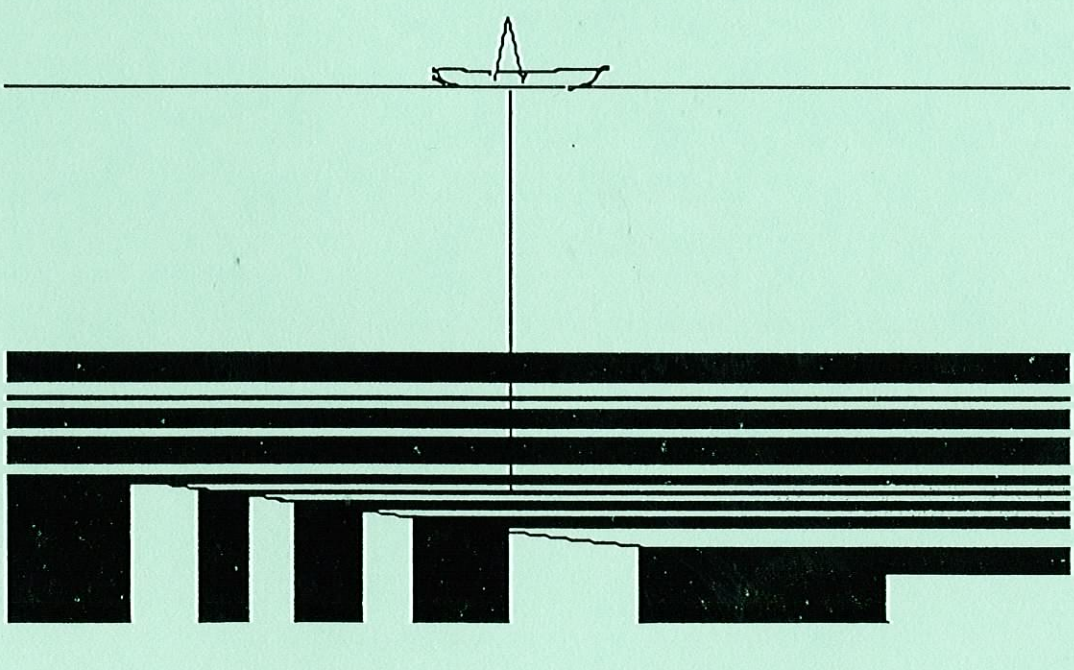
PALEOMAGNETIC OBJECTIVES FOR THE OCEAN DRILLING PROGRAM



PALEOMAGNETIC OBJECTIVES

FOR THE

OCEAN DRILLING PROGRAM

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EXECUTIVE SUMMARY

INTRODUCTION

The purpose of this report is to identify paleomagnetic objectives for the Ocean Drilling Program, to evaluate the present paleomagnetic capabilities of the JOIDES Resolution, and to recommend changes which will facilitate the achievement of those research objectives.

RESEARCH OBJECTIVES

Paleomagnetic objectives for the Ocean Drilling Program can be divided into four general areas: magnetostratigraphy, behavior of the geomagnetic field, tectonics, and the oceanic crust.

MAGNETOSTRATIGRAPHY

A. ***High-resolution correlation techniques***. Because geomagnetic polarity intervals are globally-synchronous, it has been convenient to interpret biostratigraphic ages and geochemical events in terms of the magnetic polarity time scale. Thus high-precision magnetostratigraphic studies will continue to be critical for correlating ocean sediments.

B. ***Magnetic polarity time scale.*** Although the sequence of magnetic polarity transitions is now well-established for most of the Cenozoic and Late Mesozoic, there are problem areas which require additional studies of sedimentary sequences. For example:

1. ***The Jurassic marine magnetic anomalies M38-M25.*** It is not clear whether the low amplitude features identified as M38-M25 represent geomagnetic field variations or actual polarity intervals. Drilling in the Pacific Ocean over anomaly M38 could resolve this question.
2. ***Early Cretaceous marine magnetic anomalies M10-M5.*** The absence of anomalies M10-M5 in the Atlantic has led to the suggestion that a ridge jump is responsible for a misinterpretation of the anomaly pattern. A site over anomaly M17 would resolve this and other related questions.
3. ***Middle and late Miocene polarity sequence.*** In spite of extensive efforts, global correlation of middle and late Miocene sections is still only tentative. Additional work is needed to develop an integrated framework linking biostratigraphic, magnetostratigraphic, isotopic and radiometric data.

BEHAVIOR OF THE GEOMAGNETIC FIELD

Only deep-sea sedimentary sequences are capable of providing the long continuous datable records needed to study the detailed record of small-scale variations of the geomagnetic field. These variations will provide information about:

A. ***Time-averaged behavior of the field.*** Does the geomagnetic field behave as a geocentric axial dipole or have long-term asymmetries persisted through time. The answer to this question is of major importance to the determination of paleolatitudes for plate reconstructions.

B. ***Short polarity intervals.*** These problematical features are found in rapidly-accumulating marine sediments and in some marine magnetic anomaly records. Better understanding of these features is needed to refine the magnetic polarity time scale and to determine the statistical properties of the reversal process.

C. ***Polarity transitions.*** The morphology and structure of the geomagnetic field during polarity transitions is one of the fundamental unsolved problems in geophysics. Deep-sea sediments can provide polarity transition records of surprisingly high resolution. High priority should be given to the collection of such records whenever possible, particularly the Matuyama-Brunhes transition and any transition from the Southern Hemisphere.

D. ***Geomagnetic excursions.*** The existence of many proposed geomagnetic excursions is still a matter of controversy while the nature and extent of others is still not understood. It is important to study excursions which may have occurred during the Brunhes Epoch, but excursions in older sediments are also of high interest.

E. ***Secular variation.*** In certain cases, marine sediments may be used to determine the characteristic patterns and time scales of geomagnetic secular variation for the past several hundred thousand years.

TECTONICS

The primary goal of paleomagnetic studies in the area of tectonics is the determination of apparent polar wander paths for oceanic plates and the submarine portions of continental plates. For such studies, two elements are absolutely necessary: core orientation and sample age. In addition, for sampling of the basement it is necessary to penetrate enough cooling units to average secular variation. Tectonic topics which can be addressed by the Ocean Drilling Program include:

A. ***Motion of the Pacific plate.*** Marine magnetic anomalies which predate and postdate the Cretaceous quiet zone appear to require some major change in plate motions in the Pacific Ocean. Proposed models for the reorganization of the plates during this time can not be tested until the appropriate data becomes available. Additional information is also needed concerning the Cenozoic motion of various microplates.

B. ***Origin of oceanic plateaus.*** New drilling is needed to resolve questions concerning the origin of these features and their relationship to the tectonic history of the Pacific basin.

