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MAGNETIC ANOMALIES IN EAST PACIFIC USING MAGSAT DATA

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Final Report to the National Aeronautics and Space Administration

MAGSAT Contract to C.G.A. Harrison

Introduction

This final report describes very briefly the major results obtained by us under the above funding contract. Much of the work has been described in oral presentations, and in some publications. Other publications are being prepared and will be sent to NASA when reprints are available. The work which has been done falls into four major subject areas, which will be discussed below.

Major Research Accomplishments

(1) Core versus crustal fields.

Analyses of very long marine total field profiles and the spherical harmonic spectrum derived from MAGSAT data indicated that there were considerable problems in separating the core field from the crustal field. This is basically because of two reasons. Any source anywhere will give a signal which, in general, contains all wavelengths. And secondly, the representation of the Earth's magnetic field using spherical harmonics of the magnetic potential is a poor way of discriminating between different wavelengths. An alternative method would be to use off centered dipoles within the core to represent the core magnetic field, as these are more capable of removing the longer wavelength signal from the observations and leaving in the shorter wavelength signal than are spherical harmonics.

Another problem concerning separation of core from crustal fields comes from looking at equivalent source functions for what is commonly thought to be the crustal component of the field. These source functions show almost no difference of the vertically integrated crustal magnetization between continental and oceanic areas. They also show no latitudinal variation in either continental or oceanic areas. Continental sources for long wavelength magnetic anomalies are thought to be caused by induced magnetization and should therefore show a factor of two increase between equator and pole. In the oceanic areas, sources are probably due to remanent magnetization. In view of the fact that average latitudinal movements of oceanic areas have probably been less than 30° oceanic source functions should also show a distinct latitudinal effect. One possible reason for these peculiar observations is that the intermediate degree harmonics (i.e. from degree 15 to 25 or 30) may be predominately caused by sources within the core of the Earth. If this is the case, the core field has much more short wavelength signal in it than was thought earlier, and this should tell us something about the way in which the core field is generated.

(2) We have developed methods for inverting total magnetic field data to obtain source functions for oceanic areas. These do not differ greatly from other proposed methods, and could equally well be used for continental areas. In most cases the magnetization is constrained to lie parallel or anti-parallel to the main field direction. We have had no particular problem of

dealing with results close to the magnetic equator. The major source of difficulty is in determining what the spacing of dipoles should be. If the spacing is made too close, then the magnetization values become very large and oscillate spatially. If the spacing is made to far apart, the field is not fit very well. Unfortunately there seems to be no a priori method of choosing the best spacing in view of the competing requirements of good fit and small magnetization. This appears to be a major unsolved problem in equivalent source calculations.

We have done inversions on three different areas, one in the western Pacific, and two in the northern and equatorial Atlantic. This has enabled us to calculate the typical magnetizations which are necessary to explain the observed magnetic field observations. These magnetizations are of the order of 1 to 2 $A.m^{-1}$ in a layer which comprises all of the oceanic crust (i.e. about 6 km thick).

(3) In order to account for the magnetization contrasts it must first be decided whether they are due to induced magnetization or remanent magnetization. If magnetizations are induced, then the solution produced by the simple inversion technique described above does not produce a reasonable solution, since about half of the crust is magnetized in a direction opposite to the direction of the main field. It is therefore necessary to modify the solution such that all magnetizations are positive, i.e. in the direction of the main field. This can be done by

using an annihilator. An annihilator is a magnetization within the body under consideration which produces no external field. Addition of a constant amount of this annihilator will therefore not alter the external field produced by the original inversion solution. We have produced a complete proof that the annihilator for a spherical shell is any magnetization which is proportional in intensity, and in the direction of a magnetic field whose sources are internal to the shell. In this case, if we use the main field of the Earth as this internal field we can produce a magnetization solution in which the magnetization is everywhere parallel to the main field, and also positive. Addition of the annihilator has the effect of increasing the magnetization necessary to produce the observed magnetic anomalies. In the simple case of a planar body whose magnetization is uniformly divided between magnetizations of +1 and -1, the RMS magnetization is equal to 1. However, after addition of the annihilator (a uniform magnetization of +1), the magnetization of the body is either 2 or 0, giving an RMS magnetization of 1.4. A more realistic example is one in which the magnetization produced by inversion is normally distributed about zero, with standard deviation of 1, giving an RMS magnetization of 1. If the most negative magnetization is two standard deviations away from the mean (i.e. -2) then this is the value of the annihilator which must be added to the solution to remove all negative magnetizations. The resulting magnetization is one with mean 2 and standard deviation 1, which given an RMS value of 2.2, more than twice as large as the original solution.

