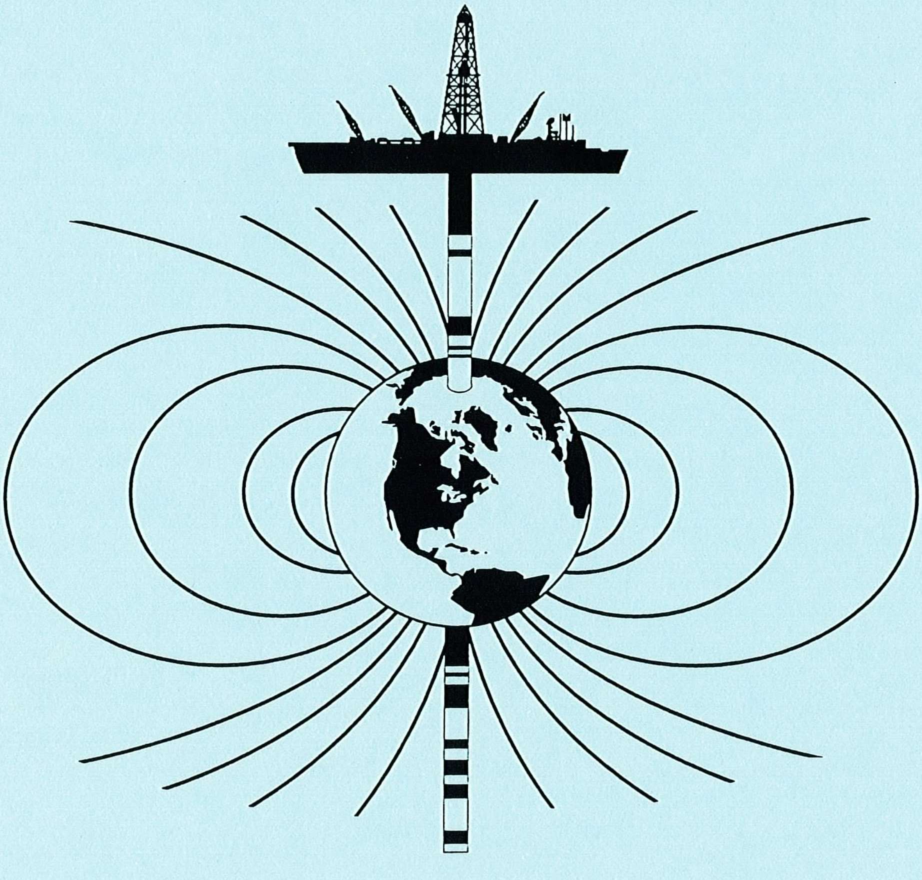
JOI / USSAC Workshop Report

Geomagnetic Polarity Transition Records from ODP Cores



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EXECUTIVE SUMMARY

A number of exciting paleomagnetic results have been obtained recently which provide important clues to the workings of the geodynamo. These results include the interpretation that the lowermost mantle influences the geomagnetic field during polarity reversals, and the demonstration that globally correlative records of relative paleointensity may be obtained from deep-sea sediments. Globally distributed paleomagnetic records of reversals and paleosecular variation are required to test these results, and therefore deep sea sediments cored by the Ocean Drilling Program are critical to address these issues.

Sampling ODP Cores

In order to obtain a geographically wide distribution of records, one or two dedicated holes will need to be drilled in each ocean basin. This will require a more active role by the paleomagnetic community in planning drilling objectives, and it will also require the five years or more it will take for the *JOIDES Resolution* to circumnavigate the globe.

A major advance in solving the polarity reversal controversy could be made by sampling the existing ODP cores that are known to contain high quality polarity reversal records. Many of these cores have been heavily sampled: a coordinated effort to sample Pleistocene reversal transitions will therefore require using the archive halves may be required. Sampling these cores may well help solve one of the last remaining fundamental questions of geophysics: how the earth's magnetic field is maintained and undergoes polarity reversals.

Improvements to the Drilling Process

Early on, the Ocean Drilling Program made a number of technological advances in the drilling process which resulted directly in greatly improved paleomagnetic data. These included zinc coating the drill string to reduce rust problems which plagued DSDP paleomagnetic results, and placing and maintaining a pass-through cryogenic magnetometer on board the *JOIDES Resolution*. In addition to improving greatly the quality of both susceptibility and magnetostratigraphic data, these advances also led to real time results, allowing hole-to-hole correlation while on site. In order to improve further the results, the paleomagnetic community proposes that the following improvements be made to the drilling process and procedures.

1) The workshop participants advocated strongly the installation of a new pass-through cryogenic magnetometer on board the JOIDES Resolution (see Appendix III). The recent advent of DC SQUID sensors in new cryogenic magnetometers provides much greater sensitivity than the existing AC sensors. The cryogenic magnetometer on board the *JOIDES Resolution* is particularly noisy due to its hostile environment, inadequate magnetic shielding and radio frequency (RF) interference. The DC SQUIDs are less prone to shipboard RF interference, and the new magnetometer would have improved (superconducting) magnetic shielding. These features further improve the sensitivity of the new system, and would allow the magnetization of a wider range of weakly magnetized sediments to be measured with precision. Improved dewar insulation in the new magnetometers also reduces liquid helium boil-off. For the new shipboard magnetometer, a liquid helium refill would be necessary every 3.5 years, as opposed to the present 10 month refill interval.

We advocate that the existing shipboard magnetometer be placed at College Station preferably in a magnetically shielded room. In this optimal environment, the instrument's performance would be greatly enhanced compared to its shipboard performance. At College Station, it could be used for analysis of archived cores, and for detailed post-cruise studies.

2) The ODP needs to develop non-magnetic core barrels, and reduce magnetic fields associated with the bottom hole assemblies. On a number of legs where magnetostratigraphic results were an important objective, such as on the Ceara Rise Leg, core-barrel overprints made it impossible to recover a magnetostratigraphic record. Stainless steel or other non-magnetic core barrels should be developed for use on legs when paleomagnetic results are an important objective.

3) Core orientation data for even the uppermost holes are important, and every effort should be made to orient these cores and archive the orientation data.

These technological changes would greatly improve the quality of magnetostratigraphic data obtained as well as increase the number of locations where useful paleomagnetic data may be obtained. As a result, we will gain a greater understanding of the earth's magnetic field and its variation with time.

GEOMAGNETIC POLARITY TRANSITION RECORDS FROM ODP CORES

I. INTRODUCTION

One of the last fundamental questions in earth sciences is how the geomagnetic field is generated and is able to reverse polarity. The past decade has generated a considerable improvement in our knowledge base regarding the geomagnetic field, on both long and short time scales. Major advances in dynamo modelling are expected from current theoretical initiatives such as CSEDI in the USA and the British Geodynamo Project; these dynamo models will ultimately include geomagnetic reversals. An increasing number of reliable records of geomagnetic field reversals have been obtained, from both sediments and lava sequences, but the number of high quality records remains too small. For real progress in understanding the Earth's magnetic field we now need to acquire a good global distribution of transition records so that a solid observational base exists to stimulate new theoretical advances.

Oceans cover 70% of Earth's surface, and therefore a global distribution can only be achieved by paleomagnetic studies of marine sediments, indicating the need for a major program of sampling of existing as well as new ODP/DSDP cores. This report discusses the justification and possible methodology for such a program.

During the last few years several new, disparate observations have come together to reveal what appears to be a remarkably simple picture of geomagnetic behavior: 1) similarities of the historical fields from the last few centuries, and paleofields from the last few million years, with presence of high latitude flux lobes, suggest persistent spatial structures. 2) low secular variation and minimal westward drift in the Pacific Hemisphere is bounded by the longitudes of the high flux lobes 3) two dominant VGP tracks are observed in transition fields; their longitudes also bound the Pacific Hemisphere; some researchers find evidence in their records for recurring patches of VGPs, regions where the field apparently stabilizes for some time during a reversal.

All of these observations point to control of the core dynamo by the mantle, but each has its associated limitations. Records of the historical field provide detailed pictures of the geomagnetic field, but the time span (a few hundred years) is pitifully short compared with those of interest. Time-averaged field models based on paleomagnetic data suffer from poor temporal and spatial distributions, causing difficulties in identifying coeval observations from different locations and in determining whether there is adequate temporal sampling. Reversal transition fields also suffer from poor spatial coverage, but by their nature records of any single reversal are constrained to a time interval of a few thousand years. Also during reversals it is possible to look at the second order structure of the geomagnetic field rather than the dominant dipole contribution; this second order structure presumably holds the key to whether interactions with the mantle control the structure of the geomagnetic field.

The excitement raised by recent interpretations of paleomagnetic records of polarity transitions attests to the importance of these data to our understanding of the earth's magnetic field. New transition records, together with a reexamination of the previously published set of records, have led to the discovery that in many reversals the virtual geomagnetic poles tend to cluster within two approximately antipodal, longitudinal bands over the Americas and east Asia. The apparent recurrence of this behavior in reversals during the last 12 m.y. has been interpreted as indicating that spatial variations in topography, composition or temperature at the core-mantle boundary may have a persistent effect on the configuration of the geomagnetic field as it reverses [Clement & Kent, 1991; Tric et al., 1991, Clement, 1991; Laj et al., 1991]. This interpretation is controversial because the spatial and temporal distribution of reversal sites is limited.

For any single reversal, other than the most recent Matuyama-Brunhes transition, there are hardly enough records to decipher any systematic structures; to date the solution has been to combine records from different field transitions and look for temporally invariant structure in the transitional field. The validity of this approach remains questionable because at some sites and times there are records of successive reversals that are essentially identical, while at others this is not the case. Nevertheless, when VGP paths for all the transitions during the last 12 m.y. are grouped together, there is a statistically significant predominance of VGPs over the Americas and East Asia [McFadden et al. 1993]. Valet et al. [1992] argue that significant groupings of VGPs occur ±90° from the dominant site longitudes; they suggest the observed clustering of transitional VGPs may be an artefact introduced by the remanence acquisition process. McFadden et al. [1993] also confirmed the statistical significance of the groupings 90° from the site longitude. However, Constable [1993] notes that the peak in VGP distribution over the Americas remains even when sites demonstrating the ±90° site effect are removed from the analysis; the problem with eliminating such sites is that as the number of records decrease any statistical analysis becomes less reliable.

The current dataset for the Matuyama-Brunhes (Figure 1) is inadequate to resolve the issue of whether the VGP groupings are controlled by the distribution of available sites or reflect genuine geomagnetic field behavior. For this reason a clear consensus has emerged in the paleomagnetic community that it is necessary to obtain transition records from a broad geographical range.

The deep sea sediment cores obtained by the Ocean Drilling Program provide the greatest potential source of additional transition records from a broad geographical range. The advanced hydraulic piston corer is the most powerful tool available for recovering sections thick enough to penetrate Pleistocene polarity reversals in high sedimentation rate sections. As a result, paleomagnetism has played an important role in the success of the Ocean Drilling Program by providing magnetostratigraphic frameworks for biostratigraphic and paleoceanographic studies. Furthermore, several of the transition records that are of critical importance to the present debate were obtained from sediments cored by the Deep Sea Drilling Project and the Ocean Drilling Program [Clement & Kent, 1985; Valet et al., 1989], and more studies are presently underway.

A coordinated effort to identify and sample the same polarity reversals recorded in existing ODP cores could potentially double the number of Pleistocene polarity transition records within two years. The new database will provide a much improved observational basis for models of polarity reversals. These new records will very probably decide the issue of whether the grouping of transitional VGPs is an artefact of a poor site distribution or whether it is real and provides important information about the interaction between the dynamo and the lowermost mantle.

In addition to the existing sediment core resources, additional sites are needed to improve the geographical distribution of paleomagnetic records of field behavior. Drilling at well suited sites, with holes dedicated to detailed paleomagnetic studies, in each of the major ocean basins would result in a radically improved basis for our understanding of geomagnetic secular variation, polarity reversals and long term field behavior.

