9-1987

Problems and Current Trends in Rock Magnetism and Paleomagnetism

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Report of the Asilomar Workshop of the Geomagnetism and Paleomagnetism Section of the American Geophysical Union

September 1986

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This report was written by members of the Asilomar Workshop of the Geomagnetism and Paleomagnetism Section of the American Geophysical Union held at Asilomar Beach, California, September 16-19, 1986.

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Foreword

This report presents the major conclusions of a workshop on rock magnetism partially supported by NSF and held at the Asilomar Conference Center, Monterey, California from 16 to 19 September, 1986. Chief organizer of the workshop was Subir Banerjee who invited 28 scientists representing various subdisciplines in rock magnetism to attend. The purpose of the workshop was to review the present status and future prospects for rock magnetic research, identify important problem areas in geomagnetism and paleomagnetism which could benefit from an increased cooperative research effort in rock magnetic theory and experiments, and to outline an approach for solving these problems in the next 5 to 10 years.

The following report presents the workshop participants'assessment of the problems and current trends in rock magnetism and our recommendations for promotion of this geophysical discipline.

Rock magnetism is a vital geophysical research topic which has contributed significantly to a wide variety of earth science disciplines and which is on the verge of additional important discoveries in global geology and geophysics. Prospects for future contributions are very bright because of a fortunate confluence of technological advances and a rekindled interest among researchers in rock magnetism and other geological disciplines and allied subjects such as condensed matter physics and materials science. The major current needs are: (1) more effective interdisciplinary research efforts with physicists, material scientists, and geologists, especially petrologists, geochemists, and sedimentologists; and (2) availability of state-of-the-art instrumentation required for advancement of rock magnetic theory and applications. Specific recommendations for future research in each sub-discipline of rock magnetism will be found under the heading, "Summary of Recommendations," following the discussion of each subdiscipline.

We address this report first to our colleagues in geomagnetism and paleomagnetism whom we wish to inform of our collective assessment of the potential important contributions that rock magnetic research can make to global geophysics. Our next audience is composed of researchers in physics, materials science, and the geological disciplines. We want to attract this group to a set of exciting and important interdisciplinary research opportunities in which we must have their cooperation and assistance. Our third and final audience consists of potential funding agencies because the realization of our goals for rock magnetic research will require planning for and funding of individual and collective research efforts. We hope these audiences as a whole will share our enthusiasm for future research prospects in rock magnetism and will join us in our efforts to realize the significant opportunities which are at hand.

This report was written by the authors listed below who used a compilation of contributions written by three subgroups into which the workshop participants were divided. It was edited by the first author and reviewed by nine researchers in rock magnetism and other geophysical disciplines to whom we are indebted. Among the latter group, we would particularly like to thank Priscilla Grew (Chair, Public Affairs Committee of AGU), Raymond Jeanloz and Michael Mayhew for their detailed and careful reviews. This report was presented to the Business Meeting of the Geomagnetism and Paleomagnetism Section of the American Geophysical Union on May 21, 1987.

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1.0 Introduction

Continental Drift, Seafloor Spreading, Plate Tectonics—these terms conjure up a picture of the whole of the earth's lithospheric plates in motion, a picture which truly represents a revolution in the earth sciences that took place in the 1960's and changed permanently our view of a more static world. And if asked as to which sub-discipline of the earth sciences has provided the crucial quantitative evidence about the past locations of discrete parts of continental and oceanic plates, the answer would be geomagnetism and paleomagnetism. Polarity stratigraphy based on radiometrically dated 180° reversals of the dipolar geomagnetic field inform us about the locations of parts of the seafloor in the past and paleomagnetically determined paleolatitudes of continental rocks provide similar information about past locations of continental plates.

Twenty years later a quiet revolution is now taking place in our current thinking in geomagnetism and paleomagnetism whose repercussions may be equally dramatic in the years to come. Second generation studies in geomagnetism and paleomagnetism are attempting to answer basic questions such as

—How does the geomagnetic field reverse?
—What is the magnitude of true polar wander?
—Is plate tectonics a cyclic process over the whole of earth's history?
—Through what distances do the "building blocks" migrate before they are assembled as continents?

A common difficulty encountered in answering most of these current paleomagnetic questions is our inadequate knowledge of mechanisms responsible for original acquistion of the paleomagnetic signal and for subsequent alteration of that signal. But before analyzing the difficulties, it is necessary to provide a brief background to the sciences of paleomagnetism and rock magnetism.