C. ***Polar wander paths.*** In order to separate apparent polar wander of the plates from true polar wander, it is necessary to have a global database that includes the oceanic plates. The current apparent polar wander paths for both the Pacific plate and the Indian plate are not well-constrained, and additional information would be very desirable.

D. ***Tectonic evolution of Antarctica.*** Paleomagnetic data could be used to determine whether East and West Antarctica were separate plates during the Cretaceous.

OCEANIC CRUST

The new capabilities of the JOIDES Resolution for re-entry, barerock drilling, and deeper penetration indicate that paleomagnetic studies will continue to be a major component of basement drilling. Prime areas of interest are:

A. ***Origin of marine magnetic anomalies.*** The magnetic structure of the basement is another fundamental unsolved geophysical problem. Primary questions involve the depth of the magnetized layer and the time at which it acquires its magnetization. Holes at least 1000 m deep should be drilled in both fast and slow spreading center environments. In addition, holes near fracture zones may permit penetration to gabbro complexes.

B. ***Ridge processes.*** Sites on east-west trending ridges are needed to assess the role of listric normal faults on the structural evolution of a ridge. In addition, it is desirable to drill into the central magnetic anomaly high which characterizes fast-spreading ridges and the low which is found on certain slow-spreading ridges.

C. ***Old ocean crust.*** Deep penetration of Jurassic age crust would provide important insights about the variations of oceanic crust through time and the effects of alteration on magnetic minerals and magnetic anomalies.

D. ***Seamounts.*** Seamounts constitute a major process of construction of the Pacific lithosphere. Despite the obvious importance of seamount magnetic anomalies, the sources and origin of their magnetization are poorly understood. To address the problem of seamount paleomagnetism, a small, simply magnetized Pacific seamount should be drilled to a depth of at least 500 m.

JOIDES RESOLUTION

SHIPBOARD EQUIPMENT

The shipboard laboratory is well-equipped to perform detailed paleomagnetic measurements. In order to continue to expand its capabilities, we recommend the following additions or modifications:

A. ***Whole-rock susceptibility logging system.*** The present magnetic susceptibility instrument should be automated and supplemented in conjunction with the development of a multi-purpose, whole-core, pass-through system.

B. ***Rock magnetic studies.*** The feasibility of using rock magnetic studies for correlation purposes and for determining the fidelity of paleomagnetic recorders could be increased by:

1. Modification of the Schonstedt alternating-field demagnetizer to provide it with the capability of producing anhysteretic remanent magnetization.
2. Installation of a pulse magnetizer or electromagnet for producing isothermal remanent magnetization.

C. ***Downhole magnetic logging.*** A new tool capable of making downhole measurments of magnetization and susceptibility will be deployed on Leg 115. Whenever possible, basement drilling legs should utilize this tool as part of the scientific program.

SHIPBOARD PROCEDURES

In order to increase the efficiency of gathering paleomagnetic data and to increase the usefulness of the data which is gathered, the following modifications in shipboard procedures are recommended:

A. ***Core orientation.*** All APC cores from one hole at each site should be oriented using the the most feasible technology.

B. ***Partial demagnetization of archive sections.*** The shipboard paleomagnetist should be allowed to partially demagnetize the archive half-section of any core at a peak field not to exceed 15 mT or the median destructive field, whichever is lower.

C. ***Deconvolution and high-density sampling.*** The routine pass-through measurement interval should be made as small as possible, given the practical limitations of shipboard operation. In addition, high-density sampling is necessary to develop deconvolution methods for continuous measurements and to study critical intervals. The Matuyama-Brunhes transition zone should be classified as a critical boundary, and paleomagnetic sampling across it should have high priority.

D. ***Other procedures.*** On cruises with a heavy APC component, a marine technician should be dedicated to the paleomagnetism laboratory.

IMPLEMENTATION

A. ***Paleomagnetists on topical panels.*** We recommend that paleomagnetists be placed on those JOIDES panels where input from paleomagnetists would serve to further the objectives of the scientific community.

B. ***Paleomagnetists and the planning process.*** Greater input from paleomagnetists in the earlier stages of the planning process could significantly aid in the realization of scientific goals.

PALEOMAGNETIC OPPORTUNITIES

The planned program for the JOIDES/Resolution for the next few years involves legs in first the Indian Ocean, then the western Pacific Ocean and finally the northeast Pacific Ocean. In each of these regions, there are possibilities for significant and important paleomagnetic studies.

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INTRODUCTION

From the very beginning, paleomagnetic studies have been an important component of the Deep Sea Drilling Program. However, with the development of the Advanced Hydraulic Piston Corer (APC) and the Extended Core Barrel (XCB) as well as with improvements in hard rock drilling capabilities, the potential contributions of paleomagnetic studies to the Ocean Drilling Program have increased substantially. At the same time, these technical improvements provide paleomagnetists with new opportunities for the study of fundamental geophysical problems. The purpose of this report is to identify research objectives which can be addressed by paleomagnetic studies, to evaluate the present paleomagnetic capabilities of the JOIDES Resolution, and to recommend changes which will facilitate the achievement of those research objectives.

RESEARCH OBJECTIVES

Paleomagnetic objectives for the Ocean Drilling Program can be divided into four general areas: magnetostratigraphy, behavior of the geomagnetic field, tectonics, and oceanic crust.

MAGNETOSTRATIGRAPHY

The chronostratigraphic analysis of deep sea sediments is one of the cornerstones of marine geology. Biostratigraphy, isotope stratigraphy, and magnetostratigraphy represent the principal techniques for studying long continuous sedimentary sequences. Because pelagic sections provide the best records for all three stratigraphies and because deep sea cores generally exhibit better preservation than land sections, the Ocean Drilling Program will provide the primary data source for high-resolution studies of both Cenozoic and Mesozoic sediments.

HIGH RESOLUTION CORRELATION TECHNIQUES

In recent years, the development of quantitive methods in micropaleontology and automatic analytical techniques in isotope geochemistry has led to the construction of biozonations and isotopic records of ever-increasing resolution. These records are being used to further our knowledge of the structural evolution of the ocean basins, the history of deep and surface ocean circulation, the record of past climates, the evolution of oceanic plankton, and the relationships among these diverse elements. However, the increased temporal resolution has also raised new questions about the geographic and environmental dependence of these stratigraphies and the globlal versus regional applicability of biostratigrapic and isotopic events.