II. GENERAL REVERSAL MODELS

Geomagnetic reversal models fall into two broad categories, those that attempt to use dynamo models to describe the physical process of reversal, and those that attempt a spatial and temporal description of the transitional field without regard for details of the dynamical processes in the core. The latter may be characterized as phenomenological or configuration models and their development has been fueled by the acquisition of an increasing number of reversal records over the past few decades. Many of these models involve a description of the geomagnetic field that includes a decaying axial dipole field, that grows back in the antipodal direction. Differences occur in how the second order field is viewed: early models tested whether reversal records were compatible with a dominantly dipole field for which all sites should show the same transitional VGP paths (Hillhouse and Cox, 1976), whether there is a standing or persistent stationary contribution to the transitional field or whether transitional fields were dominantly zonal (longitudinally invariant) in structure (Hoffman, 1977; Hoffman and Fuller, 1978, Williams and Fuller, 1981). As more records were collected it appeared that such simple explanations could not satisfy all the available data, and models became increasingly sophisticated, simulating continued secular-variation-like behavior during a reversal of the axial dipole (e.g. Williams et al., 1988; Weeks et al., 1988; Constable, 1990; Olson and Hagee, 1990). The hope has always been that such configuration models will resolve some characteristic features of the geomagnetic field during polarity transitions that can provide useful input to theoretical models of the geodynamo. The recent results outlined in the introduction deal with a larger collection of transition records than before and suggest that when there are sufficient observations available to look at the average statistics of transitional fields, simple recurring

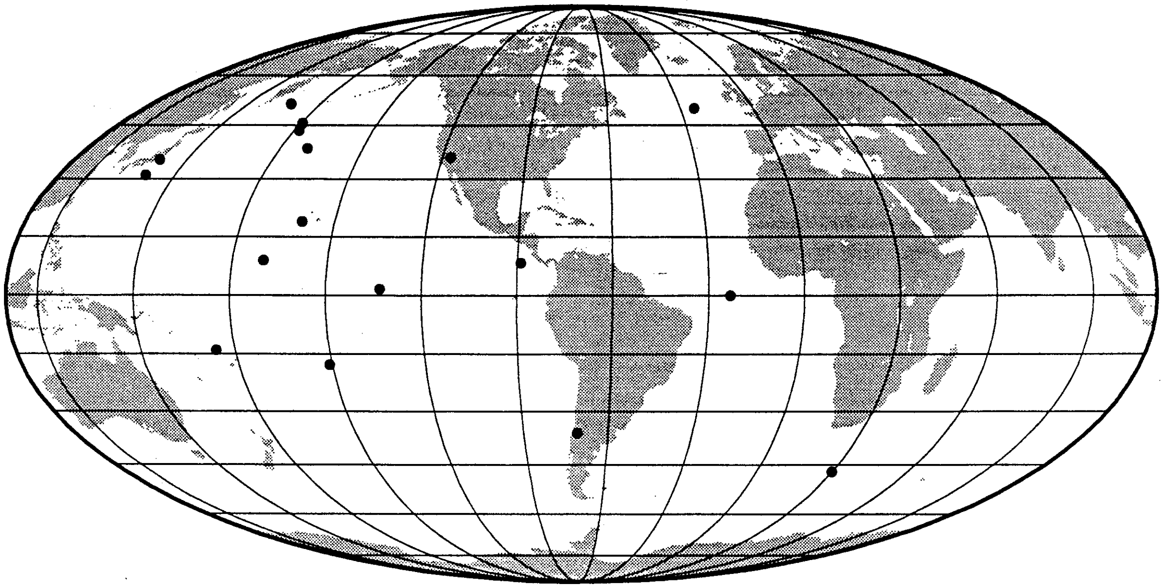

Figure 1. Locations of sites where paleomagnetic records of the Matuyama-Brunhes polarity transition have been obtained from both volcanic and sedimentary sequences. This plot includes records obtained from very low sedimentation rate cores; several of which may not be reliable records of field behavior. Additional records are needed to obtain reliable records with a good geographic coverage.

structures may indeed be characteristic of the geomagnetic field during reversal although other factors also affect the signal.

There is now a critical need to collect new data that will allow us to test better posed hypotheses about the origin of the clustering of transitional VGPs in longitudinal bands. Much debate has focussed on the fact that the sites are clustered about ±90° in longitude from the preferred bands; collecting transition records from longitudes in or close to the preferred bands would provide one means of assessing whether this is a rock magnetic or a geomagnetic signal. The lumping together of records from many different reversals provides a sufficient number of records for meaningful statistical tests to be performed, but these come at a price. The hypothesis tested is only the most general one, namely is there a clustering of VGPs in longitude. We cannot tell with the current combination of statistical tests and data whether the structure persists for long periods of time, or whether the same picture would emerge if we had global coverage for a single reversal.

There is a clear need to separate the temporal and spatial structures in the field. For example, with a series of 10 high quality sequential records of reversals from a single site we would be in a much better position to assess whether there are recurring preferred transition paths. Similarly, the current tests could be performed on the same number of records as we currently have, but for a globally distributed data set for a single reversal (the Matuyama-Brunhes is the logical choice since about half the available records come from it already). This would address two key questions. (1) Is there a consistent spatial structure for a single reversal? (2) Does that structure persist over time scales of several hundreds of thousands to millions of years?

In a parallel development to the configuration models theoreticians have been developing simulations of the geodynamo, which need input from the paleomagnetic community in order to be realistic physical representations of geomagnetic field behavior. The earliest models led to the appreciation of the importance of helicity and differential rotation in generating magnetic field (Braginsky, 1964; Roberts, 1972), but efforts were mainly concentrated on the easier solar dynamo. Parker (1955) and Levy (1972a) discussed the geodynamo in the context of an α effect, and subsequently Parker (1969) speculated further on the relationship between a changing fluid flow regime in the core and magnetic polarity reversals. These ideas were developed further by Levy (1972b). Braginsky (1975) developed a dynamical model of the dynamo, known as model-Z, and Fearn and Proctor (1984) developed a self-consistent model of the geodynamo with a balance between Lorentz and Coriolis forces. These pioneering attempts paved the way for more realistic models of the geodynamo that could be compared with observation, and we are now at a stage where numerical calculations can be guided by observation in addition to understanding fundamental aspects of the dynamics.

More recently, Zhang and Busse (1990) moved away from the simplified alpha-omega equations and investigated a full 3-dimensional dynamo driven by convection. Hollerbach and Jones (1993) found that the inner core played a crucial dynamical role in stabilizing the dynamo, and Glatzmaier and Roberts (1995) incorporated an inner core into the most ambitious nonlinear geodynamo calculation to date. Other work has attempted an even closer match with observations. Zhang and Gubbins (1993) explored the influence of lateral temperature variations in the lowermost mantle on non-magnetic convection, and Hutcheson and Gubbins (1994) found kinematic dynamos that generate magnetic fields with similar surface morphology to the present-day geomagnetic field. Gubbins and Sarson (1994) found a kinematic model with very similar field morphology, which reverses through a Parker (1969)-type mechanism and gives VGP paths along one of two critical longitudes, providing a possible model for the recently measured transition paths.

The stage is now set for the development of dynamo models capable of generating magnetic fields similar to that of the Earth with realistic dynamics. The subject will enter the stage, at last, when a full dialogue between theoreticians and experimenters is both appropriate and essential for further development of the subject. This work is rapidly converging on models capable of simulating realistic geomagnetic field behavior, including the nonlinear dynamics and, ultimately, reversal transition behavior. In order to test these models reliable polarity transition records will be required from a broad geographical distribution. Ideally, global coverage of multiple polarity reversal transitions is desired, however this is not practical in the near term. For this reason we have prioritized the observational requirements that will provide the most useful constraints on the models.

Global and Regional Coverage for a Single Reversal

Global coverage for a single reversal is the top priority. While equal area sampling of the entire earth would be ideal, it is not feasible. However, obtaining reliable records of the same reversal from each ocean basin would greatly improve the existing dataset and provide invaluable constraints on dynamo models. With a more widely dispersed global dataset it is important to obtain some more closely spaced records to examine the regional variability of the transitional field, and we therefore propose a combination of broadly spaced and clustered sites. Such a distribution of site locations would not only allow an examination of the different spatial scales of variability in the transitional field but would also provide an important assessment of the reliability of the paleomagnetic records. Records from sites separated by 500 - 2000 km should exhibit similar behavior unless the transitional fields were extraordinarily complex.

Temporal Evolution of Reversals

In addition to a spatial distribution of transition records, a temporal distribution is also required in order to understand the evolution of reversal behavior with time. A set of sequential reversals recorded at the same site would make it possible to examine the temporal variability in transitional field behavior without the uncertainties introduced by site dependent effects. A thorough examination of the Plio-Pleistocene reversals (last 5 m.y.) recorded at one site would allow such an assessment. This would require detailed sampling of the last 20 reversals.

Sampling Strategies

In order to provide the best constraints for reversal models, paleomagnetic transition records should span not only the directional change and associated intensity variation but also extend well into the full polarity intervals before and after the reversal. An ideal transition record should document a period at least three times that of the approximate diffusion time of the outer core (10 kyr). Thus a section recording 30 kyr centered over the reversal needs to be sampled in materials that provide a resolution of better than 500 years per sample.

Attempts to map or model the transitional field will require reliable measures of the magnetization vector, including the directions and intensities or relative intensities, and an independent measure of time on transitional time scales. Oxygen isotope or ^{10}Be records can provide valuable measures of the timing of local field changes and assist in the correlation between transition records from widely spaced sampling localities.

III. EXAMPLES OF NEW TRANSITION STUDIES FROM ODP CORES

The renewed interest in polarity transitions has led to an intensification of the effort to obtain new transition records from ODP cored sediments. Recent transition records from ODP cores have focused on high sedimentation rate sites which should provide more detailed information about the polarity reversal process. Results from a number of these studies were presented at the workshop.

From Leg 119 in the southern Indian Ocean, Keating used high density, repetitive sampling with 1 cc cubes to produce very detailed VGP transition records for the Matuyama-Brunhes and Jaramillo transitions. These records showed a longitudinal preference for the Americas in the Matuyama-Brunhes and Jaramillo-Matuyama transitions and antipodal (Asian) transition paths for the Matuyama-Jaramillo transition. The study was facilitated by the high remanence intensity of the samples and a setting on a basement high which resulted in an apparently continuous transition record.

From Leg 124, Oda demonstrated the value of deconvolution of continuous core pass-through measurements to obtain accurate VGP transition paths. After deconvolution, correlative M/B VGP paths with similar looping and cusps were seen for three holes from sites from the Sulu and Celebes Seas. These holes were characterized by high remanence intensity and sedimentation rate. The deconvolved long core VGP results were also similar to the VGP path obtained from discrete samples collected and measured from the same holes. The normalized intensities of these samples suggested a 4 kyr interval of low field strength centered about the VGP reversal.

From Leg 126 (northwest Pacific) and Leg 145 (northern Pacific) Cisowski showed Matuyama-Brunhes transitional paleointensity records which suggest that the field may oscillate widely in intensity, beginning a few thousand years before the directional reversal. The Leg 145 record (Hole 884C) also indicates a sharp rise in field strength immediately after the VGP transition from northern to southern hemispheres. This behavior contrasts with a broad intensity low, centered on the directional transition, which has been more commonly associated with reversal records. Both records also show broadly correlative excursions which occur only a few thousand years before the final polarity transition, which in these records is accomplished is less than 1 kyr. A comparison of these two records also indicates that significant gaps in transition records can be present in cores which show no visible signs of erosion or of a hiatus in deposition.

Matuyama-Brunhes transition data from two cores drilled from uniform high sedimentation rate lacustrine clays of Sevier Lake, Utah, as presented by Roberts and Cui, indicate that the polarity transition may have been recorded over slightly different intervals by different coercivity and unblocking temperature assemblages. This study shows that care must be taken to adequately separate the contributions of multiple remanence carriers or diagenetic alteration phases, through detailed AF and thermal demagnetization techniques. Also multiple cores of the same reversal are essential in evaluating the validity of transition records.