Because of a small percentage of ferromagnetic minerals, almost all rocks have the ability to record past magnetic fields. Paleomagnetism is the study of such natural remanent magnetism while rock magnetism provides the physical and chemical underpinning of paleomagnetism. In favorable circumstances, the most stable of these magnetic remanences is the recording of the geomagnetic field at the time of original cooling of an igneous rock or deposition of a sedimentary rock. The ability to paleomagnetically determine directions and sometimes intensities of past geomagnetic fields is unique. No other geophysical force field, such as gravity field or stress fields, has left such a discernible geological record. Paleomagnetic investigations have led, primarily over the past 30 years, to some of the most fundamental and revolutionary observations in earth sciences. Rock magnetism is becoming an increasingly critical element of paleomagnetic research. Efforts to more closely couple rock magnetic and paleomagnetic research and to encourage and support this interaction and their common advancement are badly needed.

1.1 Paleomagnetism: Importance to Geomagnetism, Geotectonics, and Geochronology

Direct instrumental records of the geomagnetic field are essentially limited to the past century. With periods of field variation extending certainly to $> 10^4$ years, the historical record is at best a glimpse at a complex and fascinating phenomenon. Recent determinations of relatively high resolution records of the Holocene geomagnetic field from paleomagnetic study of lake sediments are allowing at least limited fidelity motion pictures of geomagnetic field behavior to be developed. The current challenge is to expand the spatial coverage and to refine the resolution of the paleosecular variation records so that they become more effective and discriminatory for geomagnetic dynamo models.

On occasion, paleomagnetic records reveal field behavior far more dramatic than typical secular variation. These recordings are acquired at times when the magnetic vector takes on directions intermediate to the two polarity states, ultimately to make either full polarity reversal or to return to the same polarity state. Detailed paleomagnetic recordings of these polarity transitions and excursions (aborted reversals?) are presently providing important insight into the spatial and temporal aspects of the process of geomagnetic reversals. It is of the most importance that limits of fidelity and accuracy of a given record be known. It may well be that these observations will play a crucial role in understanding not only the workings of the geodynamo but also the thermodynamics and fluid dynamical state of the outer core.

Our present broad understanding of the mobility of Earth's crust on a variety of scales literally ranging from grains to global owes much to paleomagnetic studies. Early determination of the dominant geocentric axial dipolar nature of the time-averaged geomagnetic field allowed a straight-forward connection between paleomagnetic poles and past positions of the rotation axis with respect to a continent. The sequential positions of the paleomagnetic poles from a particular continent constitute its apparent polar wander (APW) path. Through development of APW paths for the major continents, it became evident to a few paleomagnetists as early as the 1950s that continental drift was a reality. Paleomagnetism is, of course, now the primary means of establishing paleogeographic reconstructions of major continents. Beyond the Middle Jurassic age of the oldest marine magnetic anomalies, paleomagnetism is the most direct method for studying the plate tectonic evolution of Earth.

Recent major advances in understanding the architecture and evolution of orogenic zones, especially the Western Cordillera of North America, have been aided by paleomagnetic determinations of large magnitude latitudinal transport of suspect terranes with respect to the continental interior. These studies have clearly demonstrated that motion and accretion of suspect terranes have profoundly affected the North American continental margin during the Phanerozoic. In addition, the ability of paleomagnetic studies to also determine rotations of crustal blocks about a vertical axis is a powerful and unique tool in working out deformations in regions of distributed shear. The level of crustal mobility which has become evident over the past 30 years does not allow previous simpler views of structural evolution or continental crustal growth to be retained.

The paleomagnetic discovery of reversals of the geomagnetic dipole field at irregularly spaced points in geologic time must rank as one of the most important and unexpected observations in earth sciences. Beyond providing an explanation for marine magnetic anomalies when coupled with seafloor spreading and becoming a cornerstone of plate tectonic theory, determination of the time scale of geomagnetic reversals has led to the new discipline of magnetostratigraphy. Because of the global nature of the dipolar geomagnetic field, the rapidity of its transition between the normal and reversed polarity states, and the irregular lengths of polarity intervals, magnetostratigraphy has proven to be a powerful geochronologic technique. Intrabasin, interbasin, and even intercontinental stratigraphic correlations far beyond the resolution of conventional paleontologic and stratigraphic techniques have been made using magnetostratigraphy. Resulting geochronologic refinement has allowed varied topics such as rates of biologic evolution, synchroneity of extinctions, and uplift rates of sediment source areas to be addressed at a time resolution unheard of just a decade ago. Furthermore, the stochastic nature of reversals provides a most important constraint for geodynamo models.