Biostratigraphic zonations generally use the first and last appearance datums of index or key species for subdividing geologic time and correlating sedimentary sections. However, biostratigraphic "events" are not necessarily chronostratigraphic horizons, and the preserved range of an index species may be a function of depositional environments and diagenetic conditions. Similarly, at least some of the changes which affect the isotope stratigraphy of a sedimentary sequence are the result of geologic processes which are time transgressive on a global scale. Thus the actual precision of biostratigraphic or geochemical markers is generally not accurately known with respect to absolute time. With the growing need for accurate high-resolution stratigraphic correlation in identifying paleoceanographic events, it is important to be able to determine the uncertainities associated with biostratigraphic ages and geochemical signatures.

Because geomagnetic polarity transitions are the only frequent, globally-synchronous geophysical phenomena, it is well-understood and widely appreciated that high precision magnetostratigraphy is critical to the resolution of various problems in the correlation of ocean sediments. In order to provide the most comprehensive temporal framework, biostratigraphic and isotopic events in a given section must be located with respect to the independent time scale of the geomagnetic polarity transitions. In this way it is possible to determine the synchroneity of events on a regional or global scale. In addition, because the magnetostratigraphy makes it possible to compare different types of events occurring in different places, a truly global synthesis can be developed. However, these results can only be achieved if the potential resolution of magnetostratigraphy is used to its fullest extent.

Although the sequence of magnetic polarity intervals is now well-established for most of the Cenozoic and Late Mesozoic, there are at least three problem areas for which additional studies are imperative.

MAGNETIC POLARITY TIME SCALE IN THE JURASSIC

The first of these areas is the interval represented by marine magnetic anomalies M38-M25, corresponding to the Bathonian, Callovian, and Oxfordian. For the Late Jurassic and Early Cretaceous, the magnetic polarity time scale is based on the M-sequence model for the Hawaiian magnetic lineations. Anomalies M38-M25 are closely-spaced features detected by aerial magnetic surveys. However, the anomalies are of low amplitude and were previously considered to be evidence of a Jurassic "Quiet Zone". In the Atlantic, the same time period is represented by broad anomalies and/or "quiet" crust. Because of the low amplitudes, it has been suggested that M38-M25 represent geomagnetic intensity variations rather than polarity intervals. However, magnetostratigraphic results from outcrops of pelagic sediments suggest that the reversal pattern for the Bathonian through Oxfordian may have been the same as that implied by the M25 through M38 sequence.

By drilling to basement at anomaly M38 and obtaining an age for that anomaly from the basal sediments, the age span of the M38-M25 anomaly pattern could be obtained. In addition, the magnetostratigraphy of the overlying Jurassic sediments from such a hole could provide a complete record of the M38 through M25 polarity sequence. It is probable that anomaly M38 of the Hawaiian lineations was located in mid to low southern latitudes during the Late Jurassic, so that the sedimentation rates should be adequate for detailed magnetostratigraphy.

MAGNETIC POLARITY TIME SCALE IN THE EARLY CRETACEOUS

The second area of high interest concerns magnetic anomalies M10-M5, which are Valanginian to Hauterivian in age. Because the M-sequence can not be identified in its entirety in the Atlantic, it has been suggested that the Atlantic may have ceased spreading during the Late Valanginian and Early Hauterivian (M10-M5) and that spreading later resumed with nearly the same rate and direction to give the younger portion of the M-sequence.

An alternate explanation of the difficulties in correlating the Atlantic magnetic anomaly pattern to the Hawaiian magnetic lineations is that the M-sequence is not a correct representation of the magnetic polarity time scale. One possibility is that the M-sequence incorporates some duplication of anomalies due to minor ridge jumps, especially in the interval between M15 and M5. The presence of these jumps would invalidate a magnetic polarity "time scale" which included "chrons"

M5 to M10. Therefore, it is particularly important to obtain a detailed magnetostratigraphic pattern from well-dated and paleomagnetically suitable sections. At present, the correlation of the biostratigraphy with any portion of the M-sequence from M14 through M0 is very poor and often ambiguous. No land section has recovered a complete magnetostratigraphy in this interval.

A site drilled on early Berriasian crust in a non-abyssal plain environment would recover Valanginian to Hauterivian sediments. The biostratigraphy of such a record would provide a calibration of the magnetic polarity time scale (beginning at the distinctive polarity zone M17) and would lead to a more accurate determination of the M-sequence.

MAGNETIC POLARITY TIME SCALE IN THE MIOCENE

The third problem area is, surprisingly, in the Miocene. In spite of the extensive efforts to establish an integrated time framework linking biostratigraphic, magnetostratigraphic, stable isotopic and radiogenic isotopic age data for the Neogene, the problems have still not all been solved. In particular, carbonate dissolution where the magnetostratigraphy is reasonably identifiable (e.g., Leg 73) and core disturbance by rotary drilling where the biostratigraphy is well-determined (e.g. Leg 82) have combined to render the Miocene time scale correlations somewhat tentative, particularly for the middle and late Miocene.

In addition, marine carbonate records exposed on land have not yielded satisfactory results. Subaerially exposed sections tend to span short periods of time and tend to be stratigraphically incomplete on significant time scales. Their magnetic remanence is subject to alteration by weathering, and the biostratigraphy generally reflects shallow water forms that are unsuitable for global correlation. The best place to obtain continuous, high-quality records of the Miocene is the deep sea. As noted above, existing core material is inadequate, and new coring is clearly desirable.

BEHAVIOR OF THE GEOMAGNETIC FIELD

Primarily with the exceptions noted above, the main features of the magnetic polarity time scale are well-established, in large measure as a result of the Deep Sea Drilling Project. However, the detailed record of small-scale geomagnetic variations is still virtually unknown. These variations, which occur on various time scales, are critical to understanding the processes which drive the geodynamo. Here again, deep sea sedimentary sequences provide the only means of obtaining the long continuous datable records needed to study these variations. In all cases, these studies require the use of the APC technology to collect oriented, undisturbed cores from carefully selected regions with quiescent depositional conditions, isolated from turbidite influences, and with sedimentation rates greater than 1 cm/ka.

TIME-AVERAGED FIELD

On the scale of millions of years, the primary question is whether the geomagnetic field behaves as a geocentric axial dipole or has long-term asymmetries that persist through time? A related question concerns differences in the time-averaged field between normal and reversed polarities. Although to first order, the time-averaged geomagnetic field approximates a geocentric axial dipole, data from sequences of lava flows suggest the persistence of certain higher-order components which may not average to zero. The presence of higher order components is of major importance to the interpretation of paleoinclinations for plate reconstructions. The central assumption which has been made in such studies is that the field averages to a geocentric axial dipole on the time scale of a few tens of thousands of years. Thus it is important to determine the structure of the time-averaged field over increasing intervals of time ranging from tens of thousands of years to millions of years. In order to obtain such information on the relative magnitudes of the nondipole and dipole components of the field, it is necessary to study globally-distributed sedimentary sequences of different ages, with special focus on the last five million years.

