotation rates for Pacific/hotspot Euler poles.

The New England seamount chain has also been cited as a well-known hotspot track suitable for future refinement in age progression. Its importance lies in the fact that it is the longest and clearest hotspot track in the Atlantic Ocean.

Sites on older, less well-defined hotspot tracks are needed to sort out Mesozoic plate/hotspot relative motion models and the evolution of hotspots. The Pacific, for example, contains numerous seamount chains of uncertain origin; many are linear and suspected of having been formed by hotspots. However, Pacific/hotspot motions prior to about 70-80 Ma are poorly defined because the two best-known Late Cretaceous hotspot chains, (the Emperor and Louisville seamounts) both disappear into trenches at about that age. Additional sites are needed in the Line Islands because that chain has had a complex history that probably includes hotspot volcanism prior to 70 Ma. Sites in the Marshall-Gilbert-Ellis seamounts would be useful because they appear to be roughly parallel to the Line Islands, but little is known of their history. Other linear Pacific seamount chains that have been suggested as targets are the Mid-Pacific Mountains, the Magellan Seamounts, the Marcus-Wake seamounts, and the Geisha guyots.

Hotspot drilling should also include oceanic plateaus. Though the origin of these features is uncertain, hotspot volcanism is a prime candidate as a genetic mechanism. Some authors believe that plateaus record the initial phase of hotspot volcanism or that they reflect slow plate/hotspot drift. Plateaus that have been mentioned as possibly hotspot-related are the Shatsky and Hess Rises, the Mid-Pacific Mountains, and the Ontong-Java Plateau.

An important element in understanding hotspots as a reference frame is to derive a record of their motions relative to one another and other reference frames. Thus, paleomagnetic data from hotspot chains are critical (Figure 2). The Hawaiian-Emperor chain should be considered for more sites because it has received the most attention from previous studies, but is still in need of additional data. Inferences of pre-Eocene latitudinal drift of the Hawaiian hotspot hinge mainly on one paleolatitude from Suiko Seamount, 65 Ma of age. More reliable paleolatitudes from the Emperor chain are needed to corroborate this result. Older and younger seamounts should be drilled for this purpose; Detroit Tablemount (70-75 Ma?) and a Paleocene seamount should be given high priority. As inter-hotspot drift is a topic which requires investigation, sites in the Louisville chain should be drilled because it is contemporaneous with the Hawaiian-Emperor chain. In particular, sites on the western (older) end of the Louisville chain are important because they correspond to the period for which rapid southward motion of the Hawaiian hotspot has been hypothesized. Other sites on hotspots in any ocean are needed for the same reason. Comparison of paleomagnetic data from widely separated hotspots on different plates is one way to decipher whether the hotspots have significant relative motions; consistency with relative motions is another.

V. RELATIVE MOTIONS

Relative plate motions in themselves do not constitute a "reference frame", but they are an essential component in defining other reference frames.

In the case of the "mean-lithosphere" or "no-net-rotation" framework, relative plate motions are the raw materials used to synthesize the "mean" framework. First, each plate is related to another using information from a spreading center (magnetic anomalies, fracture zone trends, etc.); next, one of the original two plates is related to a third in the same way. This procedure is followed until all plates are linked in what is called a relative plate motion circuit. The plate motions, now defined in an arbitrary co-ordinate system, are decomposed into a common part, the mean framework, and remaining random motions.

The hotspot framework does not by definition require a full set of relative plate motions, but a useful hotspot reference frame can be established only by integrating hotspot data with relative motions; only the Pacific, African, Australian and Indian plates have enough well-dated hotspot tracks to assign reasonably well-constrained local "hotspot" frameworks. Hence, a complete description of plate motions in the hotspot reference frame relies on relative plate motions. For example, documentation of the history of subduction of the Farallon plate beneath North American is not straightforward because so little of that plate is extant and convergent plate boundaries inherently do not produce an easily deciphered record of relative motions. However, one way of reconstructing Farallon-North American motions is to tie the Farallon plate to the Pacific plate using magnetic lineations, reference the Pacific and Africa plates to their hotspots, assume the Pacific and African hotspots are fixed relative to one another, and finally place North America in the African hotspot framework using Atlantic magnetic lineations.