1.2 Current Trends and Future Needs

Given the above major past contributions of paleomagnetism to various aspects of earth science, what do we view as our current directions, potentials, and problems? Previous success at using the paleomagnetic techniques in tectonic, geochronologic, and geomagnetic applications is enticing us to address ever more detailed questions and to push our knowledge farther back in geological time. Important issues of Paleozoic paleogeography require more complete understanding of continental APW paths. In turn, refinements of continental APW paths and establishments of such paths for suspect terranes can allow important advances in plate motion histories, accretionary tectonics, and overall structural evolution of our planet. Ever more detailed pictures of geomagnetic secular variation and polarity transitions are sought because no other method is available to study the evolution of the core dynamo. This quest for more detailed paleomagnetic records and pushing the records back in time is not so much the product of a penchant for details for their own sake, but is rooted in the motivation that such detailed information will lead us to insights into the physical processes which control the observations. The forces of plate motions and deformations as well as the processes responsible for the geomagnetic field will be more discernible through acquisition of detailed paleomagnetic records in strategic settings.

Current needs of tectonically applied paleomagnetic research include study of rocks in orogenic zones. This is required both from the standpoint that such areas commonly afford the only access to older rocks whose paleomagnetic directions we seek and because we desire to use paleomagnetic techniques to study orogenic processes themselves. The obvious liability is that thermal and chemical processes accompanying tectonism can often alter or obliterate the original paleomagnetic signal. The good news is that increasingly sophisticated rock magnetic techniques of separating components of different magnetic stabilities are allowing complex, multiple-component magnetizations to be analyzed, thus maximizing our success rate even in complexly deformed regions. In some favorable cases, we are discovering the effectiveness of magnetic fabric analyses and uses of paleomagnetic vectors as passively rotated line markers in working out complex, multiple-phase deformations. The revitalized subdiscipline of magnetotectonics is pursuing the rock deformation-rock magnetism connection at the grain scale with considerable success. The bad news is that chemical and thermal alteration of the paleomagnetic record in orogenic zones is sometimes difficult to recognize and wholesale remagnetizations have occurred, sometimes under conditions which are incompatible with current theoretical models of viscous and chemical magnetization processes.

In current magnetostratigraphic and geomagnetic studies, limits of resolution of paleomagnetic records in sedimentary rocks are being pushed. Discerning the time resolution of such paleomagnetic directional information and attempting as well to retrieve data on past intensities of the geomagnetic field requires a more thorough understanding of the physical processes by which different sediment types acquire their original magnetization. A topic crucial to all uses of paleomagnetic records from sedimentary rocks is that of alterations to the signal by subsequent compaction and diagenetic effects. Our present understanding of the effects of these post-depositional processes on the fidelity and accuracy of the paleomagnetic record is rudimentary.

1.3 The Paleomagnetism-Rock Magnetism Connection: The Asilomar Workshop

A common difficulty encountered in most of these current paleomagnetic research efforts is inadequate knowledge of mechanisms responsible for original acquisition of the paleomagnetic signal and for subsequent alteration of that signal. As we ask more detailed questions in more complex geologic settings, we are in need of a concerted effort to more closely connect paleomagnetic and rock magnetic research. Advances in fundamental and applied rock magnetism are required in order for the exciting new directions and promise of current paleomagnetic research to be achieved.

With the primary motivation of assessing the present status and future directions of research and identifying some critical issues of immediate concern, the Workshop on Rock Magnetism was held at the Asilomar Conference Center at Asilomar Beach, California on 16-19 September, 1986. Three topics evolved as the major umbrella subjects: theoretical and experimental fine particle magnetism; remagnetization mechanisms; and magnetization of sedimentary rocks. These topics are discussed below with their respective subtopics. Some recommendations for research in the near future for each topic are given simply as examples of immediately obvious and critical research. They are neither comprehensive nor prioritized but simply convey examples of clear significance and concern.

2.0 Fine Particle Magnetism

Among the accomplishments of rock magnetic research have been: (1) techniques for magnetic cleaning and analysis of the magnetization record, together with a mass of accumulated information on the magnetic behavior of rocks and their magnetic minerals; (2) the emergence in the 1950s of the Néel single-domain and multidomain thermoremanence theories and their application to understanding the magnetization mechanisms in minerals as well as their application to understanding viscous and chemical remanence; (3) the ability to distinguish between self-reversals as a pathologic condition in certain opaque minerals and actual recorded reversals of Earth's magnetic field; (4) the development of methods for the recovery of the ancient intensity of Earth's magnetic field; (5) the recognition of magnetization blocking temperatures and partial thermoremanence acquisition; and (6) separation and analysis of multicomponent magnetizations. As the level of rock magnetic understanding increased, so did the level of confidence in paleomagnetic results, with the resultant major impact of paleomagnetic studies on the development of the modern geosciences.