SHORT POLARITY INTERVALS

A second area of prime interest concerns the origin of certain short duration features, known as "tiny wiggles," that appear in some marine magnetic anomaly records. These features may represent short polarity intervals or fluctuations in the geomagnetic intensity. In addition, they may be regional rather than global in extent. Understanding the nature of these features is important not only because it will lead to refinement of the magnetic polarity time scale but also because the discovery of new short polarity intervals will change the distribution of polarity intervals. This, in turn, will have a major effect on statistical studies of reversal frequency and mean polarity length which are important parameters in determining the nature of the reversal process.

The short duration features are recognized throughout the Cenozoic record, but they are particularly common in the Oligocene. Complete recovery of high sedimentation rate cores in this and other time intervals would aid in clarifying the morphology and origin of these features. In addition to providing new perspective on geomagnetic field behavior, the existence of short geomagnetic intervals is important for very high-resolution correlation studies.

POLARITY TRANSITIONS

Polarity transitions are one of the most remarkable and intriguing features of the geomagnetic field, but even after twenty years of research, the detailed behavior of the field and the processes which control it are still poorly-known. Additional paleomagnetic data are critically important in providing constraints for transition models and dynamo theories. Over the past five years, deep-sea sediments have provided polarity transition records of surprisingly high resolution. This is quite fortunate because only sediments can provide multiple records of the same reversal from widely separated localities, as well as records of sequences of reversals.

The initial records of polarity transitions demonstrated that the geomagnetic field is nondipolar during a polarity transition. The newer records (many of which were obtained from sediments) suggest that although the transition field is dominated by axisymmetric components, the importance of non-axisymmetric components have been underestimated and that they also play a major role. Globally-distributed, multiple records of a single transition are essential in providing a more complete description of the harmonic content of the transitional geomagnetic field. At the present time, however, global coverage simply does not exist. For example, the most thoroughly studied transition is the Matuyama-Brunhes for which less than a dozen records exist. In addition, all of the sampling sites are in the Northern Hemisphere, which precludes the determination of a unique description of the harmonic content of the field. It is thus critically important to obtain detailed records from both hemispheres to test the axial symmetry of the field as well as to evaluate the importance of the non-axisymmetric terms.

The present lack of sites in the Southern Hemisphere is due to difficulties in finding long sequences with high deposition rates on land. Therefore, deep-sea sediments can make a very significant contribution to the determination of the transitional field geometry. We recommend that particular attention be given to any potential records of the most recent transitions, especially the Matuyama-Brunhes. Such records are easily identifiable by magnetostratigraphy and should be present at most sites with a sufficiently high sedimentation rate. In addition, it would be highly desirable to have north-south transects of sites in the Indian or Pacific Oceans because of the information which they can provide about the latitudinal variation of the transition field.

GEOMAGNETIC EXCURSIONS

Geomagnetic excursions are also important to an understanding of the geomagnetic field. They occur when the virtual geomagnetic pole deviates by more than 40° from the North or South Pole without actually resulting in a polarity transition. Most of the excursions which have been reported are from volcanic or sedimentary rocks that are younger than 500,000 years old. However, the existence of some of these excursions has been questioned, particularly when it has not been possible to find the same record of an excursion at two or more nearby sites of the same age. Furthermore, once the existence of an excursion has been established, the geographical extent of the directional variations gives important information regarding the size of the sources which produce the phenomenon.

Excursions are often interpreted as unsuccessful or aborted polarity transitions. This genetic relationship is reinforced by recent studies of polarity transitions which show excursions occurring either before or after the transition. Thus the detailed study of the existence, extent and duration of geomagnetic excursions in the paleomagnetic record is critical to an understanding of geodynamo processes.

Studies of excursions during the Brunhes Epoch are particularly important because they have the potential of being identified at several locations, and their global morphology can be investigated. However, it is also important look for excursions in older sediments to determine whether their rate of occurrence has changed through time. In many cases, only deep-sea sediments are capable of providing the regional distribution and time intervals needed to study excursions.

SECULAR VARIATION

In certain instances, marine sediments may be used to determine the characteristic patterns and time scales of geomagnetic secular variation for the past several hundred thousand years. For the period prior to the Holocene, we have little knowledge of detailed geomagnetic field behavior due to the lack of adequate continuous records that predate the most recent retreat of the glaciers. However, in certain areas of the world, there has been continuous and rapid sedimentation that has the potential of providing high resolution records of secular variation. The primary objectives of such work are to determine: 1) Whether geomagnetic secular variation has been constant over the last several 100 ka. 2)Whether there are characteristic periodicities and, if so, whether the periodicities are time stationary. 3)Whether westward drift is a permanent or ephemeral feature. 4) Whether the drift is zonal or has a latitudinal dependence. In addition, the secular variation studies can also be used to determine the nature of the time-averaged field, the global or regional nature of geomagnetic excursions, and the relationship between geomagnetic excursions and 'normal' secular variation.

Because of the need for high resolution, there are only a few areas in the world where continuous sequences of rapidly-deposited sediments occur. Many of these areas are associated with active coastal upwelling regimes, such as the Gulf of California, the California/Oregon margin, and the northwest African margin. However, certain marginal basins in the western Pacific as well as the distal edges of major submarine fans may also be suitable, and their potential should be examined further.

TECTONICS

Paleomagnetic data from ocean drilling has played a key role in understanding the tectonic and geologic history of the Earth's plates. Recent studies of terranes have demonstrated that the geologic histories of the continents cannot be fully understood without a knowledge of the tectonic history of the adjacent ocean crust. Moreover, in some areas of the oceans, the available marine geophysical data clearly shows that many tectonic models postulated a decade or more ago were too simplistic.

ROLE OF CORE ORIENTATION AND DATING

The primary goal of ODP paleomagnetic studies in tectonics is to determine the apparent polar wander for oceanic plates or the submarine portions of continental plates. For such studies two elements are absolutely necessary: core orientation and sample age. The orientation should be as complete as possible. For APC cores, this means that the individual cores should be oriented with respect to geographic coordinates so that accurate declinations can be determined as well as inclinations. The recovery of declination information is extremely important to define accurately the location of the paleomagnetic poles on the apparent polar wander path. Additionally, the declination information allows tectonic rotations, such as may occur during microplate formation and evolution, to be quantified. A core orientation device has been developed for the APC, and its regular use is highly recommended. Although the core orientation device cannot be used to determine the absolute declination of XCB and rotary drilled cores, it can and should be used to determine the off-vertical tilt of holes drilled for tectonic studies using these devices. Such information is important in the calculation of paleolatitudes and the determination of their associated error bars.