The "Circuit Breaker" Problem

Unfortunately, reconstructions made using hotspots and those made using only relative plate motion data do not, in general, agree. Discrepancies suggest that there are either problems with the assumptions involved (i.e. relative motions of hotspots, or non-rigidity of the plates) or there are errors in the reconstructions. Significant reconstruction errors are likely to arise from gaps in the relative motion circuit, which we term "circuit breakers" (Figure 3). Filling these gaps will do more than improve our understanding of local problems, it will also allow us to address global ones. In this section, we address problems in the global plate circuits, such as the circum-Antarctic and Indian Oceans, discuss problems in plate evolution, such as the spreading history of the Pacific, and finally assess tests for the validity of our basic assumption - the rigidity of the plates.

For refining the relative plate motion models, surveys of marine magnetic anomalies will provide most of the needed information. Drilling at specific sites would provide supplemental information such as the age and nature of the oceanic crust, that could discriminate between models.

Pacific-Antarctic boundary

The Pacific-Antarctic history (region A, Figure 3) of relative motion is probably the weakest link in the global circuit of reconstructions. Poorly mapped magnetic lineations are a highly probable source of reconstruction discrepancies. The major problems must be resolved by geophysical surveys of areas with sparse marine magnetic coverage. For example, the few identifications of magnetic anomalies younger than Chron 6 (20 Ma)on the Antarctic plate are all concentrated at the northern end of the plate boundary. Studies of these anomalies farther south, and more detailed studies of anomalies of the same age on the Pacific plate, will greatly reduce uncertainties in reconstructions of the Pacific plate relative to Antarctica for early Tertiary time. It appears that for part of its evolution (at least Chron 31-24, and possibly until Chron 18 or even Chron 13 time), the current Pacific-Antarctic ridge was, in fact, two separate plate boundaries. The data required to improve reconstructions of these two plate boundaries must be acquired in poorly surveyed areas; south of the Campbell Plateau on the Pacific plate, and adjacent to the corresponding part of the Antarctic margin, for anomalies 25-6. Geophysical surveys in these areas of the southern oceans are important for the resolving discrepancies between the two tectonic reference frames.

Africa-Antarctic Boundary

The history of relative motion between Africa and Antarctica (Region B, Figure 3) is the key to understanding the dispersal of the fragments of Gondwana after their initial breakup in the Late Jurassic. Models of the Indian ocean strongly depend on an understanding of the relative motion of Africa with respect to Antarctica. Although magnetic anomalies indicate that seafloor spreading has been taking place since the Late Jurassic, the relative motions of these two plates are not well constrained. There is no data from the Cretaceous Quiet Zone (118-84Ma) and an array of reconstructions has been proposed for the configuration of the Southwest Indian Ridge at Chron 34 (84 Ma). Because of poorly constrained magnetic data, the first reconstructions were based on the assumption that the well-defined fracture zones (such as the Prince Edward FZ) are flow lines describing Africa-Antarctica relative motion with a single rotation since the Late Cretaceous. This simple model was challenged by new identifications of magnetic anomalies in the vicinity of the Prince Edward Fracture Zone. Drilling a few well-chosen holes to obtain critical ages would help discriminate among the various proposed models.

M-Sequence south of Kerguelen

Another gap in the reconstruction of the evolution of the Indian Ocean is the M sequence south of Kerguelen (region C, Figure 3), relating India and Antarctica.