With these developments, we have seen a steady rise in the standards of published paleomagnetic research. Rock magnetic studies aimed at the characterization of the carriers of the magnetic record are now considered to be essential to most paleomagnetic investigations. These studies aim to correlate microscopic observations on magnetic phases in rocks to the paleomagnetic signature and rock magnetic properties, and to identify the basis for paleomagnetic noise.

Efforts in theoretical rock magnetism must continue for their intrinsic interest and in order for applied rock magnetism and paleomagnetism to advance. Strong connection with modern physics must be encouraged so that relevant advances, such as irreversible thermodynamics, can be incorporated into rock magnetic theory.

2.1 Thermoremanence and Viscous Remanence

Since the pioneering work of Louis Néel and Takesi Nagata in the early 1950s, rock magnetists have attempted to refine their understanding of the fundamental processes by which rocks can attain a strong and stable remanent magnetization upon cooling in the presence of a weak field such as Earth's. This process is referred to as thermoremanence, or TRM. It provides the essential basis upon which much paleomagnetic research rests.

The importance of this process is evident in igneous rocks. Even in sediments, however, individual grains may have derived their magnetization from TRM processes in the source rock or from chemical remanence (CRM) processes that share many similarities with TRM in their theoretical treatment. Metamorphic or milder heating events can reset or partially reset the magnetic record, producing considerable complications due to the acquisition of a partial TRM; that is, a thermal remanence acquired in a restricted range of heating and cooling.

Viscous remanence (VRM) processes act as a kind of accommodation of the magnetization of a grain to an ambient magnetic field (or a lack of one). They are most visible in the production of overprints in rocks due to the influence of the present (Brunhes epoch) magnetic field. Viscous processes depend upon relaxation phenomena that are also central to theories of TRM.

Recent theoretical research has seen a growing sophistication in attempts to model TRM and VRM mechanisms more realistically, using both equilibrium and non-equilibrium domain wall configurations. However, advances in theoretical rock magnetism are badly needed on several fronts. A particularly important theoretical question which is still in need of a first-order theory is the behavior of pseudo-single-domain (PSD) grains, those containing a small number (<20) of domains. In comparison to theories of TRM and VRM in single-domain and larger multidomain grains, our understanding of PSD behavior is rudimentary. Given that the remanent magnetism of a wide variety of rocks is almost certainly carried by such PSD grains, development of PSD theory is a theoretical problem of utmost importance.

New techniques of synthesis are opening opportunities for experimental verification of TRM and VRM theories in a more precise and consistent manner. Additional investigations into the basic physics of paleointensity determinations are called for, not only for their paleomagnetic applications, but also for the insight this can provide into fundamental mechanisms such as the blocking and unblocking of magnetization.

2.2 Synthetic Materials

While the raw material of paleomagnetism consists of natural magnetic materials found in rocks and sediments, theoretical and experimental students of rock magnetism often have turned to synthetic materials in order to achieve a more controlled and more easily understood environment for solving the important first-order problems. Synthetic production of fine particles of magnetic minerals by a variety of techniques (glass-ceramic, sol-gel, hydrothermal, flux-growth, and others) has begun to make available to the rock-magnetic community a variety of high-purity materials which are capable of precise characterization. Some of these techniques are making available magnetic grains of controlled size and shape and internal strain in a magnetically and chemically inert matrix, offering samples for experimentation that are both simple and stable. The importance of simple, well-characterized synthetic materials is evident in dramatic differences in coercivity versus grain size behaviors between crushed magnetites and precipitated magnetites. There exists an urgent, widespread need for suites of well-characterized magnetic minerals, such as the titanomagnetites, titanohematites, titanomaghemites, and others. Collaborative efforts between the synthesizers and experimenters should be encouraged to the greatest extent possible.

Among the experiments that need to be performed on synthetic samples are the determination of fundamental constants such as the exchange constant, the anisotropy constants, the magnetoelastic constants, the cell-edge and Curie temperature constants as a function of composition. Many of these constants have not been determined adequately for a reasonable range of titanium concentration in the titanomagnetites. Knowledge of these constants is absolutely essential for successful theoretical modeling of magnetization processes such as thermoremanence.