It turns out that the annihilator is probably not important in marine studies of this nature because the magnetization is almost certainly remanent (see next section). But in continental studies it must be used since most researchers think that the magnetization is induced.

(4) We have also done an analysis of magnetization values measured in rocks of marine origin. Induced magnetizations are almost always much lower than those necessary to explain the observed magnetization patterns, especially when the effect of the annihilator is added on to the inversion solutions. The only exception to this is that unweathered and unmetamorphosed pillow lavas have an average induced magnetization in a field of 50 μT of 1.75 $A.m^{-1}$. But since the thickness of rock made up of such material is almost certainly less than 0.5 km, induced magnetization in such a layer can only make a small contribution to the observed magnetic field anomaly.

Remanent magnetizations are in general much stronger than induced magnetizations for oceanic rocks. Magnetizations range from an average of 24 $A.m^{-1}$ for fresh pillow basalts down to 0.8 $A.m^{-1}$ for weathered gabbros. This means that in principle there are strong enough magnetizations within the oceanic crust to explain the long wavelength magnetic anomalies observed at satellite altitudes provided that the spatial organization of the magnetization is of long enough wavelength. As an example, suppose that there is a lineated structure within the oceanic crust (thickness 6 km) with a sinusoidal magnetization variation giving an RMS magnetization of 2 $A.m^{-1}$. The RMS field at a satellite altitude of 400 km will be 3.8 nT if the magnetization signal has a wavelength of 1000 km, but only 0.035 nT if the magnetization signal has a wavelength of 300 km. One of the major problems of interpretation of long wavelength magnetic anomalies, therefore, is how the remanent magnetization gets enough power at the long wavelength end of the spectrum to explain the observed anomalies.

Papers Published Under the Contract

1982 H.M. Carle and C.G.A. Harrison. A problem in representing the core magnetic field of the Earth using spherical harmonics. GRL, 9: 265-268. (Reprints already sent.)

C.G.A. Harrison and H.M. Carle. Modelling the core magnetic field of the Earth. Phil. Trans. Roy. Soc., A306, 179-191. (Reprints already sent.)

1983 C.G.A. Harrison, Magnetic anomalies, Reviews of Geophysics and Space Physics, 21, 634-643. (Reprints included with this report).

Abstracts of Papers Presented on Work Performed Under the Contract

(Copies included with this report.)

1980 C.G.A. Harrison, H.M. Carle. Observations of long wavelength magnetic anomalies over ocean basins using MAGSAT data. 26th International Geological Congress, Paris, 7-17 July. Abstracts, p. 822. Invited Paper.

1981 C.G.A. Harrison and H.M. Carle. MAGSAT magnetic anomalies in the eastern Pacific Ocean, IAGA meeting, Edinburgh, August.

H.M. Carle, C.G.A. Harrison, Total magnetic field power spectra, EOS, 62: 847.

1982 C.G.A. Harrison and H.M. Carle, Core dipole models for excursions, invited paper presented at a Meeting for Discussion at the Royal Society, London, 27 January-28 January. "The Earth's core: Its Structure, Evolution and Magnetic Field," organized by S.K. Runcorn, K.M. Creer and J.A. Jacobs.

C.G.A. Harrison, The problem of the division of magnetic field signals observed on the surface of the Earth into portions of crustal and core origin. U.S. Geological Survey Geomagnetism Workshop, Golden Colorado, 13-15 April (invited talk), EOS, 63, 655.

H.M. Carle, C.G.A. Harrison, Equivalent source magnetizations in the central Pacific, EOS, 63, 908.

1983 C.G.A. Harrison, H.M. Carle, K. Hayling, Global magnetization contrasts calculated from long wavelength magnetic anomalies, invited paper, EØS, 64, 213.

C.G.A. Harrison, H.M. Carle and K. Hayling, Equivalent source solutions for long wavelength magnetic anomalies in the north cental Pacific and north Atlantic oceans, Symposium I3, International Union of Geodesy and Geophysics, Hamburg, 15-27 August.