Rigid Plate Hypothesis

Reconstructions and assessments of reference frames assume that plates are rigid. How rigid are the plates and what is the nature of deformation within them? Satellite Laser Ranging (SLR) measurements across the expanse of the Pacific plate and in relation to adjacent plates is in agreement with the predictions of the model for present-day plate motions, but intraplate measurements from Hawaii to Huahine indicate intraplate extension on the order of 12+5mm/a, as does the corresponding Very Long Baseline Interferometry (VLBI) measurement from Hawaii to Kwajalein. As suggested by the COSOD II report, a system of stress measurements made 10 degrees apart within the Pacific plate is needed to address this problem. This grid of stress measurements, combined with SLR and VLBI measurements of strain, would reveal much about the true rigidity of a single large plate.

Pacific Cretaceous Quiet Zone - high spreading rate problem

The evolution of the Pacific plate is enigmatic. It grew from a minor role in the Izanagi-Phoenix-Farallon-Pacific oceanic group to dwarf its neighbors. In the west and east Pacific, the isochrons of the Jurassic-Cretaceous and Cretaceous-Tertiary mixed-polarity superchrons document this tectonic history with relative clarity, however the evolution of the Cretaceous seafloor of the central Pacific (region D, Figure 3) is obscure. The Cretaceous Normal Polarity Superchron (also known as the Cretaceous Quiet Period, KQP) when there were no geomagnetic reversals, lasted from about 118 to about 84 Ma. Without magnetic isochrons as a guide, deciphering the development of the Pacific during the Cretaceous Quiet Period has proven difficult. To fit the region into tectonic models, some have simply interpolated between western and either eastern or southern Pacific lineations, or extrapolated across the KQZ. This approach results in half spreading rates in excess of 120 mm/a. Moreover, recent studies have postulated that complex reorganizations, including ridge jumps and the formation of microplates, occurred during the Quiet Period.

A few ages obtained by drilling in critical areas along hypothesized flow lines could discriminate among these models and clarify the evolution of the Pacific plate.

VI. CONCLUSIONS

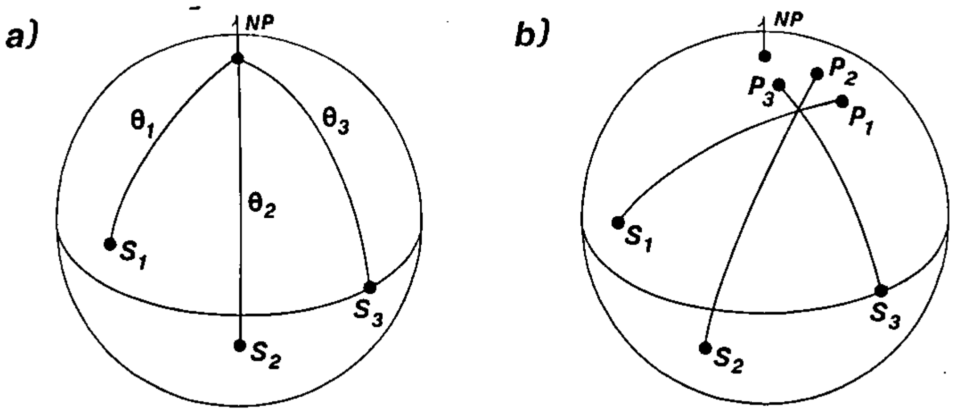
The Ocean Drilling Program can contribute significantly to the resolution and refinement of tectonic frames of reference in a variety of ways.

Paleomagnetic data from the ocean basins are extremely sparse. New data are badly needed both to study the non-dipole components of the magnetic field and to establish APW paths for purely oceanic plates. Much can be learned from sites drilled largely to meet other objectives. Deep basement re-entry holes, which sample time intervals long enough to average out secular variation, are preferred. Sediments cored using the APC offer high age resolution and would thus be very useful, but sediment paleomagnetic data are often subject to systematic inclination errors, and to magnetic overprinting. For these reasons, reliable core orientation is vitally important, and it may be necessary to develope non-magnetic core barrels for use at selected sites. Similarly, additional APC cores should be acquired at selected sites to assure that enough sample material is available for detailed paleomagnetic studies.