2.3 Domain Structure in Fine Magnetic Particles

Of paramount importance to our understanding of the influence of domain structure of the magnetization in fine magnetic particles is the study of domain patterns in materials with well-controlled grain size and composition. Domain structure style and the number of domains must be determined as a function of (1) grain size; (2) field strength; (3) time and temperature in order to elucidate mechanisms for TRM and VRM acquisition; and (4) both low-temperature and high-temperature oxidation in order to better understand acquisition of chemical remanence (CRM).

The time is now at hand to upgrade our domain-imaging techniques with state-of-the-art instrumentation including computerized signal-enhancement systems for superior-quality optical microscopes, magneto-optical and Scanning Electron Microscope (SEM) and Transmission Electron Microscope (TEM) methods, the latter including Scanning Electron Microscopy with Polarization Analysis (SEMPA). Some observations would extend studies of magnetic structure into the critical sub-micrometer size range and into the third dimension. The obvious need for sophisticated instrumentation to facilitate these research directions is discussed below.

2.4 Summary of Recommendations

2.4.1 Theoretical and experimental research should be pursued vigorously to develop an advanced theory of pseudo-single domain grain behavior.

2.4.2 Research should be carried out on comparison of different crystal growth methods to produce the best simulation of natural magnetic materials.

2.4.3 A suite of well-characterized synthetic single- and polycrystals of magnetic oxides should be prepared and made available to laboratory researchers for the determination of magnetic parameters.

2.4.4 Much more increased collaborative research is needed between rock magnetists and materials scientists involved in material synthesis and analysis.

2.4.5 State-of-the-art techniques in magnetic domain imaging should be applied to natural and synthetic magnetic minerals.

3.0 Remagnetization Mechanisms

Paleomagnetism would be a far simpler field of study if the primary magnetization acquired upon formation of a rock or sediment were the only record imprinted within a specimen. Unfortunately, in many cases a wide variety of subsequent processes act to alter, eradicate, or replace the original magnetization. Samples containing three or more separate and distinct components of magnetization are routinely used in paleomagnetic analyses, a situation that makes imperative a full understanding of remagnetization mechanisms and environments. There are two major mechanisms for remagnetization: physical and chemical. In the first, partial reheating for short or prolonged durations leads to resetting of remanence. In the second process, original magnetic minerals can undergo chemical alteration and/or new magnetic minerals form long after formation of the rock unit.

3.1 Thermoviscous Remagnetization

Geological samples typically have suffered prolonged exposure to the geomagnetic field, often at moderately elevated temperatures during intervals of burial or tectonic uplift. There is commonly the potential for thermoviscous remagnetization. Thermoviscous behavior is a fundamental magnetic property intimately related to thermoremanence and viscous remanence and must be accounted for by any adequate theory. For paleomagnetism, more precise knowledge of time-temperature relationships is critical for thermochronometric calibration of magnetization components and in general as a basis for evaluating the origin of magnetizations in the rock record. Assessment of the importance of thermoviscous effects relies heavily upon theoretical time-temperature relationships derived from single-domain theories. Recent observations for magnetite-bearing rocks show wide disparity with standard theory and indicate that thermoviscous effects are more important than has been realized. It is unclear whether an alternate theory of thermoviscous behavior is in fact called for, the temperature-dependent anisotropy relationships in the standard theory need to be re-evaluated, or rather if the observed discrepancy points to a dependence on domain state.

In order to provide additional practical tests and constraints upon theory, additional observations are needed with well-characterized rock samples, covering a range of magnetic compositions and grain sizes, and which have acquired thermoviscous magnetization over geological time intervals. In parallel, laboratory experiments designed to more precisely determine the temperature dependence of intrinsic magnetic anisotropy for a range of known magnetic grain sizes and compositions are clearly essential for further understanding.

3.2 Chemical Remagnetization

Magnetic effects of chemical changes suffered by rocks and sediments are ubiquitous. The materials we are now called upon to study include many igneous and sedimentary rocks which are rather complex and open geochemical systems. The rocks can be from folded tectonic belts where mild or severe metamorphism may have resulted in multiple generations of the same mineral (e.g. detrital and authigenic magnetite) and attendant acquisition of multiple components of chemical remanent magnetism (CRM). The general problem is thus a dual one in which it is necessary to understand the magnetic effects of partial or total destruction of the original magnetic mineral suite while dealing with the acquisition of CRM in newly created magnetic minerals. Given that rocks often contain combinations of magnetic mineral groups with varying responses to changing Eh and pH conditions, a full understanding of chemical remanence in a range of rock types presents a formidable challenge.