For tectonic studies, paleomagnetic data is of limited use without precise and accurate age control. For basaltic cores, the dating must be done using Ar40-Ar39 techniques because low temperature alteration causes conventional K/Ar ages to be systematically low. For most sediments, good age control requires a well-constrained biostratigraphy and/or magnetostratigraphy. Holes drilled in areas of low biologic productivity will likely be of limited paleomagnetic interest because the fossils needed to anchor the biostratigraphy or the magnetostratigraphy may be absent. On the other hand, sediments deposited in areas of high biologic productivity, such as carbonate sections laid down above the CCD, should provide excellent age constraint for paleomagnetic measurements.

For basaltic cores to be useful for tectonic studies, a lengthy section of core material must be recovered. A single lava flow may be many meters thick, but it averages the magnetic field over a period of only a few years. To average out secular variation and make a reliable estimate of the paleolatitude, many igneous units must be cored. The exact number of units needed depends on the rate of eruption or emplacement; however, studies indicate that at least 20 units must be sampled. Thus, a hole may have to penetrate several hundred meters into basement.

Some of the tectonic problems that could be addressed by ODP paleomagnetic studies are the evolution of the Pacific basin plate, including the motion of the entire plate during and before the Cretaceous Long Normal Polarity Chron as well as recent motions of microplates, the origin of oceanic plateaus, and the determination true polar wander.

PACIFIC BASIN PLATE

The Cretaceous Long Normal Polarity Chron (83-119 Ma) represents a 36 million year "blind" spot in models of Pacific basin plate motion based on marine magnetic anomalies. The data from marine magnetic anomalies that predate and postdate the Cretaceous quiet zone appear to require a major change in plate motions. However, all of the proposed models are speculative due to the lack of magnetic reversal information. A primary paleomagnetic objective of ODP sites in the Pacific should be to obtain paleolatitude data to address the following questions: 1) Was the "Pacific plate" a single plate during the Cretaceous Long Normal Polarity Chron or did parts move independently? 2) What was the rate of absolute motion of the Pacific Plate during the Cretaceous Long Normal Polarity Chron? 3) What was the tectonic history of the boundaries of the Izanagi, Farallon, Kula and Phoenix plates with the Pacific plate? (4) How does the motion of the Pacific plate relate to the formation and transport of terranes currently located on the Circum-Pacific margin?

An oceanic site with carbonate sediments suitable for detailed biostratigraphy, for example, the Ontong-Java Plateau, could be used to answer these questions. Sites north of the Mendocino Fracture Zone, such as the Hess and Shatsky Rises, are particularly needed.

In addition, reconstruction of the tectonic history of the Pacific basin plates before the Cretaceous quiet zone is hampered by the lack of previous DSDP sites of appropriate age. Paleolatitude data is needed on all ODP sites drilled into Cretaceous-Jurassic Pacific crust. These new sites could also serve the magnetostratigraphic needs discussed above. Possible sites include M25 in the north Pacific and M38 of the Hawaiian lineations.

With regard to microplate tectonics, the APC could provide paleomagnetic data that would constrain models of the tectonic evolution of recent microplates, like the Juan de Fuca plate and Easter Island plate. Additionally, such data could aid in confirming hypotheses that call for the incorporation of microplates into the Pacific (such as the Chinook plate) or the splitting off of sections of the Pacific (such as the Bering Sea plate). Declination data could be used to discriminate whether microplates rotate as coherent units or shear internally.

ORIGIN OF OCEANIC PLATEAUS

The Ocean Drilling Program could also provide new insights into the origin of oceanic plateaus. The formation of the plateaus in the Pacific basin has been attributed to a variety of mechanisms including extreme ridge crest volcanism, hotspot activity, meteorite impacts and anomalous (continental) crust. Information on the paleolatitude of the Pacific oceanic plateaus as a function of time would provide the data needed to test these various theories of plateau formation. It would also provide information about the relationship between the oceanic plateaus and the tectonic history of Pacific basin plate itself.

Plateaus are generally good sites for obtaining paleomagnetic samples because their summits have remained above the CCD, and thus biostratigraphic age control is good. Possible sites to address plateau evolution are the same as those needed to study plate motions in the Cretaceous Quiet Zone. In addition, older plateaus, such as the Magellan Rise, should be re-examined.

POLAR WANDER PATHS

In order to separate apparent polar wander of the plates from true polar wander, it is necessary to have a global database that includes the oceanic plates. The current apparent polar wander path for the Pacific plate is only poorly known and is based principally on older DSDP data. For that reason, there is a general need for more and better Pacific paleolatitude data.

New paleomagnetic data are needed to constrain the apparent polar wander path of the Indian Ocean during both the Mesozoic and Cenozoic. The Mesozoic data is necessary to determine the early evolution of the plate. Jurassic/Cretaceous sites in the Argo Abyssal Plain and in the Somali Basin are thus of tectonic importance. Additionally, the apparent polar wander path of the Indian plate during the Tertiary is poorly known and fully-oriented cores of this age are highly desirable.

Only when the Pacific and Indian paths are adequately defined will it be possible to determine more accurately the paleomagnetic reference frame, with respect to which plate motions are often measured, and to measure its movement with respect to the hotspot reference frame, which is, by definition, true polar wander.

TECTONIC EVOLUTION OF ANTARCTICA

Paleomagnetic data could be used to test whether East and West Antartica were separate plates during the Cretaceous. The lack of suitable exposures on land makes it unlikely that this question will be solved without appropriate ODP sites. This question is critical to any synthesis of global plate motions.

OCEANIC CRUST

Ever since Leg 34, deep crustal penetration has been an important goal of the Deep Sea Drilling Program, and paleomagnetic studies of core samples have been an integral part of this effort. These studies have had as their objectives the identification of the magnetic source layer, the determination of paleolatitude variations, and the characterization of faulting and rotation of crustal blocks in the ridgecrest environment. While considerable progress has been made on these issues, major questions remain to be solved. The new capabilities of the JOIDES Resolution for re-entry, barerock drilling, and deeper penetration indicate that paleomagnetic studies will continue to be a major component of basement drilling.

ORIGIN OF MARINE MAGNETIC ANOMALIES

Lineated magnetic anomalies are integral to plate tectonics, yet questions still remain as to their origin and the magnetic structure of the basement. The major questions involve the depth of the magnetized layer and the time at which it acquired its magnetic remanence. Although a five hundred meter thick source layer is advocated by some, the available data is still insufficient to resolve the issue. Only one hole (504B) has reached the underlying sheeted dike complex, and the data even from that depth (1076 m) were inconclusive. Deepening of Hole 504B (currently underway) may resolve the issue of the depth of the magnetized layer at this location, but it does not resolve the issue of whether this hole is typical of the oceanic crust as a whole (or even of the immediate vicinity).