Verosub presented Jaramillo and Matuyama chron data from a non-ODP ocean core taken in the equatorial Pacific which supports Valet's assertion that the long term intensity of the geomagnetic field continuously decays after a reversal, but rebounds sharply immediately after the next reversal.

In summary, the above studies illustrate the importance of acquiring transition records from high sedimentation rate environments which exhibit strong remanence signals and relatively simple magnetic mineralogy. Island arc drilling environments generally will satisfy these criteria, and their sediments appear to be especially amenable to ^{10}Be analysis. In addition, the island arc environment offers the possibility of obtaining correlative transition sections from the associated onshore lava sequences.

IV. ASSESSING THE RELIABILITY OF POLARITY TRANSITION RECORDS

There are two approaches to assessing the reliability of polarity transition records; 1) consistency checks using multiple records from nearby locations, and 2) the assessment of rock magnetic characteristics of the sediment. Consistency checks will be discussed further in the next sections which deal with the global distribution of reversal records. Here we outline potential rock problems and ways of detecting them.

Several effects common to marine sediments can conspire in various ways to decrease the fidelity of a geomagnetic reversal record. These effects can be divided into two main categories: 1) changes in the magnetic mineralogy, and 2) inclination-shallowing in non-bioturbated sediments.

Changes in magnetic mineralogy

The ideal marine sediment (for a paleomagnetist) would contain a single type of magnetic mineral (for example, magnetite), with a very limited range of grain sizes. In real marine sediments this condition is not always realized due to processes that affect the input and preservation of magnetic minerals in sediments. The most important of these processes are magnetite dissolution and magnetic iron sulfide growth during reduction diagenesis, variable productivity of magnetotactic and dissimilatory iron-reducing bacteria, and variations in sediment lithology and sources.

In most marine sediments, pore fluid chemistry becomes reducing at depths ranging from a few cm below sea floor to several hundred meters below sea floor. In such sediments reactions which are of most importance to paleomagnetists are those resulting in the reduction of iron and sulfate, the products of which can form the magnetic iron sulfides greigite (Fe_3S_4) and pyrrhotite ($\sim Fe_7S_8$). In the presence of abundant organic carbon or H_2S these reactions commonly dissolve a large portion of the originally deposited magnetite in the sediments. Growth of magnetic sulfides and dissolution of magnetite will degrade the paleomagnetic signal of a reversal record by both reducing the intensity of the original (magnetite-carried) magnetization, and by the addition of a secondary remanence component carried by the sulfides.

Magnetotactic and iron-reducing dissimilatory bacteria can produce both fine-grained magnetite and greigite. The role of these organisms as remanence carriers in marine sediments is not entirely understood, but some studies have suggested that bacteria-produced magnetite can be the dominant remanence carrier in marine carbonates (e.g., Chang et al., 1987). Variations in magnetic mineral production by bacteria can have the same effect on remanence in marine sediments as reduction diagenesis.

Changes in sediment lithology and sources will not have a large effect on the direction of the remanence recorded by the sediment, but will have an effect on the intensity of the measured remanence. Obvious, macroscopic sediment variations can either be avoided, or else explicitly delineated in a reversal record. Small changes in the aeolian component of pelagic sediments (either dust or ash inputs) have been linked to variations in the amount and type of magnetic minerals in marine sediments, and so may affect both the demagnetization characteristics and the absolute intensity of magnetization recorded in the sediment. A more subtle change in measured remanence intensities can be caused by variations in porosity (which can range from >70% to < 30% in marine sediments). Samples are commonly measured using volume units, assuming a standard sample volume. When assumed volumes are used (or are not corrected for measured porosities), variations in porosity will produce variations in remanence intensity, and in volume susceptibility. In light of this, unless porosities are uniform throughout the sampled interval, mass units of magnetism should be used, and all samples should be weighed before measurement.

Inclination shallowing

Inclination shallowing due to compaction is common in non-bioturbated marine sediments. The degree of shallowing is a complex function of magnetic mineral size and shape, sediment composition (particularly clay mineral content), porosity, and burial depth. Variations in these factors in the sediments containing a polarity transition may produce anomalous changes in inclination, which will affect the distribution of VGPs calculated for a given transition In heavily bioturbated sediments inclination shallowing is nearly absent (see review by Tauxe, 1993).

Careful selection of sites can minimize the effects of magnetic mineral changes and inclination shallowing on reversal records. Ideally, a site will have relatively uniform lithology, be uniformly bioturbated, and lie above the sulfate reduction front in the sediments. Not all of these conditions will be realized at every site (or a site may be affected by some of the above-mentioned factors, but be included based on the importance of its location), so careful rock-magnetic tests should be performed on the sediments to monitor variations in magnetic mineralogy and compaction-induced anisotropy. Measurements from a standard set of rock-magnetic techniques should be made on sediments containing the polarity transition as well as on sediments containing the stable polarity interval immediately preceding and following the transition. Such measurements will serve to evaluate possible adverse effects of magnetic mineralogy changes, and as a basis to normalize measured remanence intensities for relative paleointensity studies of the transition records. Solid verification of uniform magnetic mineralogy in sediments containing a given polarity transition will greatly enhance the reliability of the measured natural remanence record of that transition.

Standard measurements such as anhysteretic remanent magnetization (ARM), saturation isothermal remanent magnetization (SIRM), and susceptibility (χ) are easy to obtain, but do not always provide accurate determinations of the identity and amount of remanence carriers in marine sediments. ARM, SIRM and χ alone cannot distinguish important changes in magnetic mineralogy (e.g. different combinations of fine-grained magnetite and greigite). Also, changes in χ can be due to variations in non- magnetic phases such as clay minerals or ultrafine grain (SP) magnetite or greigite. These standard techniques should therefore be supplemented by additional methods which can more accurately determine the quantity and types of remanence carriers. Sediments with variable (or no) bioturbation should be routinely measured for magnetic anisotropy in order to evaluate, and possibly correct for, inclination shallowing.

Several methods are available which utilize relatively common measurement apparatus, which should be combined with relatively new and more specialized methods developed using more specialized instruments.

Equipment to perform all of the rock-magnetic techniques listed in Table 1 is available at the Institute for Rock Magnetism, while most other paleomagnetic laboratories have the equipment needed to perform the most of the "common" techniques. In conjunction with the other laboratories participating in this project, a standard suite of rock-magnetic tests combining both "common" and "specialized" methods can be performed. This standard suite of tests should include (p)ARM, SIRM, Susceptibility, one (or more) thermal methods (mIRM), hysteresis measurements (including determination of Susceptibility), AMS or ARMA, and SIRM(T=20K). A few sites should be selected for more detailed studies, including FC/ZFC cryogenic SIRM heating. The rock-magnetic characterization studies can be accomplished by combinations of visits by outside researchers to the IRM, and work conducted by IRM personnel. The facilities at the IRM are free of charge, and limited travel support is available to visiting scientists without travel funds.

Common equipment methods

- *Thermal methods:*
  - Bulk sediment Curie temperature measurement
  - Thermal demagnetization of SIRM or multi-component IRM (mIRM)
  - AF methods:
    - partial ARM spectra
- *Susceptibility methods:*
  - frequency-dependence of χ
- *Hysteresis methods:*
  - hysteresis parameters (Js, Jrs, Hc, Hcr)
  - ferrimagnetic fraction of susceptibility: χ_f ($\chi_f = \chi_{total} - (\chi_{sp}+\chi_{para}+\chi_{dia})$)
- *Magnetic anisotropy* (to characterize compaction, inclination shallowing):
  - anisotropy of magnetic susceptibility (AMS)
  - ARM anisotropy (ARMA)

Specialized equipment methods

- *Cryogenic Susceptometer methods:*
  - SIRM (at T= 20°K) heating:
    - determines SP magnetite, greigite content, identifies magnetite and pyrrhotite (110°K and 33°K transitions)
  - SIRM (at T=20°K, field-cooled and zero-field-cooled) heating (Moskowitz et al., 1993): can identify chains of biogenic magnetite, and relative amounts of biogenic magnetite chains with non-biogenic magnetite and/or magnetic sulfides
- *Mossbauer absorption spectra methods:*
  - ^{57}Co absorption spectra is sensitive to ^{57}Fe content and valence.
  - Mossbauer can identify magnetite, greigite, maghemite, pyrrhotite
  - Mossbauer techniques may also be able to determine relative amounts of simple mixtures of iron oxides and sulfides

Table 1. Rock Magnetic Methods

V. EXISTING TRANSITION RECORDS FROM LAVAS

Fundamental problems still arise in the interpretation of transition records. The basic question is how much of the record reflects geomagnetic field behavior and how much is a result of artifacts introduced by the recording process. Because neither the geomagnetic signal nor the fidelity of magnetic recording is independently known, the answer to this question will require obtaining multiple records in the same geographic region of the same reversal from sediments with varying sedimentation rates and differing sedimentary environments, and comparing these with a record of the same reversal recorded in lavas. By comparing reversals recorded in different types of paleomagnetic recorders it will be possible to assess more directly the effects of the remanence acquisition process on the signal of geomagnetic field.

Many of the volcanic records have come from volcanic islands and active continental margins, so that it should be easy to target drilling sites near existing and potential volcanic transition localities. There are 5 or 6 principal locations around the globe where Neogene reversal records are presently available for comparison with marine sediment records. These are the Hawaiian Islands, the Society Islands, the southern Andes, the western U. S., the island of Reunion, and Iceland.

Hawaiian Islands

Hawaiian hotspot chain lavas record transitional directions from many of the Pleistocene and Pliocene reversals. The Matuyama-Brunhes transition is recorded in superposed flows from Haleakala caldera on Maui. The upper and lower Jaramillo magnetozones are also represented there, but only one or two transitional directions have been found. The upper Olduvai transition is recorded by lavas making up the north wall of Molokai [Hoffman, 1991]. Two Pliocene transition zones have been discovered on Oahu and are currently under investigation, probably the lower Mammoth and the Gilbert-Gauss reversal boundary. In those lavas, from Waianae volcano, three geomagnetic excursions (probably fragments of reversal records) were thoroughly studied 15 to 20 years ago. Finally, two older, successive transition records of Pliocene reversals (around 4.5 Ma) have been studied on Kauai [Bogue & Coe, 1982; Bogue & Coe, 1984]. All these records include substantial sections of pre- and post-transitional directions. The Molokai and Kauai records, and also the Oahu excursion records, include absolute paleointensity determinations.

The Society Islands

In similar fashion, Society Island lavas also record transitional directions of some Pleistocene and Pliocene reversals. Lavas from Tahiti record transitional directions belonging to the Matuyama-Brunhes, upper and lower Jaramillo, and the lower Cobb Mountain reversals [Chauvin et al., 1990]. The upper Jaramillo is the best record, and includes absolute paleointensity determinations and pre- and post-transitional directions. The island of Moorea records transitional directions of upper Olduvai age, which are currently under investigation. Huahine Island flows record many intermediate directions of the upper Kaena reversal [Roperch & Duncan, 1990].

Southern Andes

The Matuyama-Brunhes reversal, including pre- and post-transitional directions, is recorded in basaltic andesite lavas from an arc volcano that is the subject of an extensive study by an interdisciplinary group of volcanologists, geochemists, and petrologists [Brown et al., 1994]. The Andean and other magmatic arc sequences have been relatively little prospected for polarity transitions to date, and have great potential for future study.

Western U. S.

The type locality of the Cobb Mountain Subchron (1.12 Ma) consists of several basalt flows and a rhyolite flow with intermediate directions from central California [Mankinen et al., 1978]. The Miocene Steens Mountain reversal, probably the most complete transition record in lavas to date, is found in basaltic lavas from Oregon, though it may be too old (16 Ma) to be reached by APC coring in high sedimentation rate deposits [Mankinen et al., 1985]. In addition, several sections in the North Cascade magmatic arc are high-potential targets for transition records.