Despite these difficulties, significant progress has been made in recent years in understanding magnetic effects of some important chemical changes, including low-temperature oxidation of oceanic crustal materials. Although important details remain to be addressed, it is clear that low-temperature oxidation causes titanomagnetites in young oceanic pillow basalts to oxidize to cation-deficient titanomaghemites, increasing the ferric:ferrous ratio while retaining spinel crystal structure. For single-domain grains the original direction of the magnetic remanence is dominantly retained during this oxidation but the magnitude of remanence is degraded. These rock magnetic effects of an important and widespread chemical change thus explain some of the age dependence of the crustal sources of marine magnetic anomalies.

Much paleomagnetic work with important geochronological and tectonic implications has been and is being done on red sediments. Combined rock magnetic and paleomagnetic studies have recently helped to clarify arguments on the relative timing of deposition and magnetization. Although the carrier of magnetic remanence in many red beds has long been identified as hematite, the remanence characteristics of hematite grown in situ are poorly understood. There are three sources of secondary hematite in red beds: precipitation from aqueous solution, alteration from non-magnetic precursor minerals such as biotite, and alteration from a magnetic precursor such as iron oxyhydroxide. Each reaction must be studied separately in a series of well controlled experiments. A more thorough understanding of remanence acquisition in red sediments remains one of the most important issues in research on chemical remanence.

Recent discovery of apparently widespread Permian remagnetization of large portions of North America and Cretaceous age remagnetization of regions of China provide additional major impetus for study of CRM. The observation that many such remagnetizations seem to be acquired during tectonic folding adds even greater importance to the task if rocks in orogenic belts are to increasingly be targets of paleomagnetic study.

When designing a program of research on chemical remanence, one must realize that CRM can result from two fundamentally different processes: (1) a new magnetic mineral can chemically precipitate and acquire a "growth" CRM as the grains increase in volume, or (2) a crystallographic change can occur (with or without chemical change) resulting in "crystalline" CRM. Because both processes can occur by alteration of a previous remanence carrying magnetic mineral, effects of host remanence on acquired CRM must be understood. Approach to studies of CRM can be made on three fronts: (1) Theoretical and experimental programs to develop a theory of growth CRM as a function of magnetic field, grain size, and effective anisotropy constant are badly needed. By comparison with equivalent theory of thermoremanence, existing chemical remanence theories are rudimentary. (2) Similar development of theory and critical experimental approaches are needed for study of the relative effects of a magnetic field and host remanence when CRM is formed by alteration of a magnetic precursor mineral. (3) Techniques for effective recognition and separation of secondary CRM from original magnetic remanence components must be developed. Certainly theory and experiment on the first two topics must show progress before this latter topic can adequately be addressed.

A general need in rock magnetism which is particularly acute for studies of chemical remanence is the development of a systematic "magnetic petrology." The petrology of the iron-titanium oxides, iron sulfides, iron oxyhydroxides, and other magnetic minerals along with studies of the associated rock magnetic record is a subject which has received little attention. Yet such petrologic study in conjunction with conventional petrologic studies is fundamental to any serious program of research on chemical remanence. For example, combined petrologic and rock magnetic study of rocks showing progressive metamorphism would be crucial to understanding CRM in orogenic zones. Because such studies would require analyses down to single grain scale, availability of specialized instrumentation such as described above is essential to developing magnetic petrology.

3.3 Summary of Recommendations

3.3.1 An advanced theory of Thermoviscous Remanent Magnetization (TVRM) should be developed.
3.3.2 A vigorous program of experimental research should be carried out to test the applicability of Thermoviscous Remanent Magnetization (TVRM) theories to natural and synthetic materials.
3.3.3 Chemical Remanent Magnetization (CRM) mechanisms due to grain-growth should be understood from a combined theoretical and experimental approach.
3.3.4 The influence of magnetic field and host remanent magnetization should be studied when Chemical Remanent Magnetization (CRM) is acquired upon the alteration of a precursor mineral.
3.3.5 New magnetic and non-magnetic techniques should be developed for effective recognition of secondary Chemical Remanent Magnetization (CRM) in rocks for paleomagnetic studies.
3.3.6 A systematic magnetic petrology should be developed by collaboration between rock magnetists, and igneous and sedimentary petrologists.