As there are good reasons to suspect that the magnetic structure may vary within the ocean basins (for example, due to variations in spreading rate), more such holes are needed. In particular, it is desirable to have holes from both fast- and slow-spreading environments to determine how this affects magnetic structure. A possible target in a slow spreading environment is deepening Holes 417D and/or 418 in the Atlantic Ocean where a reentry cone already exists and excellent recovery rates of basalts were achieved. Hole 504B should also be deepened as much as possible. As drilling through the sheeted dike complex in this location seems improbable, we recommend drilling of a new hole, near a fracture zone, where crustal thinning may permit penetration to the gabbro complex.

For over a decade, the hypothesis that there is a direct correlation between the amplitudes of marine magnetic anomalies and the bulk geochemistry of the underlying extrusive rocks (specifically Fe-Ti enrichment) has been accepted, largely without critical testing. Recent detailed studies of medium- to fast-spreading centers have shown that there may be a correlation between the tectonic style and the geochemistry of the extruded rocks, both at propagating rift offsets and at the distal ends of individual ridge segments. The observation of enhanced magnetic anomaly amplitudes over these areas has served to increase interest in this hypothesis. What is needed now is critical testing of the theory, both with surface rocks and at depth within the crust. The latter should be located in a zone of high-amplitude magnetic anomalies with Fe-Ti enriched surface rocks. Drill holes located in well-characterized propagating rift, such as the Galapagos or Juan de Fuca Ridges, would be appropriate for solving the magnetic, geochemical and tectonic problems associated with these features.

RIDGE PROCESSES

Sampling of basement rocks can also provide information on questions relating to processes occurring at mid-ocean ridges. The first of these involves the structural evolution at a ridge itself. It has been suggested that listric normal faults arising from the extension process can lead to large-scale block rotation in the vicinity of the ridge crest. The existence of such rotations would considerably limit the inferences which could be drawn from paleomagnetic directions obtained from the crustal blocks. Unfortunately most of the existing paleomagnetic data is from north-south trending ridges from which the amount and direction of tilt cannot be easily determined. Any site that extends into basement on an east-west trending ridge could address this problem, provided it sampled enough cooling units to average secular variation.

Other questions relate to the nature of the magnetic anomaly directly over the ridge. Most medium- and fast- spreading ridges have a well-defined central magnetic anomaly high that directly overlies the axis of current spreading. Early studies of this phenomena attributed this magnetic contrast to low temperature oxidation of the surface rocks. Recent modeling experiments and deep-tow magnetometer studies have shown that this mechanism is inadequate to explain the nature of this feature . Drilling into the axis of spreading that underlies the central high should provide the samples necessary to unravel the processes that are responsible for this major crustal formation process. Drilling in this area requires the capability of bare rock drilling and is consistent with the other bare-rock drilling goals as stated in the COSOD report.

In areas of the ocean where spreading centers are near continental margins, rapid sedimentation can bury the axis of spreading and the volcanism associated with it. Because of the confined hydrothermal circulation under such conditions, crustal temperatures can be dramatically elevated, with temperatures at the basement-sediment interface in excess of 300° C. Where this occurs, intense alteration of the crust can result in subdued magnetic anomalies, even for Brunhes age crust. Well-characterized examples are the Middle Valley on the northern Juan de Fuca Ridge, the Escanaba Trough on the southern Gorda ridge, and the Guaymas Basin in the Gulf of California. Detailed geophysical studies of these areas are currently underway, and one or more of these sites is planned for deep crustal penetration with ODP drilling. The high crustal temperatures in these locations provide a unique opportunity to study accelerated basalt and sediment diagenesis and the related changes in magnetic properties. Magnetic studies of the returned drill core samples, and the magnetic logging at these sedimented spreading centers will lead to a better understanding of the effects of a high temperature hydrothermal system on the magnetic anomaly source layer.

OLD OCEAN CRUST

As discussed in the magnetostratigraphy section, the northwest Pacific M-sequence record contains the problematical magnetic anomalies M38 to M25. The sediments overlying these anomalies are a prime target for magnetostratigraphic studies. However, coring into the basement of one of these low amplitude anomalies would provide a check on the polarity determined from the basal sediments and would aid in determining the nature of the oceanic crust which gives rise to these low amplitude magnetic anomalies. In particular, coring of M38, the oldest identified anomaly would allow determination of the ages of anomalies M25 - M38 and/or determination of the cause of the small variations in amplitude.

It is also important to have deep penetration of very old (Jurassic age) oceanic crust, which has never been sampled to any significant extent. The deepest penetration was 29 meters (Leg 76), and from the constant inclinations found there, it appears that only a very brief time interval was sampled. Deeper sections of Jurassic crust are required, particularly in the "quiet zones", where it is necessary to assess whether the crust is more viscous, more weakly magnetized, or has some other unusual property. The full extent of low temperature alteration of magnetic minerals of the oceanic crust is unknown. Holes in Jurassic oceanic crust would also provide much-needed paleolatitude data for oceanic plates during Mesozoic time as discussed in the tectonics section.

SEAMOUNTS

Seamounts constitute a significant constructural feature of the Pacific lithosphere. Moreover, models of seamount magnetic anomalies provide the primary constraint for motion of the Pacific plate. Despite the obvious importance of seamount magnetic anomalies, the sources and origin of their magnetization are poorly understood.

To address the problem of seamount paleomagnetism, it would be necessary to drill deeply (>500 m) into a small, simply magnetized Pacific seamount. The paleomagnetic studies should be done in conjunction with geochemical, petrological, and isotopic studies. The target seamount should be old enough (>5 my) so that the chemical alteration process has reached a plateau. Deep drilling is required in order to obtain lithologies and alteration states representative of the sources of the magnetic anomalies. To utilize fully the magnetic information, the hole should be logged with a down-hole magnetometer/susceptometer tool as well as standard logging tools. In order to constrain the internal structure of the seamount, drill core studies should be coupled with a down-hole seismic experiment and, if possible, a seismic tomography experiment.

JOIDES RESOLUTION

SHIPBOARD EQUIPMENT

The shipboard laboratory currently is well-equipped to perform detailed paleomagnetic measurements on sediments and hard rocks, and this represents a major advance over that which was available on the Deep Sea Drilling Project. We consider that the major areas for improvement to be development of a whole-rock susceptibility logging system, improved provision for rock-magnetic studies of recovered materials, and deployment of a downhole magnetic logging tool. We therefore recommend the following additions to or modification of shipboard equipment.