Reunion Island

Three sequences of lavas record intermediate field directions that define the Reunion chron. Currently investigation is underway to extend the record higher and lower and to obtain absolute paleointensity data [Hoffman, pers comm. 1994].

Iceland

Iceland has provided many transition records in Pliocene and Miocene lava flows over the past several decades. In East Iceland there are 21 extensive sections of basaltic lava of age between 2.5 and 13 Ma (Watkins and Walker, 1977), many of which record transitional directions of the paleofield. Several of them are currently the focus of detailed studies. There are three ODP sites off the west coast of Norway which have provided good magnetostratigraphic records.

Summary Recommendations for Targets for Sediment-Lava Record Comparisons

The Iceland region is a prime high-latitude target for deep APC coring. This would enable comparing sediment and lava records for a series of reversals at one site. The best high-latitude southern hemisphere target would be the eastern Pacific next to the southern Andes. The Hawaiian and Society Islands offer the best opportunities for comparing lava records of series of reversals with those carried by sediments deposited in tropical waters. Reunion Island is a potentially valuable Indian Ocean target.

VI. SAMPLING AND MEASUREMENT OF EXISTING CORES

Examining reversals in existing cores entails three processes: (1) identifying the cores suitable for study (see the next section), (2) defining an appropriate methodology, and (3) convincing ODP, in particular the Information Handling Panel and Planning Committee, to allow sampling in archive core halves. The first process is important because only a small number of existing cores are suitable for high-resolution transition studies and because the third process is unlikely to go forward without a well-defined subset of cores identified for study. The second process in vital because it will only be possible to do this study once, so it must be done properly.

Preliminary Screening

The first necessary step in reexamining existing DSDP and ODP cores is to find those core sections that contain reversals suitable for study. Screening will follow procedures that are designed to minimize the amount of work needed and the disturbance to archive cores and maximize useful paleomagnetic results. The following procedures, in order, are designed to progressively weed out unsuitable cores.

1. Suitable cores should have sediment accumulation rates of 3-4 cm/kyr or more, because lesser rates are unlikely to produce suitably high resolution because of severe smoothing of the geomagnetic signal.

2. Shipboard or shore based paleomagnetic data taken from these cores should be examined as a first indication of reliable magnetic recording properties.

3. If reconnaissance pass-through magnetometer core data, demagnetized to 15 mT, have not already been acquired, the archive halves should be measured in such a magnetometer, stepwise demagnetized, up to this level.

4. Suitable cores should not display any sedimentary disturbances that could compromise the reliability of the transition record.

5. For cores that pass the above tests, the working half should be sampled at approximately 10-20 cm intervals (avoiding the transition itself), for approximately 50 kyr above and below the transition. These specimens will be used for magnetic property studies to determine whether the sediments are reliable magnetic recorders.

6. Appropriate parameters to be measured from these reconnaissance samples are alternating and thermal demagnetization behavior, anhysteretic remanent magnetization acquisition and decay, isothermal remanent magnetization acquisition and decay, susceptibility, multi-component isothermal remanent magnetization decay.

7. Sedimentary records suitable for further study should have the following properties: The remanence should display stable behavior and the carrier should be magnetite or low-Ti titanomagnetite. The reversal should reverse through nearly 180°. The before and after paleoinclinations should be near to the expected geocentric axial dipole value. Additionally, susceptibility should not vary by more than approximately a factor of three, showing that there are not large changes in the abundance or type of magnetic grains.

Additional Work

Once core sections have been identified that are suitable for high- resolution transition studies, the working halves of those sections should be examined to see if the transition region has been disturbed by previous sampling. Presumably this will be known from step 5 in the above section. If possible, the working half of the core section should be sampled. It is anticipated, however, that most transitions will have been extensively disturbed.

If it is necessary to sample the archive half, the proposed study should first be approved by a committee including paleomagnetists. Such a committee would insure that the study is necessary and well-planned.

Assuming the study is approved, sampling of the archive half by using a 1-2 cm u-channel is preferred. The u-channel should be measured with a high resolution pass- through magnetometer, but not demagnetized above 15 mT. The u-channel sample should then be cut into thin subsamples for additional detailed measurements. Additional measurements should be directed towards isolating the primary remanence in each sample, for the directional study of the transition, and towards determining the type of magnetic carrier and its variation through the transition.

Rationale for Sampling Archive Core Halves

Sampling of archive halves will be necessary because it is critical to obtain multiple reliable records of transitional field vectors and these require pristine cores. Archive half sampling has precedence in DSDP and ODP history since organic geochemistry, interstitial water, and other whole-round samples have been routinely taken for many years. Sampling archive halves makes much sense, because it makes a large contribution to the science of transition studies at minimal cost to the drilling program.

Paleomagnetic properties are ephemeral and are degrading with time. Thus, if the transitions are not sampled, they may be lost. What is more, the number of suitable cores will be small and the measurements will be nondestructive. It is anticipated that alternating field demagnetization will be used on these samples and thus the samples can be returned to the archive halves. Additionally, suitable magnetic transitions will be in monotonous sediments, so these sediments are unlikely to be of great interest to other scientists.

VII. NEW DRILLING PROGRAMS

In spite of the important role paleomagnetism has played in the success of the ODP there has been a general reluctance to propose drilling plans based primarily on paleomagnetic objectives. There are two reasons for this. First, it has proven difficult using only shallow piston core data, to predict the quality of the magnetostratigraphic data from any given site, particularly at depth. Secondly, the primary drilling requirements for paleomagnetic study, mainly long continuous sequences of undisturbed sediment, are also those of the paleoceanographic community. Therefore paleomagnetists have been able to obtain reasonable sections by simply passively following along with the drilling plans proposed by the paleoceanographic community.

The polarity reversal controversy requires however that paleomagnetists take a more active role in directing the drilling plan. In particular to ensure that the ship drills in locations that will provide the most important polarity transition records, and to make sure that multiple holes are cored allowing the type of detailed sampling strategy required by the high resolution paleomagnetic studies.

Based on an initial examination of the magnetostratigraphic records obtained from DSDP and ODP APC holes it is clear that new sites will need to be drilled in order to approach a uniform distribution of sampling sites. Therefore future drilling sites need to be identified that have a high probability of providing detailed Pleistocene polarity transition records from a wide geographic distribution. The goal is to identify and rank a set of drill sites which will be the basis of drilling proposals to be submitted to ODP. The scientific merit of this problem is important enough to drive the location of the drill ship, and this project would allow the Ocean Drilling Program to make a major contribution to solving an important thematic problem. Careful selection of one site per ocean basin which would be multiple HPC'd with two or more dedicated holes for paleomagnetic and secular variation data could greatly advance our understanding of geomagnetic field behavior.

Improvements to the Drilling Process

In order for these new drilling efforts to succeed, measures must be taken to improve the drilling tools and methods so that the magnetization of the cores is affected as little as possible by the coring process. Previous measures, such as zinc-coating the drill string to reduce rust effects and placing and maintaining a functioning paleomagnetics laboratory onboard the *JOIDES Resolution*, greatly increased the amount of information extracted from the cores. For example during several legs (Legs 108, 114, 121, 138, 145...), the pass-through magnetometer provided real time magnetostratigraphic results which directly aided the drilling decision process. Whole core magnetic susceptibility data (now taken as a given result), is a very useful tool for between hole correlation, but would be impossible with the rust problem which plagued DSDP coring efforts.

Equipment

The present pass-through cryogenic magnetometer is outdated and has problems with low sensitivity. The paleomagnetic community feels it is time to replace the existing magnetometer with a newer, more sensitive, DC-squid pass through cryogenic magnetometer. This instrument can make more sensitive measurements, allowing more lithologies to be studied. Furthermore, it makes these measurements more rapidly, so that greater core throughput and more measurements are possible.

The paleomagnetic community desires to limit magnetic disturbance of sediments by reducing the magnetic field of the drill string. Log measurements suggest that the bottom-hole assembly is the main culprit, so it is desirable to obtain and use non-magnetic or less magnetic BHA's. This will also improve the reliability of magnetic orientation as the current single non-magnetic drill collar set up still causes a magnetic field at the location of the tensor tool.

Procedures

Oriented APC cores are highly desirable, so the paleomagnetic community feels that such cores should be routinely oriented and the orientation data should be published in the Initial Reports volumes and archived in the ODP data base. It is also desirable that the tensor tool not be run for long periods of time without retrieving the data, because this jeopardizes a large number of orientations in the case of malfunction. It is recommended that a single tensor tool deployment not exceed approximately 3 hours. There is a consensus that oriented cores from near the seafloor can be important, so the operations staff is encouraged to be flexible in allowing shallow cores to be oriented. Finally, the orientation data are useless if the sinker bar assembly is misoriented, so the system should be routinely checked, before and during orientation operations.

Other procedures that will help obtain and preserve transition data are as follows. Shipboard pass-through measurements are intended for reconnaissance work only, since there are problems with deconvolving directions. Thus, AF demagnetization of archive halves at sea should not exceed 20 mT. If sedimentary sequences are recovered by APC, having sedimentation rates greater than 5 cm/kyr, consideration should be given to taking a repeated core of the section for dedicated transition studies. Finally, some flexibility is needed in defining the dedicated transition core, because even in repeat cores of the same section, the best one for study may not be the second or third.

VIII. SUMMARY

Deep-sea sediment cores obtained by the ODP potentially hold the key to one of the most lively debates in geophysics - the behavior of the earth's magnetic field during polarity reversals. At this workshop we have laid out the criteria for sampling from the theoretical standpoint, we have catalogued the available transition records from both lavas and sediments, and we have outlined the methods and techniques to be employed in a coordinated effort to sample polarity transitions in existing ODP cores.

By coordinating a large-scale effort to study both the existing core material and to plan to acquire additional records the paleomagnetic community can directly address the issue of field behavior during polarity reversals. Although obtaining a broad geographical distribution of polarity transition records will make it possible to test directly the longitudinal confinement or preferred patches models, it is also very likely that the additional records will provide a radically improved observational basis for an entirely new model for geomagnetic reversals.

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A SYNTHESIS OF MAGNETOSTRATIGRAPHIC RESULTS FROM PLIOCENE-PLEISTOCENE SEDIMENTS CORED USING THE HYDRAULIC PISTON CORER.[1]

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INTRODUCTION

The hydraulic piston corer (HPC) and the advanced hydraulic piston corer (APC) recover thick sequences of mechanically undisturbed deep-sea sediment which are ideal for paleomagnetic study. Since the first use of the hydraulic piston corer on DSDP Leg 64, magnetostratigraphy has played an increasingly important role in many of the biostratigraphic and paleoceanographic objectives of both the DSDP and the ODP. In spite of this importance, however, it has proven difficult to predict the success of magnetostratigraphic studies at a given site, particularly at depth. In order to aid in planning new drilling programs it is important to try to understand where the high quality records have been obtained and what the important factors are that affect the quality of the records. This was our objective in reviewing the magnetostratigraphic results obtained from sediments cored using the hydraulic piston corer or advanced piston corer. We present here a summary evaluation of the distribution and qualitative ranking of the Plio-Pleistocene magnetostratigraphic results obtained to date from DSDP and ODP advanced piston cored sites.

We surveyed the Pliocene - Pleistocene magnetostratigraphic results published in the Initial Reports or Scientific results volumes DSDP Legs 64-96 and ODP Legs 100-133, the extent of the published records available to date. We also included results from ODP Legs 138 and 145 for which only the data presented in the site reports were available. This survey was limited to the Pliocene -Pleistocene sediments in part because we are primarily interested in examining high resolution, high fidelity records. High resolution paleomagnetic records have recently yielded exciting results regarding not only polarity transitions, but also secular variation, and paleointensity variations in the geomagnetic field. Also, the uncertainties in the biostratigraphical constraints that might affect the correlation of observed polarity zonations with the Geomagnetic Polarity Time Scale (GPTS) are minimal within the Pliocene-Pleistocene. In addition, magnetostratigraphic results from this time interval are more numerous, and from a greater geographical distribution than older records. Shipboard laboratory techniques and methods are generally standardized so that the differences in quality between records most likely originate in factors intrinsic to the sediment and the recording process and are not the result of different laboratory approaches.