While much can be learned from paleomagnetic data from sites of opportunity, problems related to the hotspot reference frame must be addressed by drilling at specific sites to obtain accurate age data for individual seamounts which make up hotspot tracks. Happily, basement holes in seamounts are also ideal sites for paleomagnetic studies. Recent drilling in the Indian Ocean has done much to improve our knowledge of the hotspot histories of the Australian and Indian plates, but elsewhere ages are poorly constrained. In the Pacific, the histories of the Hawaiian segment and the latter part of the Emperor segment are well known, but the early history of the Emperor chain is constrained largely by the drilling results from Suiko Seamount. Drilling on Detroit Tablemount and a Paleocene seamount in the Emperor chain should be given high priority. To determine the amount of drift between Pacific hotspots, sites in the Luisville chain should be drilled because that chain is now recognized as being contemporaneous with the Hawaiian-Emperor chain. Other linear chains, such as the Mid-Pacific Mountains, Magellan Seamounts, Marcus-Wake Seamounts and the Geisha Guyots, must be studied to establish the pre-Tertiary hotspot history in the Pacific. In the Atlantic, the New England seamount chain is the longest hotspot track, and a prime candidate for study. Data from the New England chain would add on additional plate to the set of plates for which hotspot motions are constrained.

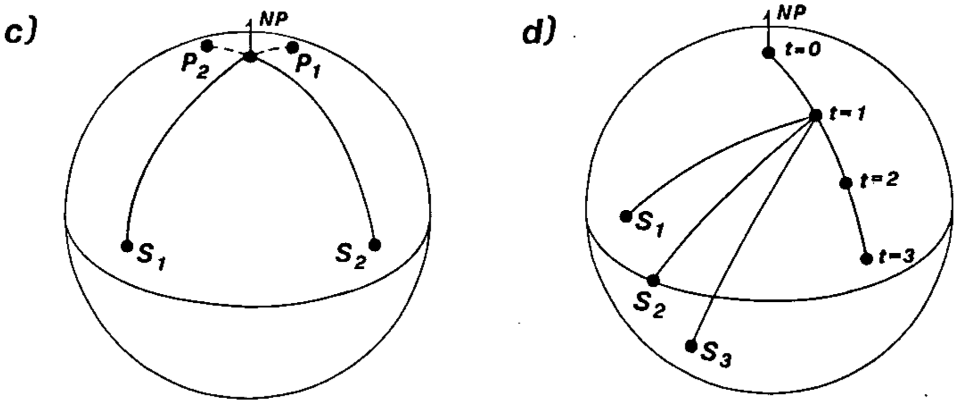
Relative plate motion models are important because they enable comparatively precise reconstructions and because they must be used in conjunction with other reference frames. Relative motion models rely heavily on motion "circuits", and the primary weakness of this frame of reference is that portions of the spreading histories of some key plate boundaries, which we term "Circuit Breakers", are poorly known. To close these circuits, marine geophysical surveys the Pacific-Antarctica and Africa-Antarctica boundaries, the M-sequence south of Kerguellen and in the Pacific Cretaceous Quite Zone (KQP) are badly needed. Drilling would play an important supporting role; basement ages obtained from a few well-chosen sites, particularly in the Quiet Zone, would help to resolve spreading histories.

Figure 1. Paleomagnetic reference frame: the geocentr
dipole (GAD) hypothesis and nonGAD perterbations.
(a) If the GAD hypothesis is correct, all pale
sited as a given time give the spin axis
location of the time-average paleomagnetic po
The addition of nonGAD fields causes the pale
poles to be scattered away from the spin axis.
nonGAD fields are purely zonal harmonics, as
the pole will be displace along the grea
containing the site and spin axis. The pre
nonzonal terms, as in (b) causes the pole dis
to be asymmetric about the spin axis. The
paleomagnetic poles versus time (d) is c
apparent polar wander path (APWP). It primar
the effect of plate motion, but also is aff
fluctuating nonGAD fields as well as the shif
spin axis relative to the entire earth (tr
wander).