4.0 Magnetization of Sedimentary Rocks

More and more, earth scientists are attempting to exploit the remanent magnetization of sediments. As our knowledge of the geomagnetic field and of tectonic displacements has improved, we ask increasingly detailed questions of the rocks; not just for information on polarity, but for detailed records of paleosecular variation and polarity transitions; not just for the gross picture of continental drift, but for relative displacements as small as 500 kilometers. To do this well, we need to know more about processes which affect acquisition and subsequent alteration of the remanent magnetization in sedimentary rocks at both the fundamental and practical level. The viability and robustness of geochronological and geotectonic inferences from paleomagnetic study of sedimentary rocks will naturally follow from determination of the limits to which detailed geomagnetic records can be extracted.

4.1 Fidelity of the Magnetic Recording

Because properly chosen sedimentary sections offer the potential of continuous high resolution records of geomagnetic directional behavior, much effort is being expended to extract this information. As examples of the desired detailed records of geomagnetic field behavior sought in paleomagnetic studies of sedimentary rocks, consider polarity transitional and paleointensity records which can serve as important constraints on geomagnetic dynamo behavior. The degree to which a given record reliably depicts actual geomagnetic field behavior depends on critical parameters such as lag time (lock-in depth), resolution (lock-in range), and fidelity of the primary remanent magnetism of various types of sedimentary rocks. In addition, subsequent alteration or replacement of the primary remanent signal by compaction and chemical processes must be understood. The challenge then is to develop and utilize rock magnetic knowledge and methodology in innovative ways to shed light on the degree of reliability of a given recording.

It is now generally believed that post-depositional detrital remanent magnetization (pDRM) arising from mobility of magnetic carriers within fluid-filled voids is the dominant process involved in the magnetization of sediments, at least prior to diagenesis. However, the influences of processes such as gradual dewatering and bioturbation are not yet well understood. Accordingly, the depth and time dependence of the acquisition of pDRM require further study. Use of independent event markers in the sedimentary record (such as Be^{10} profiles) may aid in deciphering the original magnetic recording process. Another factor which may be important to the magnetization of sediments is the role of bacterial magnetite. It has been suggested that such biogenic magnetite may be the dominant source of magnetic carriers in marine sediments. Additional work is needed to determine the nature of bacterial magnetite and its importance to the magnetization of sediments.

Some general goals for future research on this topic would include: (1) New methodologies to characterize the magnetic grain-size distribution in sediments. These methodologies could be applied to remanence acquisition studies (natural or laboratory), paleointensity studies, and the identification of early diagenetic processes in sediments. (2) Studies of DRM/pDRM processes designed to determine time lags, smoothing, and systematic directional and amplitude errors in the paleomagnetic record carried by sedimentary rocks. Such studies should include quantification of these parameters using depositional experiments in the laboratory and in the natural setting using box cores and sediment traps. Also required are detailed comparisons between natural recordings of the same geomagnetic signal in sediments of various environments and in contemporaneous nearby volcanic sequences which, from the geologic standpoint, acquire magnetic remanence instantaneously.

4.2 Diagenesis, Compaction, and Strain Effects

One of the most fundamental, yet least understood aspects of sedimentary paleomagnetism is the influence of geochemical processes on the rock magnetic and paleomagnetic properties of sediments. The post depositional formation of authigenic magnetic minerals or the diagenetic alteration of primary remanence carriers can cause profound changes in the magnetic signal which may affect interpretations of paleofield behavior, magnetostratigraphy and tectonic reconstructions based on paleolatitudes. There is a critical need for integrated rock magnetic and biogeochemical studies in different sedimentary environments to evaluate how magnetic minerals are created or altered in response to ambient and paleoenvironmental conditions. From such studies, we should be able to establish key rock magnetic and geochemical criteria by which authigenesis and diagenesis can be recognized in the geologic record.

Compaction effects on the remanence of sediments may become important after DRM lock-in and early chemical and biological processes have occurred, but prior to actual lithification. The effects of compaction on remanence are difficult to recognize in the paleomagnetic record since, instead of degrading the signal, they can introduce a systematic bias to shallower inclinations. Because inclination data are so important for interpreting paleomagnetic studies, it is critical to conduct laboratory experiments and field studies to assess the effects and relative importance of factors that might produce inclination shallowing. These would include: (1) magnetic mineral and matrix grain sizes and shapes, (2) sediment lithology and water content (porosity), (3) total volume change accompanying compaction, and (4) timing and presence of cementation.