The objective of this survey was to identify those sediments which are high fidelity records of polarity history. Therefore the following criteria were used to qualitatively rank the magnetostratigraphic records:

Category 1: These records exhibit clear antipodal, normal and reverse polarity records in which the directions are close to the expected GAD directions without excessive scatter. The polarity zones allow an unambiguous correlation with the Geomagnetic Polarity Time Scale. Examples of Category 1 records include Sites 580 in the northwest Pacific, 664 in the Norwegian Sea, and 767 from the southwestern Pacific (Figure 1) . The Category 1 sites are listed in Table 1.

Category 2: These records exhibit nearly antipodal, normal and reverse polarity directions, however the correlation with the GPTS is complicated by core recovery problems or coring disturbance. These sites would be worth drilling again to obtain a high fidelity magnetostratigraphic record. Category 2 sites are listed in Table 2.

Category 3: In Category 3 records, both polarities appear to have been recorded however unusually large amounts of scatter cause an ambiguous correlation with the GPTS. The category 3 sites are listed in Table 3. An example of such a record is shown in figure 2

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obtained from Site 722 on the Owen Ridge. Zones of opposite polarity can be defined however, short polarity chrons can not be identified and the correlation with the GPTS is difficult at best.

Category 4. In some cases the sediment exhibits a coherent and apparently stable remanent magnetization, however, the dispersion is too great to allow a polarity assignment. An example of such a record obtained from Site 721 on Owen Ridge is shown in Figure 3. The directional records from these sites can not be interpreted in terms of polarity. Category 4 sites are listed in Table 4.

Category 5: Category 5 records differ from Category 4 in that the magnetizations are at or below the instrumental noise level and therefore no interpretable magnetization exists.

FACTORS AFFECTING THE QUALITY OF MAGNETOSTRATIGRAPHIC RECORDS

Magnetostratigraphic records ranking 1, 2, and 3, were obtained from 77 out of more than 200 sites cored by DSDP and ODP using the APC. This is a significant underestimate of the success rate because no attempt has been made to account for coring at sites where recovery of Plio-Pleistocene pelagic sedimentation was not an objective. A significant number of sites were located to address tectonic or geochemical objectives, and it is clear that drilling into deformed sediments of accretionary prisms or in hydrothermal systems associated with midocean ridges will not recover the type of material suitable for polarity stratigraphy. The percentage of successful magnetostratigraphic results increases dramatically when only sites located in areas of pelagic deposition are considered.

Category 1 & 2 sites often exhibit remarkable records which clearly document the history of the polarity of the geomagnetic field. One of the most important advances made by DSDP and ODP is that very high sedimentation rate sections have been recovered using the APC, which provide high resolution records of polarity history. Three examples of such records are shown in figure 1. Note the high sedimentation rates in these sections; it is not uncommon to find a 50 m thick Brunhes chronozone. Such high resolution records, together with nearly continuous pass-through measurements, provide important insights into the global nature of short duration phenomena such as excursions. Although a number of excursions within the Brunhes have been documented in lavas and lake sediments, an examination of the high resolution polarity records obtained from DSDP and ODP indicate that these phenomena are not observed on a global scale in deep-sea sediments. Therefore while these features may provide important insights into the workings of the geomagnetic field, they are not effective tools for correlation in deep-sea sediments.

Much can also be learned from examining the sites where quality records were not obtained. It is useful to consider the factors that affect these records separately as extrinsic and intrinsic factors. The extrinsic factors are those which do not originate in the inherent properties of the sediments, but are usually problems originating from the drilling process. Examples of these problems include poor core recovery, core orientation and remagnetizations resulting from exposure to strong magnetic fields encountered in core barrels and the bottom hole assembly (BHA). These extrinsic factors are particularly important to take note of because these are problems that can be remedied for future drilling. Intrinsic factors originate in the inherent properties of the sediments themselves and by separating these types of factors we stand to increase greatly our understanding of sediment magnetization.

Extrinsic Factors

Problems with core recovery that produce both obvious and more subtle gaps in the stratigraphic record, can be effectively reduced using real time, shipboard core-to-core correlations and by coring multiple holes at a site. Difficulties with core orientation have had serious effects on several legs which drilled in equatorial regions. As discussed previously in this workshop report, many of the problems with core orientation result directly from drilling operation procedures. The shipboard paleomagnetist and co-chief scientists must recognize the need to closely monitor the core orientation process.

A more difficult problem is the common occurrence of core barrel remagnetization. It has been clearly demonstrated that some of the core barrels have strong internal magnetic fields which in some sediment lithologies are capable of overprinting the original remanent magnetization. In many cases this overprint makes it impossible to retrieve any useful magnetic polarity information from the sediments. The overprint often is identified as a pervasive, radial magnetization, in which the declination is always directed from the center of the core outward usually with some additional vertical component. This type of magnetization is most readily observed, and is most detrimental to the paleomagnetic record, at equatorial or low latitude sites (Schneider and Kent, 1990), however it has also been detected at higher latitudes (Hailwood and Clement, 1991). The remagnetization evidently caused the failure to obtain a magnetostratigraphic record from the Ceara Rise, a leg where a magnetostratigraphic time framework was an important scientific objective. This type of remagnetization is most likely to affect sediments which exhibit a large, low coercivity component with a relatively weak but stable characteristic remanent magnetization. Because of the large, soft component, a magnetization acquired by exposure to a locally strong magnetic field may completely swamp the characteristic remanence. Attempts to demagnetize the core barrel have been attempted but with only moderate success (Schneider and Kent, 1990). Using non-magnetic core barrels, possibly made out of stainless steel may be the only way to ensure useful paleomagnetic results from the many sediments capable of providing useful records which are now remagnetized during the drilling process.

Intrinsic Factors

Dissolution of Magnetic Oxides

A common intrinsic factor that acts to degrade the paleomagnetic signal is the dissolution of magnetic oxides during reduction diagenesis. Early experience in magnetostratigraphy of carbonate rich deep-sea sediments showed a correlation with the disappearance of a measurable paleomagnetic signal with the first downhole appearance of authigenic pyrite in the sediments. Later workers identified and quantified the processes at work in the reduction of the iron oxides that carry the stable magnetic remanence (Canfield & Berner, 1987; Karlin et al., 1987; Musgrave et al., 1993; Tarduno, 1994). Musgrave et al, [1993] and Tarduno [1994] demonstrated that the depth below the sea floor at which the remanence intensity decreased was related to the amount of organic matter delivered to the sea floor which is at function of water depth in this region.

In many cases it appears that the reduction diagenesis has completely erased the paleomagnetic signal, and therefore sites with an originally high input of organic matter are poor targets for paleomagnetic study. However there are a few cases where the intensity is observed to increase again, below the zone of reduction diagenesis and a polarity record is obtained which appears to be original. This may indicate that the supply of organic matter to the site varied with time, meaning that the reduction diagenesis has proceeded to different extents in different portions of the section. It also may mean that other factors, such as overall sediment lithology had a role in affecting the reduction diagenesis. For example in the North Atlantic Ocean, as documented in the DSDP Leg 94 sites, the Pliocene sediments are carbonate rich and commonly exhibit very low intensities and the presence of pyrite indicates that these sediments have undergone reduction diagenesis. However, a stable polarity zonation is observed below this interval, suggesting that these older sediments did not experience the reduction diagenesis to the same extent as the younger sediments [Clement & Robinson, 1985]

DISTRIBUTION OF SITES

In order to examine further the factors that affect the quality of the magnetostratigraphic records we plotted the site locations of the ranked magnetostratigraphic records. The distribution of category 1-4 sites is shown in figure 4. This distribution represents the APC sites that exhibit measurable magnetization. More insight into what affects the distribution of useful magnetostratigraphic records may be obtained by examining the distribution of category 1-3 sites; those that yield interpretable polarity results. This distribution is plotted in figure 5. And finally the distribution of the best quality records (category 1 and 2) are shown in figure 6.

The number of category 1 and 2 sites is relatively small and does not provide a large enough number of sites to base an analysis of the distribution on. For this reason we included the distribution of the piston core results from the Lamont-Doherty Earth Observatory collection. These results from these piston cores meet our criteria for category 1 records although they are limited to lower sedimentation rate sediments (in order for reversals to be observed in a conventional piston core length). The combined distribution of category 1 & 2 APC sites together with the Lamont piston core localities is plotted in Figure 7.

Plotting these distributions makes it possible to evaluate better the two major working hypotheses of the source of the magnetic carrier in deep sea sediments. The first of these is that the magnetic carrier is lithogenic, small grains of magnetite transported from terrigenous sources to the deep sea. The second of these is that the magnetic material is biogenic, produced in place by magnetotactic bacteria or other organisms that yield magnetite. Fossil magnetosomes have been found in deep sea sediments and they provide an explanation for the source of magnetically stable magnetite.

The distribution of the high quality magnetostratigraphic results are plotted on a map of deep-sea sediment lithology for comparison of the paleomagnetic data and the sediment composition (Figure 8). The observed distribution of category 1 & 2 records can be broken down into two types of regions. The first are regions of high terrigenous input. This includes the high latitudes, particularly in the Pacific and the North Atlantic, and to a lesser degree the Southern Ocean, where there is an abundant supply of terrigenous material delivered to the sites primarily as ice rafted debris. Likewise, the Indian Ocean which receives a tremendous supply of terrigenous material from the Himalayan Mountains, and the Equatorial Atlantic which receives abundant aeolian input from Africa. The observed concentration of category 1-2 records in these areas tends to confirm the interpretation that detrital material is critically important to the paleomagnetic recording process.

The one region that runs counter to this interpretation is the Equatorial Pacific. This region receives very little input of terrigenous material, and yet a number of important magnetostratigraphic records have been obtained from this region. The alternative interpretation is that biogenic material is an important contributor to the paleomagnetic record, and if so, it will tend to be more important in areas where there is enough organic matter delivered to the sea floor in order to support the magnetotactic bacteria which generate the biogenic magnetic material.

To examine this idea further we plotted the distribution of category 1-2 sites and the Lamont piston core sites on a global map of photosynthesis in the modern ocean (Figure 9). The photosynthesis map shows the distribution of productivity in the modern ocean and provides a first order indication of where we would expect increased amounts of organic matter being delivered to the sea floor. An excellent agreement is observed indicating that some, but not too much, organic matter is required to produce a high quality magnetostratigraphic record. This would be expected if the bottom dwelling organisms that produce biogenic magnetite require a supply of organic material to survive. Another possible factor in this is that the amount of silica may be an important factor in affecting the quality. Silica content may affect reduction diagenesis leading to less dissolution of the magnetic oxides and greater preservation of the paleomagnetic record. Sediments accumulating beneath regions of high biological productivity have greater concentrations of silica, hence the possible correlation.

This distribution may be somewhat biased as most of these sites were cored for paleoceanographic objectives, and therefore sites were not drilled into regions, such as the red clay zones in the Pacific, where it is clear that no reasonable fossil record will be obtained. On the other hand, useful magnetic records have been obtained at least from the upper intervals of cores taken in red clay sediment, indicating that terrigenous input is more important than biogenic magnetite. Therefore it is probably not to wise to draw firm conclusions from these distributions, because the sampling distribution is uneven. However based on the comparisons of the distribution of quality records with surface sediment lithology and the surface productivity maps, a reasonable correlation between the distribution of high quality magnetostratigraphic records and surface biological productivity is observed.