time = 0 GAD

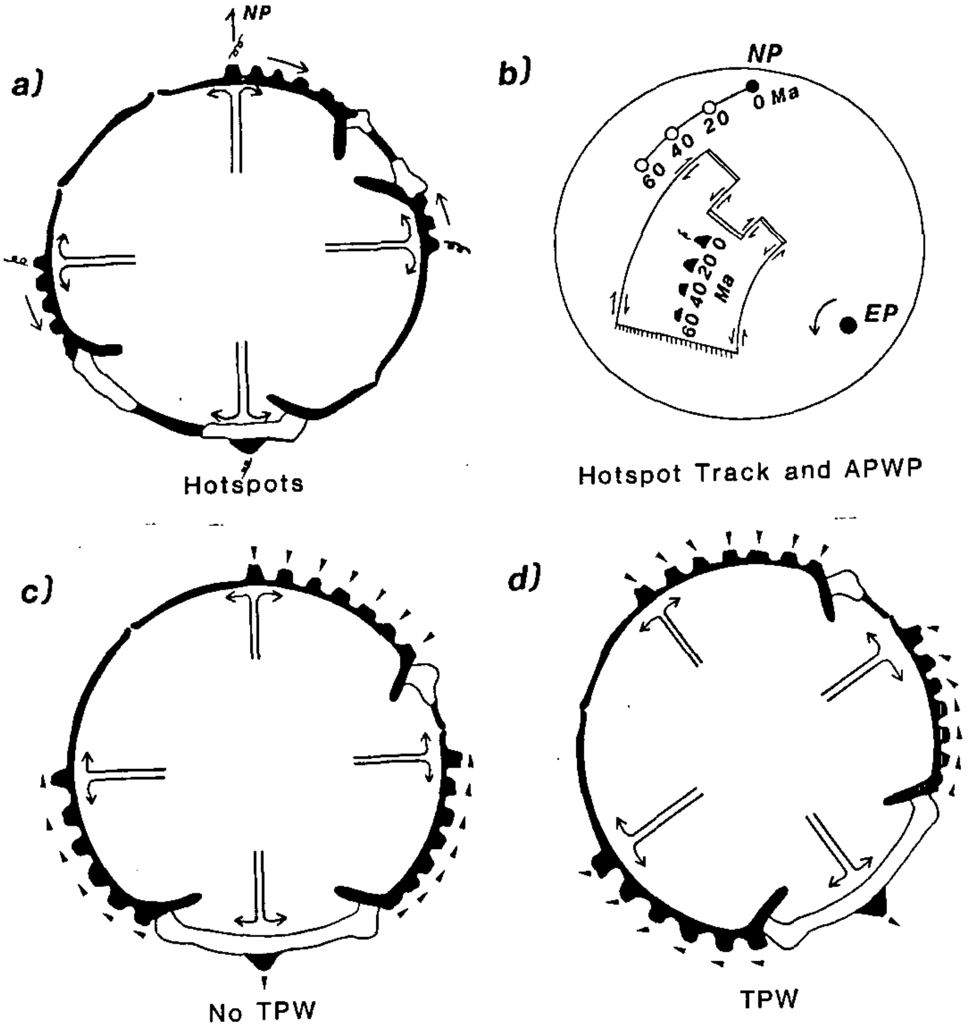
time=0 nonGAD
nonzonal + zonal component



time=0 nonGAD
zonal component

time≠0 GAD
APWP

Figure 2. Hotspot tracks and paleomagnetic data: a, hotspot tracks produced by plate motions relative to a framework of deep mantle sources; b, Hotspot track and APW patharc both fixed with respect to the plate. If the hotspot is fixed with respect to the plate. If the hotspot is fixed with respect to the spin axis and the GAD applies, then the Hotspot Euler Pole (HEP_ and the Paleomagnetic Euler Pole (PEP_ obtained from the Hotspot track and the APW path will be coincident; c, in the absence of True Polar Wander (TPW), and subject to the GAD assumption, the paleomagnetic latitudes of seamounts in the chain will be invariant; d, in the case of TPW, however, paleomagnetic latitude within the hotspot chain vary.