C.G.A. Harrison and H.M. Carle, Continent-ocean basin magnetization contrasts calculated from long wavelength magnetic anomalies, Symposium I3, International Union of Geodesy and Geophysics, Hamburg, 15-27 August.

Future Publications

In addition to the above publications and abstracts, the contract supported the M.Sc. work of Mr. Mark Carle. Mr. Carle is due to defend his thesis on September 30. When this thesis is approved, copies will be sent to NASA.

In addition, the P.I. plus his students are preparing a paper for special issue of the Journal of Geophysical Research, and this will be sent to NASA when reprints are available.

Reportable Items

There were no inventions or innovations (other than scientific ones described in the publications) resulting from this contract, nor were there any subcontracts awarded under the contract.

IAGA
Edinburgh.

MAGSAT MAGNETIC ANOMALIES IN THE EASTERN PACIFIC OCEAN

C.G.A. Harrison
H.M. Carle (both from Rosenstiel School of Marine and
Atmospheric Science, University of Miami, Miami,
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A preliminary survey of the first few days of MAGSAT total field data shows the presence of anomalous field components with wavelengths on the order of 400-1500 km. The sources of such anomalous field are not clearly established but the study of their spatial distribution might give some clue as to their origin.

The typical MAGSAT profile shows the anomalous field peaks at 50 to 70 nT within 20 degrees of either pole which are probably the results of auroral effects. In the mid-latitude regions the above mentioned medium wavelength anomalies are observed having maximum amplitude of 20 nT.

In general the shape of the profiles supplied by the vector and scalar instrument agree. However, a calibration problem of the vector instrument appears to exist in that the difference between the two magnetometers can vary from +20 nT to -20 nT in a single orbit. Furthermore, these differences appear to grow and decay with time, producing orbits where the maximum absolute differences are about 2 nT and orbits where absolute differences in excess of 20 nT are common.

We shall examine the spatial correlation and coherence of magnetic anomalies above the eastern Pacific Ocean basin in order to determine the possible sources for these anomalies. Sources will be determined by a matrix inversion method. The results of the magnetization contrasts necessary to explain the anomalies will allow us to determine something about the probable thickness of the magnetized bodies causing the anomalies, provided that we can place limits on the maximum magnetization capable of being carried by certain rock types.

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(a) Oral presentation only

TOTAL MAGNETIC FIELD POWER SPECTRA

H.M. Carle
C.G.A. Harrison (both at Rosenstell School of Marine & Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, Fla. 33149)

The spectral characteristics of total field profiles encircling the Earth, and generated from the MAGSAT spherical harmonic field model are examined. If total field values are used, the simple pattern which might be predicted is masked by the operation of obtaining vector magnitude from scalar potential. This magnitude is the square root of the sum of the squares of three space differentials of the scalar potential. Each of these differentials can be expressed as a finite sum of various harmonics of the fundamental wavelength, the circumference of the Earth. The squares of the differentials, & also their sums, have a finite number of harmonics, but when the square root is taken, the resulting expression has an infinite number of harmonic terms. We therefore suggest that if spectra of regional field anomalies along profiles are to be taken, the best way of deriving the anomalous data is to take the squared total field and subtract the squared field derived from the spherical harmonic representation of the core field.

Another important result of this work is that the anomalous field will contain significant power in all wavelengths from DC to higher harmonics. In other words, the removal of a core field produced by spherical harmonic coefficients up to a certain degree and order does not necessarily remove all long wavelength components from the anomalous field. This may have implications for the way in which core fields are removed from total field data.

1. Fall meeting, 1981

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Core Dipole Models for Excursions

by C. G. A. Harrison, Rosenstiel School of Marine and Atmospheric
Science, University of Miami, Florida, U. S. A.

Several models for reversals of the Earth's magnetic field have been proposed which use spherical harmonic expansions of the Earth's magnetic potential as a starting off point for the models. It can be shown that spherical harmonic expansions, while having mathematical advantages such as simple computation, and easy upward and downward continuation, are not ideal representations of the core field. To begin with, they do not seem to represent any physical reality within the core. Secondly, it can be shown that they do not remove all of the long wavelength component of the field observed at the Earth's surface. By writing down the total field as a function of spatial derivatives of the spherical harmonic potential, it can be easily shown that removal of the field caused by lower degree harmonics of the potential (usually up to harmonic 12 or 13) still leaves a significant long wavelength component in the field at the surface of the Earth. Since long wavelength fields are almost impossible to produce by crustal sources, they must be caused in the core of the Earth, but are not completely allowed for by modelling the core field using spherical harmonics. It is therefore suggested that a more reasonable model of the field consists of dipoles arranged within the core of the Earth. These dipoles can be used to model fairly well the current sources within the core which are responsible for the magnetic field, so that they can be considered to have some physical reality. Modelling of excursions and reversals using dipoles located within the core of the Earth will be discussed. An attempt will be made to understand what is happening to the dipoles during the process of a reversal using data from the most recent reversal of the Earth's field. Data on excursions recorded in Neogene Icelandic lava flows will also be discussed using the dipole model of the Earth's field.