SUMMARY AND RECOMMENDATIONS

The distribution of magnetostratigraphic records obtained by piston coring deep sea sediments provides intriguing hints as to the variables that are important in affecting the quality of the polarity record. Further insights, however, will need to be gained from studies at individual sites with attention given to the possible factors outlined here. In order to move towards a more quantitative assessment of these factors it is important that future workers report not just the down hole variations in magnetization directions, intensities, and rock magnetic properties, but also to report the means of these values along with the observed dispersion about the means. In sections where the magnetic properties vary considerably, sorting these variations into lithologic or rock magnetic units which exhibit internally consistent properties, will provide a more clear picture of the variations. Summarizing the data in these ways, although not always of direct relevance to the specific individual leg objectives, will make direct comparisons of results from other sites and other regions much more straightforward.

It is also important that steps be taken to reduce the effects of the extrinsic factors discussed here. This will not only improve the quality of magnetostratigraphic data but it will also make the underlying intrinsic factors affecting the recording fidelity of sediments more clearly evident.

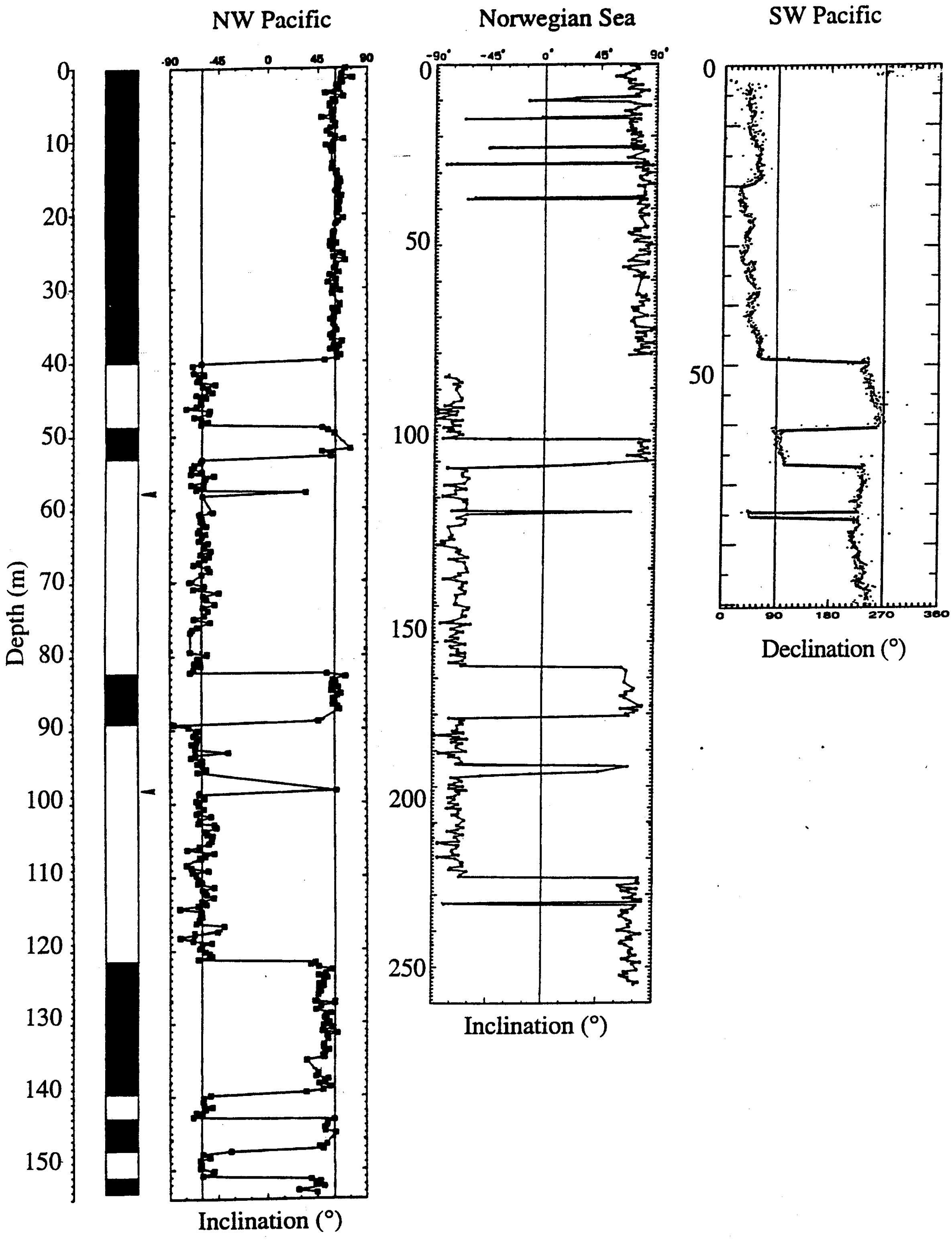

Figure 1. Examples of Category 1 magnetostratigraphic records obtained from DSDP Site 580 in the NW Pacific, ODP Site 644 in the Norwegian Sea and ODP Site 767 from the SW Pacific.

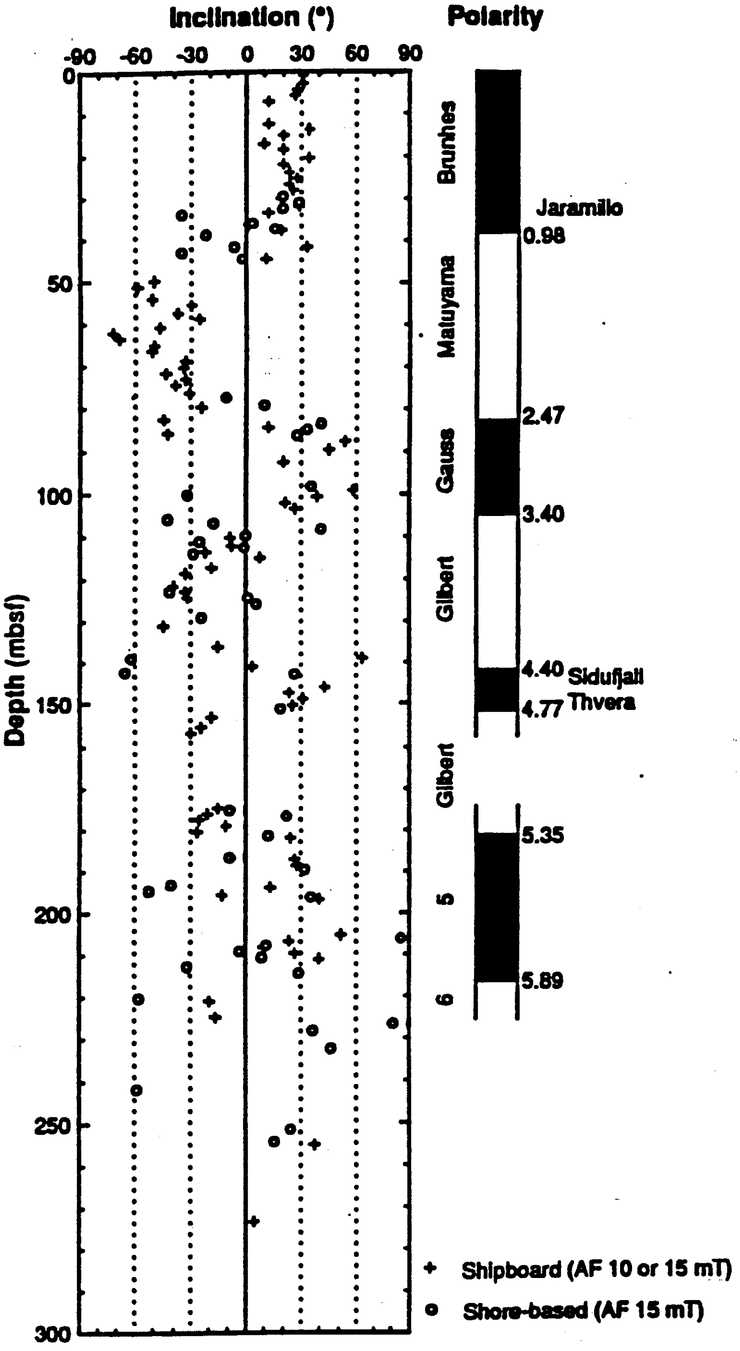

Figure 2. An example of a Category 3 record obtained from Site 722 located on the Owen Ridge. In spite of considerable scatter evident in the magnetization directions, the directions can be interpreted in terms of polarity and correlated with the time scale.

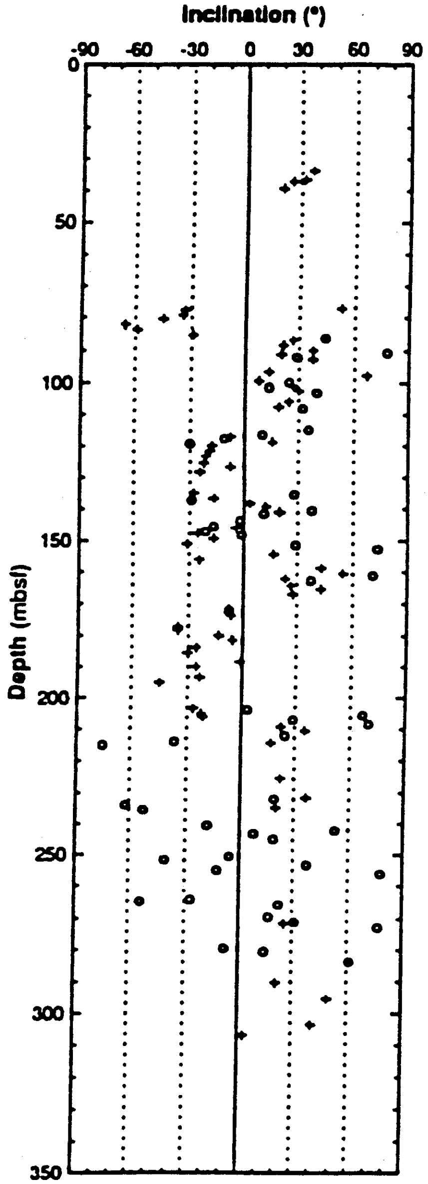

Figure 3. An example of a Category 4 record obtained from Site 721 located on the Owen Ridge. These sediments exhibit measurable magnetizations, but no polarity interpretation may be made given the extreme amount of scatter in the data.

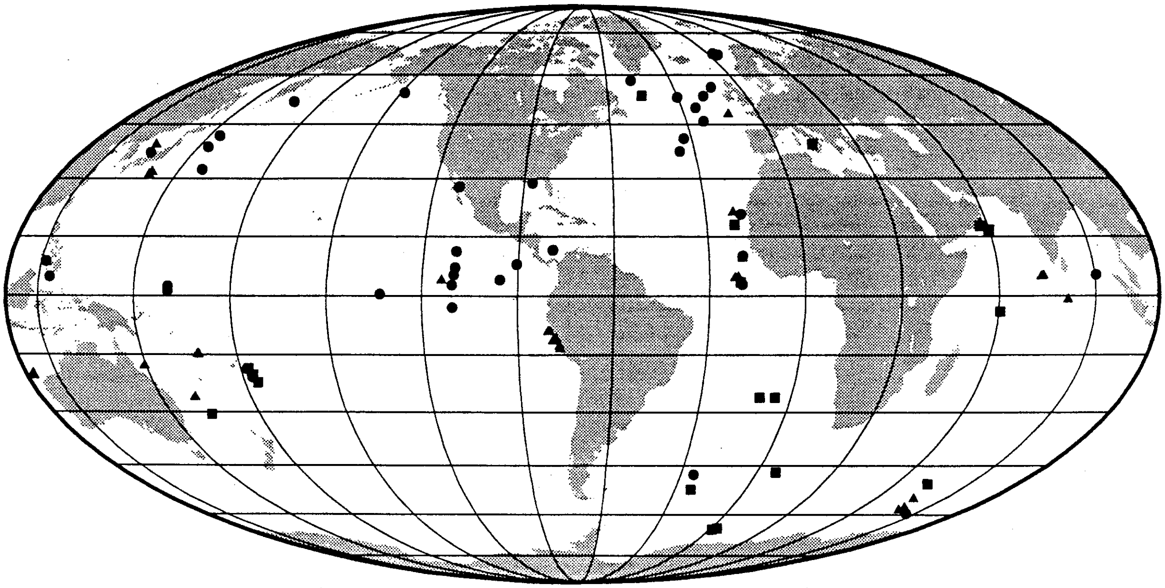

Figure 4. The distribution of DSDP and ODP APC Sites yielding Category 1 - 4 records. Category 1 and 2 sites are represented by circles. Category 3 sites are represented by squares and Category 4 sites are represented by triangles.