WHOLE-ROCK SUSCEPTIBILITY LOGGING SYSTEM

High resolution whole-core susceptibility measurements with a sampling interval of 5 cm or less have proved extremely useful for detailed within-site, between-hole correlation of HPC sections. They can also provide useful paleoceanographic information such as the resolution of glacial-interglacial cycles. The present Bartington instrumentation should be automated and supplemented with a narrower (7.2 cm diameter) dual-frequency sensor and a dedicated plotter to display down-core susceptibility variations in real time. This capability could be incorporated into a multi-purpose whole-core pass-through system which would enable the simultaneous measurement of additional parameters such as P-wave velocity and GRAPE density. The entire system should be sufficiently simple so as to be operated by the marine technicians on watch.

ROCK MAGNETIC STUDIES

Rock magnetic measurements have proven to be useful as correlation tools as well as for assessing the fidelity of hard rocks and sediments as recorders of the geomagnetic field.

Many of the paleomagnetic objectives of ODP depend on the accurate recording of the ancient magnetic field by sediments and igneous rocks and on the ability to recover the primary field direction. For sediments, the accuracy of magnetostratigraphic studies and time series of geomagnetic field behavior depends critically on where in the sediment column the remanence is fixed and whether the magnetization is altered after deposition. For igneous rocks, it is equally important to understand the nature of the magnetic carriers and their evolution with age and alteration. At present, however, there is only a fragmentary understanding of the mechanisms controlling remanence acquisition and the physical and chemical processes which affect the remanence and its stability. Therefore, shipboard and shore-based rock magnetic investigations should accompany and support paleomagnetic studies whether their primary aim is magnetostratigraphy, tectonics, geomagnetism, or the nature of the source layer. These rock magnetic studies should be able to provide information about the nature and origin of the magnetic particles responsible for the remanence and the effects of such factors as dewatering, compaction, diagenesis and authigenesis. To encourage rock magnetic studies, we recommend the following additions to the shipboard paleomagnetic laboratory:

1) Modification of the Schonstedt alternating-field demagnetizer for the purpose of producing an anhysteretic remanent magnetization (ARM) in a sample. The modification involves inserting a coil capable of producing dc fields inside the mu-metal shield. The demagnetization properties of the ARM produced in a sample provides information about the magnetic carriers. In addition, a method which uses both ARM and magnetic susceptibility can be used for the rapid detection of changes in the grain-size distribution of the magnetic carriers.

2) Installation of a pulse magnetizer or electromagnet for producing an isothermal remanent magnetizations (IRM) in a sample. IRM acquisition and demagnetization curves and back-IRM/high-field IRM ratios can all be used to assess changes in the composition of the magnetic carriers.

DOWNHOLE MAGNETIC LOGGING

Logging of basement drill holes with downhole magnetometers and susceptibility tool can be a valuable high-resolution technique for understanding the magnetic properties of oceanic crustal sections. Magnetic logging experiments done on Hole 395A and the Cyprus Drilling Project Hole CY-4 have shown that the technique can not only distinguish magnetic polarity units but can characterize flow morphology and boundaries, map alteration zones, define crustal lithology, and even identify magnetic grain size variations within individual rock units. Used in conjunction with magnetic studies of the recovered core samples and standard geophysical logging data, magnetic logs can be a major resource for crustal drilling legs.

In response to a University of Washington proposal, the National Science Foundation has funded the construction of a downhole magnetometer and susceptibility tool. Consisting of a 3-axis fluxgate magnetometer and weak-field susceptibility sensor (with associated temperature sensors), the instrument will have the capability to be expanded to include a vertical-field gradiometer and self-potential electrodes. The instrument is being designed to be run in conjunction with (and directly behind) the bore-hole televiewer. It would not require a separate logging run to be deployed. The tool is expected to be operational for Leg 115 and will then become part of the standard downhole logging package. We recommend that whenever appropriate, shipboard paleomagnetic studies on basement drilling legs utilize these high-resolution downhole tools as an integral part of their scientific program.

SHIPBOARD PROCEDURES

In order to increase the efficiency of gathering paleomagnetic data and to increase the usefulness of the data which is gathered, certain shipboard procedures, carried over from the Deep Sea Drilling Program, should be modified to reflect recent improvements in equipment and instrumentation.

CORE ORIENTATION

The ability to orient cores greatly increases the potential paleomagnetic information available from ODP cores and is an important advance in drilling techniques. The Eastman-Whipstock multishot tool has been demonstrated to orient cores to within a few degrees. This orientation capability makes it possible to conduct magnetostratigraphic studies in equatorial regions (as demonstrated during ODP Leg 108) and is critical for studies of both geomagnetic field behavior and plate motions.

We recommend that orientation of all HPC cores from one hole at all sites be made mandatory in order that the most useful paleomagnetic results can be obtained. Orientation is particulary critical when sites are located within 15° of the Equator. We also recommend that ODP continue to explore ways to improve core orientation, including the testing of new core orientation devices (such as digital systems) that may be faster than the multishot tool. ODP should also work to eliminate core handling and measuring procedures that add to the uncertainty in the orientation of cores.

PARTIAL DEMAGNETIZATION OF ARCHIVE SECTIONS

The pass-through system associated with the cryogenic magnetometer is capable of providing the high resolution records that are critical for determining geomagnetic field behavior and detailed magnetostratigraphy. However, the measurement of only the natural remanent magnetization of samples is of limited use because of the presence of secondary magnetizations which frequently obscure the true paleomagnetic record. The pass-through alternating-field demagnetizer in-line with the cryogenic magnetometer is designed to provide low field, partial alternating-field demagnetization of core sections. The instrumentation has been shown to be effective at randomizing the low coercivity secondary components without imparting ARMs or other spurious magnetizations. This process is physically and chemically non-destructive.

We recommend that the shipboard paleomagnetist be allowed to partially demagnetize the archive half-section of any core at appropriate peak field levels not to exceed 15 mT. The field level should be determined by progressive partial demagnetizaion of discrete samples and should not exceed the median destructive field. Although this will alter the magnetization of the cores in the archive half-sections, we view magnetization as a potentially ephemeral property. Because future sampling or measurement of the archive half sections is not likely to take place before mechanical or chemical changes have affected the magnetization, we feel that the value of the information which can be obtained warrants using this method on-board.

DECONVOLUTON AND HIGH-DENSITY SAMPLING

Many important problems facing paleomagnetists may be addressed by detailed studies which provide high resolution records of field behavior. The pass-through equipment currently onboard greatly facilitates these studies, and deconvoution of these data will improve the resolution even more. For optimum results from deconvolution, the measurement interval must be as closely spaced as possible. We recommend that the routine measurement interval be as small as possible, given the coring operations and time limitations which exist on a cruise.