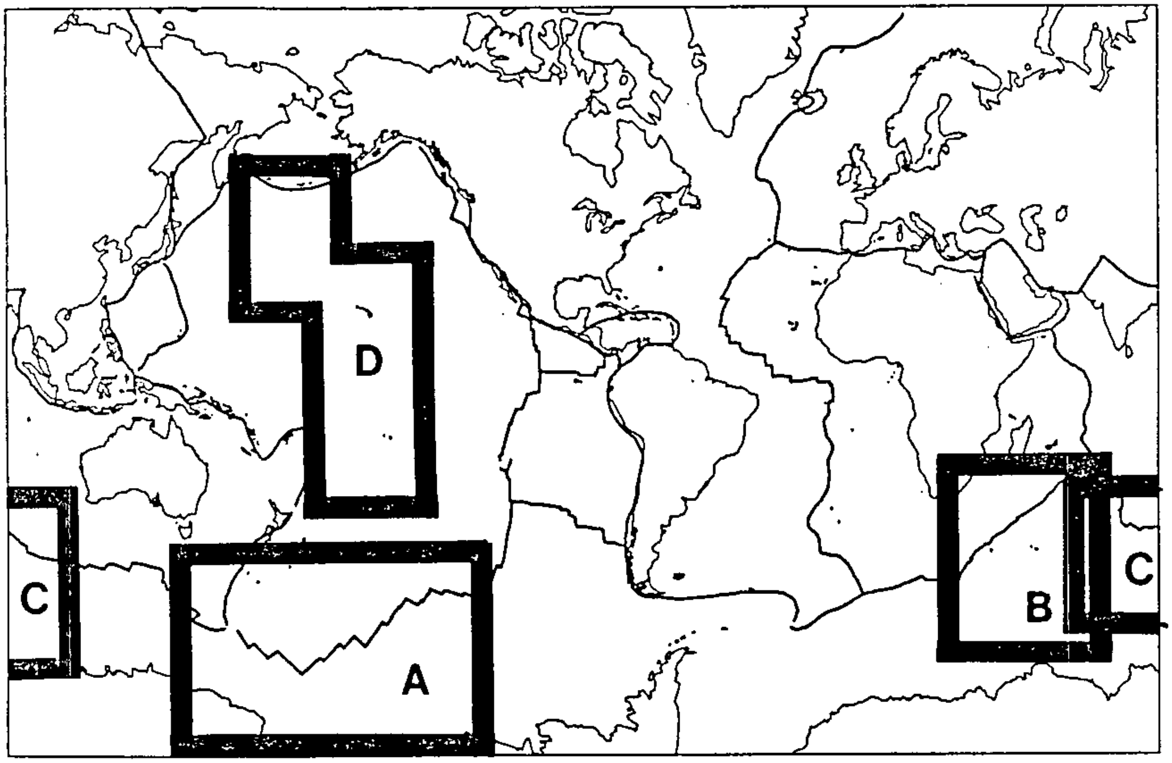
Hotspots

Hotspot Track and APWP

No TPW

TPW

Figure 3. "Circuit breakers" in the global plate circuit. Heavy lines show plate boundaries. Several spreading boundaries have problematic histories that confound efforts to link the relative motions of the plates. Boxes show problem areas: A, the Pacific-Antarctic boundary; B, the African-Antarctic boundary; C, the Mesozoic evolution of the Antarctic plate in the vicinity of the Kerguelen Plateau; D, the Cretaceous Quiet Period evolution of the Pacific plate. Observations at carefully selected sites within the areas indicated by the four boxes are esential to establishing relative plate motion circuits over the last 150 Ma.



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