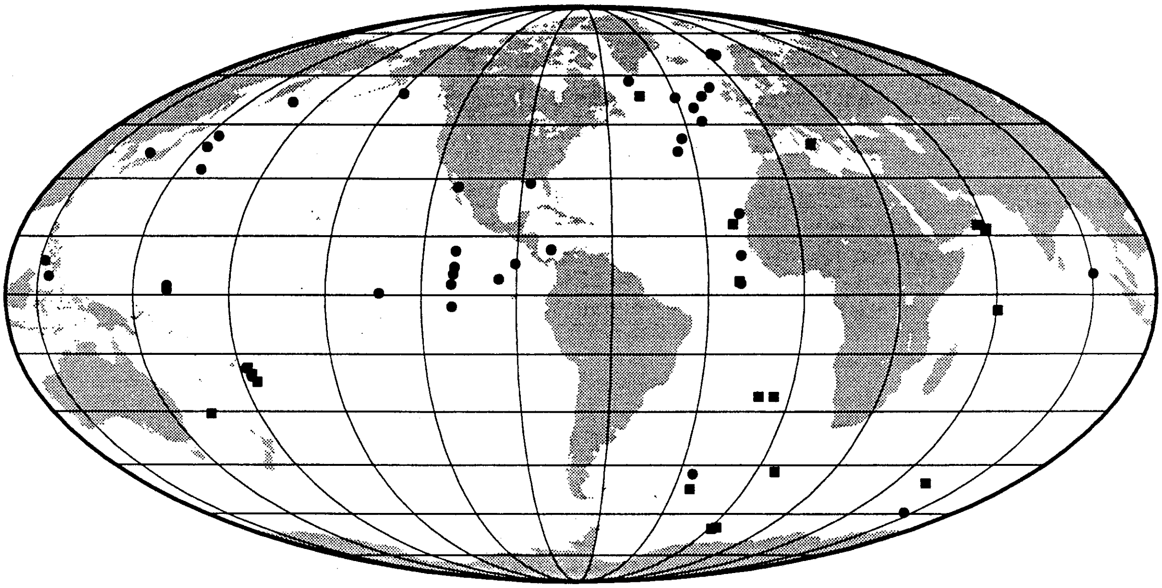

Figure 5. The distribution of DSDP and ODP APC sites yielding Category 1 -3 sites: those sites which provide interpretable Pliocene-Pleistocene polarity records. Category 1 and 2 sites are represented by circles, and Category 3 sites are represented by squares.

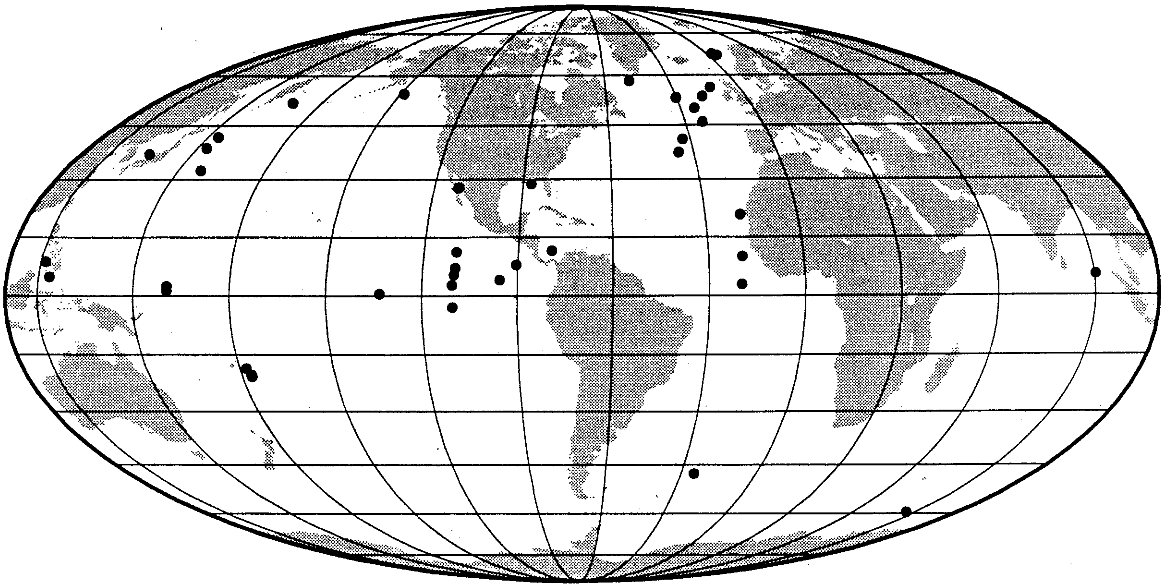

Figure 6. The distribution of DSDP and ODP APC sites yielding Category 1 -2 sites: those sites with straightforward polarity records.

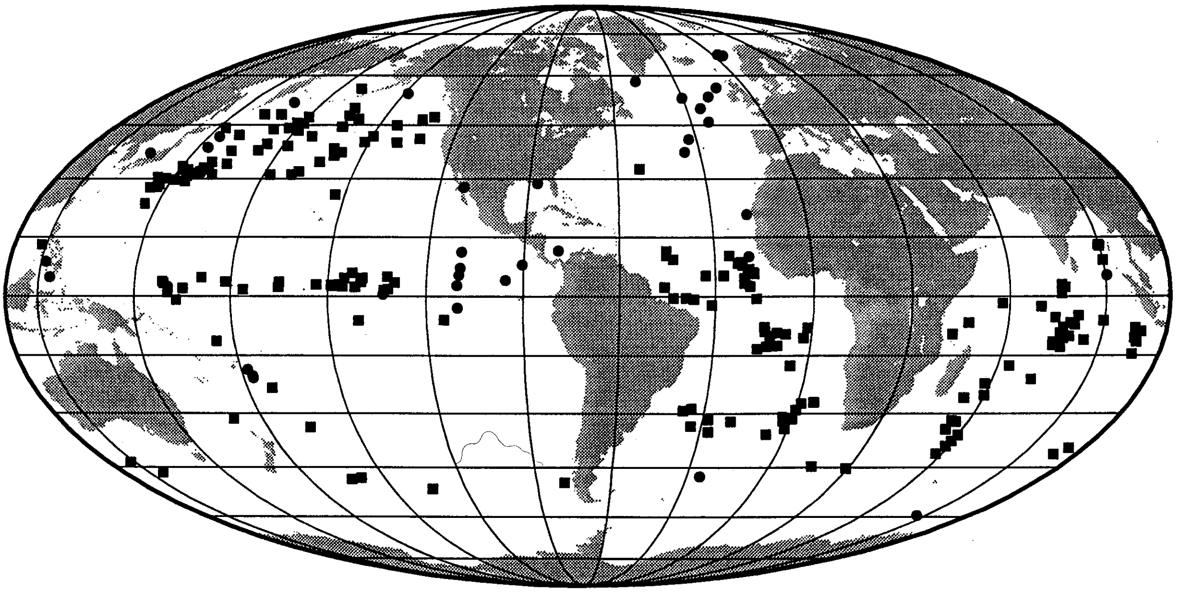

Figure 7. The distribution of DSDP and ODP APC sites yielding Category 1 -2 sites (circles) and the locations of piston cores from the Lamont-Doherty Earth Observatory collection which produced category 1 records (squares).

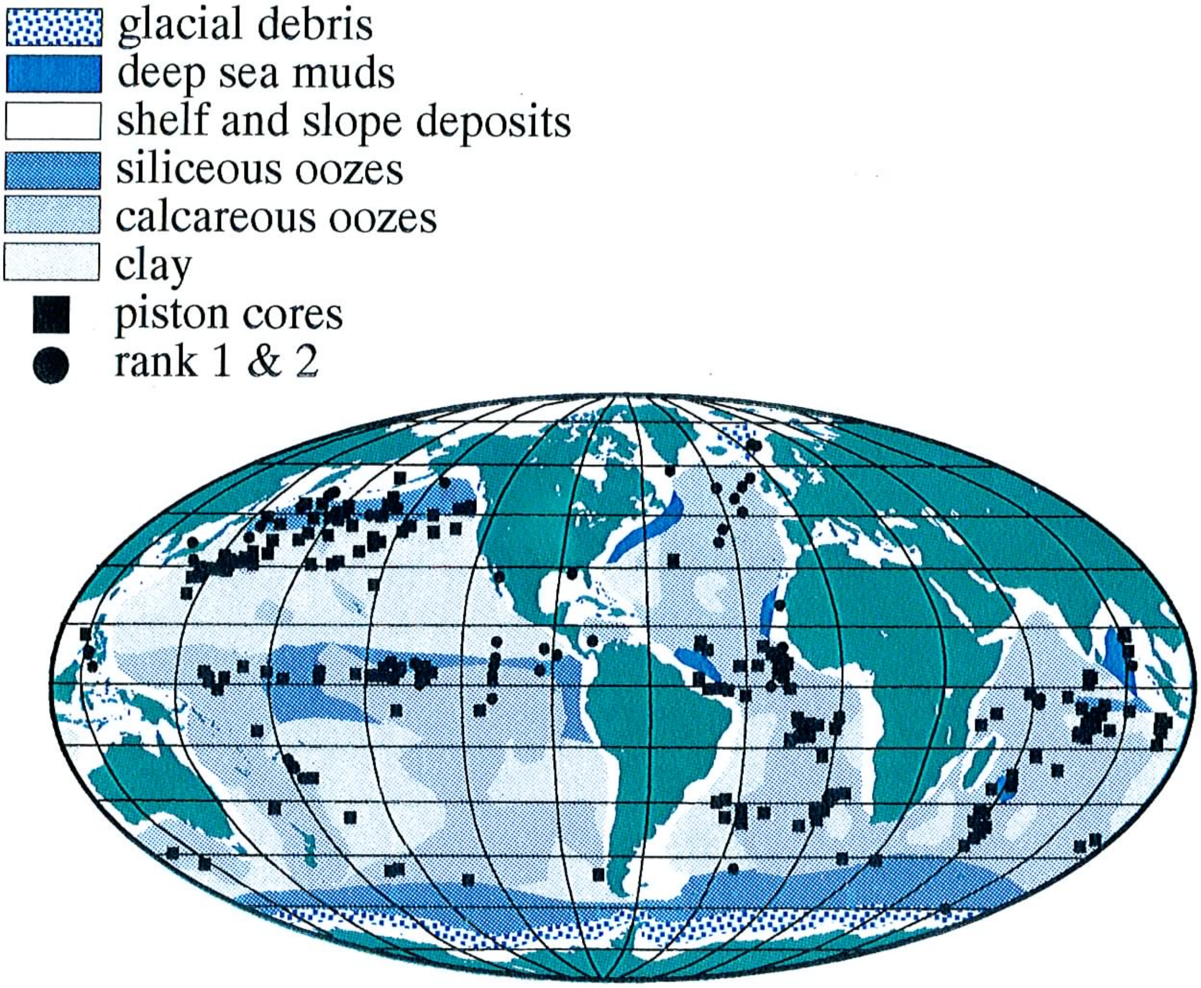

Figure 8. The distribution of DSDP and ODP APC sites yielding Category 1 -2 sites (circles) and the locations of piston cores from the Lamont-Doherty Earth Observatory collection which produced category 1 records (squares) plotted on a map of surface sediment lithology (modified after Berger, 1974). A good correlation exists between the location of good quality magnetostratigraphic records and sediments rich in terrigenous input.