Diagenetic processes now appear to be ubiquitous within the sedimentary environment even penecontemporaneous to primary deposition. It is imperative that we understand the impact of these processes on the rock magnetic behavior of sediments.

Combined paleomagnetic, rock magnetic, geochemical, and sedimentologic studies of sediments in a wide variety of sedimentary environments are needed. In addition, studies of effects of shear strain on magnetized sediments are badly needed. Theoretical modeling of strain effects on different shape magnetic particles and carefully controlled field experiments conducted where finite strain in rocks may be quantified by structural geology techniques are of particular importance.

4.3 Summary of Recommendations

4.3.1 New methodologies should be sought to characterize the effective magnetic grain size distribution in sediments and sedimentary rocks.
4.3.2 Research on Depositional Remanent Magnetization (DRM) and Post-Depositional Remanent Magnetization (pDRM) processes should be undertaken to determine time lags, smoothing processes, and directional and amplitude errors in the paleomagnetic record.
4.3.3 Integrated rock magnetic, geochemical, biogeochemical, and sedimentologic studies should be carried out in a wide variety of sedimentary environments.
4.3.4 A renewed study of inclination error in the paleomagnetic records in sediments should be pursued from both theoretical and experimental viewpoints.
4.3.5 A strong emphasis should be placed on magnetic anisotropy studies in sediments and sedimentary rocks to determine quantitatively the magnitudes of paleo-strain suffered by these recorders.

5.0 Overall Recommendations

Rock magnetic research has enjoyed a number of successes in the past few decades, but in order to maintain the pace of paleomagnetic contributions, a far greater understanding of magnetization processes in rocks must be attained. The paleomagnetism—rock magnetism connection needs to be enhanced by:
(1) encouraging the advancement of rock magnetism as a subdiscipline especially as applied to the issues of clear paleomagnetic relevance, and
(2) continued and enhanced inclusion of rock magnetic studies as an integral part of all paleomagnetic studies.

Two major themes are evident in the research needs outlined above in the body of this report:
(1) There is a clear need for more interdisciplinary research between rock magnetism and other disciplines.
(2) An initiative to provide critical instrumentation and ''homes'' for such instruments is required urgently. These two major recommendations are described below in detail.

5.1 Interdisciplinary Research

Given the requirement for carefully designed experiments on well-characterized synthetic materials in basic rock magnetic experiments, interaction with materials scientists engaged in research on magnetic recording materials and on fundamental magnetic properties is increasingly needed. Development of magnetic petrology is clearly required for advancement of knowledge of remagnetization phenomena. Geochemical problems must be tackled in order to address problems of diagenesis of sediments and remagnetization problems as well. Sedimentological processes, such as compaction and dewatering, need to be better understood and incorporated into the theory of acquisition of pDRM. These promising avenues of rock magnetic research will require much closer future collaboration of rock magnetists with physicists, petrologists, mineralogists, geochemists and sedimentologists. In order to encourage this interdisciplinary research, we recommend that a series of Asilomar-type conferences and AGU special sessions be arranged to take place within the next two or three years to pursue common ground between disciplines and to identify critical topics and experiments.

5.2 Critical Instrumentation and Facilities

New techniques for preparation of synthetic materials are opening up promising research directions in basic experimental rock magnetism. Theoretical and experimental advances in analysis of domain configurations are quite exciting. Many of these studies will require chemical analysis, x-ray study and strain determination of very small fractions of natural and synthetic samples. Specialized domain imaging instruments are also needed. Instruments for magnetic measurements such as SQUID gradiometers of narrow bore or new instruments for simultaneous observation of magnetization and domain state are needed for microsamples.

In order to make available the most sophisticated instruments to the largest number of scientists in a cost-effective manner, establishment of one or two national experimental centers equipped with the required sample synthesis and characterization, and unique magnetic measurement systems could be the best approach. These centers would actively promote visits by scientists from other laboratories for use of specialized equipment and for holding specialist forums. Alternatively, providing more equipment to individual investigators may still be an effective approach for some problems. We believe the need for critical instrumentation is obvious and the proper approach should be chosen carefully. We note that the Earth Sciences Board of the National Research Council is currently writing a report which targets a program in Physics and Chemistry of Earth Materials as one of the most critical funding needs for advancement in earth science research. We have recommended to them that such a program should definitely include research in rock magnetism as a major component. In a similar vein we have drawn the attention of another panel of the National Research Council which is presently deliberating on the policy for national centers for science and technology to the need for a renewed commitment to rock magnetism.