Ultimately, high quality deconvolved data will reduce the number of discrete samples required for detailed studies. However, until the details of deconvolution of the pass-through data are thoroughly understood, high-density sampling of critical intervals is still required for high resolution studies. In particular, we feel that "U-channel" sampling of critical intervals is justifiable and necessary. We recommend that the Matuyama-Brunhes transition zone be classified as a critical boundary and that detailed paleomagnetic sampling across it be given priority, particularly in the second APC hole at high sedimentation rate sites.

OTHER PROCEDURES

We believe that detailed shipboard paleomagnetic measurements of APC cores are of sufficient value that we recommend that a marine technician be dedicated to the paleomagnetism laboratory during heavy APC cruises where high resolution stratigraphy is a priority. We also urge that the "generic pass-through" equipment be developed to a state such that it may be routinely operated by the marine technicians on watch. Finally, we endorse the present policy of archiving shorebased and shipboard data and the effort to curate paleomagnetic sample residues.

IMPLEMENTATION

PALEOMAGNETISTS ON TOPICAL PANELS

In order to achieve the objectives set out in this document we recommend that paleomagnetists be placed on those JOIDES panels where input from paleomagnetists would serve to further the objectives of the scientific community. At the present time a paleomagnetist is a member of the Sediments and Ocean History Panel. She will soon rotate off this panel. The workshop strongly recommends that this position be filled by a paleomagnetist who has a background in magnetostratigraphy and an interest in ocean history.

There is one person with a background in rock magnetism and paleomagnetism on the lithosphere panel. We strongly recommend that someone with this background continue to be included on this panel, since an understanding of the magnetic properties of the oceanic crust is of great importance in the understanding of the origin of marine magnetic anomalies, ridge crest processes and alteration.

PALEOMAGNETISTS AND THE PLANNING PROCESS

At the present time the participation of paleomagnetists in the regional panels is minimal although one has served on the Central and Eastern Pacific panel. Greater input from paleomagnetists in the earlier stages of the planning process could significantly aid in the realization of scientific goals. For example, if piston cores were taken from potential drill sites it would be possible to predict whether the magnetic properties of at least the upper part of the sedimentary column would yield good magnetic stratigraphy. This information would be of considerable importance in siting holes that are designed to yield both magnetostratographic and biostratigraphic information. In many cases, information from nearby piston cores is available and should be taken into account when site planning is done.

It is important that the maximum scientific return be obtained from the ODP program. This can only be accomplished if input from paleomagnetists is obtained early in the site selection procedure. We expect that in the future more proposals with paleomagnetic objectives will be forthcoming. This can only be regarded as a healthy evolution of the Ocean Drilling Program.

PALEOMAGNETIC OPPORTUNITIES

The planned program for the JOIDES Resolution for the next few years involves legs in first the Indian Ocean, then the western Pacific Ocean and finally the northeast Pacific Ocean. In each of these regions, there are possibilities for significant and important paleomagnetic studies.

INDIAN OCEAN

The drilling program presently planned for the Indian Ocean provides excellent opportunities for many paleomagnetic objectives outlined in this report. The Arabian Sea proposal (the so-called "Neogene Package") is aimed, in part, at establishing correlations among many different stratigraphies. Of particular interest for tectonic, magnetostratigraphic and high-resolution field behavior is the transect comprising the Kerguelen South and North Legs, the Broken Ridge-Southeast Indian Ridge transect and the 90 East Ridge transect. The collection of oriented cores and the provision for access of paleomagnetists to polarity transition records should be made a high priority for these legs.

WESTERN PACIFIC

The western Pacific is the one area where the objectives of 1) coring very old crust, 2) resolving the magnetostratigraphic questions related to the M-sequence, 3) determining the nature of the M38 - M26 anomalies, 4) discerning the cause of the small amplitude magnetic anomalies, and 5) acquiring Mesozoic paleolatitudes may all be met simultaneously. Because so many relatively important problems can be addressed at the same time, it is imperative that coring into M38 be added to the agenda of western Pacific drilling.

NORTHEAST PACIFIC (TRANSECT)

Problems associated with the behavior of the geomagnetic field require a broad array of sampling sites to distinguish global from regional effects. Longitudinal transects covering a band of latitudes are an efficient means of separating the two components. A transect of sites in the northeast Pacific Ocean could address a variety of questions pertaining to the geomagnetic field. From the Equator to the North Pole, specific sites of interest include:

1.) Eastern Equatorial Pacific - A suite of oriented APC cores in the siliceous and carbonate oozes of the high productivity zone within 15° of the Equator could provide important information on the persistence of long-term quasi-stationary non-dipole features. Furthermore, it could also provide the equatorial records of polarity transitions which are so critically needed for comparison with records from higher latitudes. The area would also be a prime location for the study of the Miocene magnetostratigraphic problems mentioned earlier. In contrast to many Atlantic sites, equatorial Pacific sections do not seem to be severely affected by dissolution and foreshortening of the sequence. This work would also complement the recently proposed Late Cenozoic paleoenvironment drilling program.

2) Gulf of California - The finely laminated sediments along the margins of the Gulf of California provide an excellent setting for high resolution paleosecular variation studies spanning the last few hundred thousand years. A double APC site would allow comparison with ongoing detailed paleomagnetic work on DSDP Site 480, Searles Lake, and other lakes in North America.

3) Northern California and Oregon Margins - Offshore of northern California and Oregon, expanded Plio-Pleistocene hemipelagic sections with good magnetic properties occur on the distal ends of submarine fans (e.g., DSDP Site 34), on the elevated flanks of the Gorda Ridge, and in certain areas along the continental margin (DSDP Sites 173, 175). Sedimentation rates vary from about 4 cm/ka to over 100 cm/ka. These sediments could thus provide records at a variety of resolutions and time scales for the study of Plio-Pleistocene secular variation, transitional field behavior, and the nature of short excursions and polarity changes. In addition, the magnetostratigraphy provided by these studies would be very useful to paleoclimatic work on the California Current and coastal upwelling which was recently proposed as an outcome of the INPAC workshop.

4) High Latitude Seamount Platforms - A series of seamount-associated platforms spans the northeast Pacific from the Gorda/Juan de Fuca Ridges into the Gulf of Alaska. While at present there is little information on the sediments from these benches, the platforms occur above turbidite influence and may preserve a good record of hemipelagic sedimentation extending from the Eocene to the present. Such sediments may be very useful in looking at axial dipole symmetry and fine

scale fluctuations of the geomagnetic time scale. These sites are also of primary interest to biostratigraphers and paleoceanographers.

While such a transect is feasible in the current and proposed schedule of the ODP, at a future date, a complementary transect spanning the South Pacific would be highly desirable.