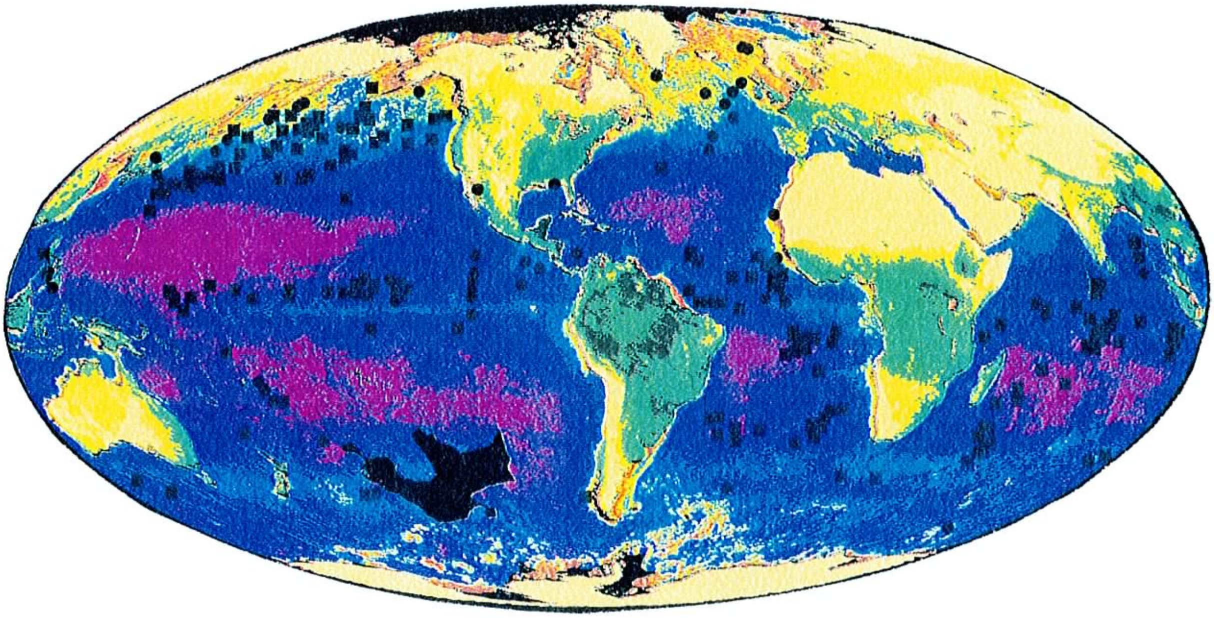

Figure 9. The distribution of Category 1 -2 sites and piston cores plotted on a map of photosynthetic production in the modern ocean (courtesy of NASA/GSFC). The photosynthetic production (violet (low) to orange (high)) provides a rough proxy for the distribution of the supply of organic matter to the sea floor.

Table 1.
DSDP and ODP Sites Yielding Category 1 & 2 Magnetostratigraphic Results

Sites	Leg	Lat(°)	Long(°)
480	64	27.9000	-111.6500
502	68	11.4903	-79.3797
503	68	4.0507	-95.6353
513	71	-47.5832	-34.6400
552	81	56.0000	-13.0000
573	0	0.5000	-133.3000
574	85	4.1300	-133.3100
575	85	5.9000	-135.0200
577	86	32.4418	157.8067
579	86	38.5780	153.5087
580	86	41.6245	153.9730
606	94	37.3300	-35.5000
607	94	41.0000	-32.9000
608	94	45.8368	-23.0875
609	94	49.8600	-24.2300
610	94	53.2100	-18.8000
611	94	52.8412	-30.2597
625	100	28.8317	-87.1660
642	104	67.2220	2.9293
644	104	66.6783	4.5767
646	105	58.2093	-48.3691
658	108	20.7492	-18.5808
660	108	10.0135	-19.2456
664	108	0.1073	-23.2275
665	108	2.9512	-19.6678
710	115	-4.3117	60.9800
711	115	-2.7427	61.1630
745	119	-59.5948	85.8542
758	121	5.3841	90.3612
767	124	4.7914	123.5033
768	124	8.0000	121.2198
769	124	8.7854	121.2945
792	126	32.3993	140.3801
798	128	37.0384	134.7997
803	130	2.4330	160.5403
805	130	1.2281	160.5285
834	135	-18.5678	-177.8620
837	135	-20.2220	-176.8230
838	135	-20.8270	-176.8900
839	135	-20.7090	-176.7750
841	135	-23.3455	-175.2980
844	138	7.9213	-90.4808
845	138	9.5823	-94.5900
848	138	-2.9941	-110.4800
850	138	1.2972	-110.5210
851	138	2.7702	-110.5720
852	138	5.2927	-110.0760
853	138	7.2109	-109.7510
854	138	11.2238	-109.5940
881	145	47.1023	161.4916
882	145	50.3633	167.5998
883	145	51.1985	167.7686
884	145	51.4505	168.3369
885	145	44.6883	-168.2720
886	145	44.6897	-168.2400
887	145	54.3655	-148.4460

Table 2.
DSDP and ODP Sites Yielding Category 3 Magnetostratigraphic Results

Sites	Leg	Lat(°)	Long(°)
521	73	-26.0738	-10.2645
522	73	-26.1140	-5.1297
589	90	-30.7120	163.5000
647	105	53.3313	-45.2620
650	107	39.3567	13.9008
659	108	18.0772	-21.0262
666	108	3.4973	-20.1672
689	113	-64.5168	3.1002
690	113	-65.1605	1.2049
701	114	-51.9847	-23.2121
704	114	-46.8796	7.4207
709	115	-3.9150	60.5517
721	117	16.6778	59.8645
722	117	16.6218	59.7953
727	117	17.7680	57.5886
728	117	17.6802	57.8257
731	117	16.4705	59.7025
737	119	-50.2278	73.0324
835	135	-18.5010	-177.3030
836	135	-20.1420	-176.5000
840	135	-22.2207	-175.7490

Table 3.
DSDP and ODP Sites Yielding Category 4 Magnetostratigraphic Results

Sites	Leg	Lat(°)	Long(°)
548	80	48.0000	-12.0000
571	85	3.9900	-114.0500
588	90	-26.1117	161.2277
657	108	21.3315	-20.9488
661	108	9.4468	-19.3861
667	108	4.5692	-21.9113
668	108	4.7687	-20.9270
679	112	-11.0625	-78.2709
680	112	-11.0650	-78.0778
681	112	-10.9767	-77.9577
682	112	-11.2665	-79.0622
683	112	-9.0274	-80.4055
684	112	-8.9921	-79.9058
685	112	-9.1130	-80.5835
686	112	-13.4802	-76.8915
687	112	-12.8630	-76.9905
688	112	-11.5378	-78.9429
714	115	5.0600	73.7867
716	115	4.9333	73.2833
717	116	-0.9298	81.3901
723	117	18.0518	57.6083
724	117	18.4625	57.7865
725	117	18.4873	57.7006
726	117	17.8161	57.3715
730	117	17.7314	57.6920
747	120	-54.8110	76.7940
748	120	-58.4408	78.9981
751	120	-57.7260	79.8148
762	122	-19.8872	112.2541
763	122	-20.5867	112.2085
782	125	30.8605	141.3141
786	125	31.8746	141.2263
793	126	31.1058	140.8881
799	128	39.2203	133.8667
812	133	-17.8140	149.6050
813	133	-17.8330	149.4950
814	133	-17.8330	149.5140
832	134	-14.7960	167.5730
833	134	-14.8761	167.8800

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Appendix I

Workshop Agenda

Monday, Nov. 7, 1994

9:00	Introductory Remarks
9:15	Dyanmo Theory
9:45	Reversal Statistics
10:15	Coffee Break
10:30	Existing Plio-Pleistocene Polarity Transitions
10:45	Reversal Atlas
11:00	Current Transition Studies
12:00	Lunch, FIU Faculty Club
1:30	Current Transition Studies
2:30	Transition records from Volcanics
3:00	Break
3:15	Working Groups
5:00	Refreshments
7:00	Dinner

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9:00	Reliability of Transition Records
10:00	ODP Drilling Procedures
10:30	Break
10:45	Discussion of a new shipboard Magnetometer
11:30	Synthesis of HPC & APC magnetostratigraphic records
12:00	Lunch, FIU Faculty Club
1:30	Working Groups
3:00	Break
3:30	Summary Presentations by working group chairs
5:00	Discussion and Wrap-up

Appendix II.

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Appendix III

December 5, 1994

Dr. Joris Gieskes
Chair, Shipboard Measurements Panel
Scripps Institute of Oceanography
University of California, San Diego
La Jolla, CA 92093-0215

Dear Dr. Gieskes:

The participants of the JOI/USSAC Geomagnetic Polarity Reversal Workshop (held in Miami November 7-8, 1994) advocate the installation of a new pass-through cryogenic magnetometer on board the *JOIDES Resolution*. The existing 2G Enterprises cryogenic magnetometer was installed in 1985. Since that time, 2G Enterprises has built 7 long-core pass-through magnetometers and 42 discrete sample rock magnetometers, and much has been learned about optimal cryogenic magnetometer design.

Notable among the technological advances is the recent advent of DC (as opposed to AC) SQUID sensors. The achievable noise level of the DC squid magnetometers is about $3*10^{-9}$ emu in contrast to about 10^{-7} emu for systems using the standard AC squids. The cryogenic magnetometer on board the JOIDES Resolution is particularly noisy due to its hostile environment, inadequate magnetic shielding and RF interference. The DC squids are less prone to shipboard RF interference, and the new magnetometer would have improved (superconducting) magnetic shielding. These features further improve the sensitivity of the new system, and would allow the magnetization of a wider range of weakly magnetized sediments to be measured with precision.

In addition to the advent of DC squids, improved dewar insulation in the new magnetometers reduces liquid helium boil-off. For the new shipboard magnetometer, liquid helium refill would be necessary every 3.5 years, as opposed to the present 10 month refill interval. This will result in substantial savings, reducing the refill frequency and the necessity for refills at remote ports. The present shipboard cryogenic magnetometer cannot be used to measure the remanence of weakly magnetized (<1 mA/m) discrete samples. The shipboard (Molspin) fluxgate magnetometer can only be used for relatively strongly magnetized sediments and is extremely slow. The new cryogenic magnetometer would measure discrete samples quickly and with high precision.

The processing of sediment cores using the present shipboard magnetometer is very often too slow to keep up with core flow, especially for legs with high rates of sediment retrieval. The tracking speed on the new magnetometer would allow the core measurement process to keep up with core retrieval. The in-line core demagnetization capability will be greatly improved with the new system, from 30 mT maximum peak field to 70 mT. This will be important for sediments with high coercivity magnetic overprints. Such overprints are common and may often be attributed to the drilling process.

The on-board magnetometer software has been progressively improved over the last ten years, mainly through the efforts of shipboard scientists. It has never been optimal however, and needs to be completely rewritten, preferably in conjunction with the installation of a new magnetometer. We advocate that the existing shipboard magnetometer be placed at College Station preferably in a magnetically shielded room. In this optimal environment, the instrument's performance would be greatly enhanced compared to its shipboard performance. At College Station, it could be used for analysis of archived cores, and for detailed post-cruise studies.

According to 2G Enterprises, a new DC SQUID magnetometer could be delivered in 12 months and could be installed during a 5 day port call. All participants in the Geomagnetic Polarity Reversal Workshop strongly advocate this purchase. We believe that it would substantially improve the data quality of shipboard magnetostratigraphies, and would improve the rate at which sediment cores could be processed in the shipboard paleomagnetic laboratory.

Sincerely,

Dr. Bradford M. Clement
Convener, Geomagnetic Polarity Reversal Workshop

cc.
Rob Kidd, PCOM Chair
Tim Francis, ODP
Audrey Meyer, USSAC Chair