Geomagnetic Workshop. Held at Golden, Colorado, April 13-15, 1982.
Organised by Joe Cain.

THE PROBLEM OF THE DIVISION OF MAGNETIC FIELD SIGNALS OBSERVED ON THE SURFACE OF THE EARTH INTO PORTIONS OF CRUSTAL AND CORE ORIGIN

C. G. A. Harrison, Rosenstiel School of Marine and
Atmospheric Science, University of Miami,
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The spherical harmonic analysis of the Magsat field has been carried out to degree and order 23 of the magnetic potential. If the mean square value of the field produced by each degree of harmonic, summing over all orders for each degree, is plotted against the degree of harmonic (abscissa), it is found that the points generally lie on two straight lines. One straight line, representing harmonics from degree 2 to degree 13 has a large negative slope. The other straight line, representing harmonics from 14 to 23 has a very small negative slope. This has been interpreted as suggesting that the core field is responsible for the first 13 degrees of harmonic, and that the crustal field is responsible for all higher harmonics, plus some contribution from the lower harmonics, which is hidden by the core field contribution. It is possible to show that the magnetizations necessary to give the observed values of the spherical harmonics of the potential from degree 14 to degree 23 are too large to be caused by normal crustal magnetizations. The situation is compounded even more if lower and higher harmonics are included.

The field signal due to harmonics of the potential has wavelength information all the way from the circumference of the Earth down to shorter wavelengths. This can be shown by an elementary analysis of the spherical harmonic functions.

These two observations suggest that we still have no rational way of separating core from crustal magnetic fields. It is suggested that off-centered core dipole models may offer a better way of determining the core field, and hence allow us more successfully to separate the field into core and crustal components.

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Equivalent Source Magnetizations in the Central Pacific

H.M. CARLE (Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida, 33149)
C.G.A. HARRISON (Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida, 33149)

The equivalent source technique is applied to the 2° X 2° Magsat scalar magnetic anomaly field for the calculation of long wavelength crustal magnetization contrasts in the central equatorial Pacific. The study region extends from the equator to 40°N and from 150°E to 200°E. This region encompasses one of the largest positive oceanic anomalies which is apparently associated with the Emperor and Hawaiian seamount chains. Solutions assuming an induced magnetization are derived and are corrected using the annihilator for a spherical shell. The sources are assumed to be dipoles located within the oceanic crust, and the optimal spacing for these dipoles in order to produce a satisfactory inversion is between 2.7 and 3.0°. The dipole intensity is converted to magnetization by dividing by the volume of crust represented by each dipole, and it is found that the maximum magnetizations necessary to explain the long wavelength magnetic anomalies in this area are about .5 A m^{-1}. The magnetization pattern seems to be loosely connected with the positions of the basins and rises in the area.

1. Fall Meeting, 1982

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8. a. As Above

   b. No P.O. Necessary

   c. Student Rate Applicable

9. C

Global Magnetization Contrasts Calculated from Long Wavelength Magnetic Anomalies

C. G. A. HARRISON
H. M. CARLE
K. HAYLING (all at the Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida 33149)

It is often believed that the core magnetic field of the Earth can be adequately described by spherical harmonic functions up to about degree 14. By the same token, spherical harmonics of degree 15 or higher should be caused by sources within the crust or very upper mantle, since Curie point considerations prohibit there being sources from most of the mantle. Langel et al. and Cain et al. have produced spherical harmonic models of the total field up to degree 23 and 29 respectively. In both these models therefore there is significant contribution from crustal sources. Using a method outlined by Chapman and Bartels it is possible to derive a simple equivalent source model for spherical harmonics of potential, which can easily be transformed into spherial harmonics of vertical dipole moment per unit area within a thin spherical shell. Equivalent source models have been generated for both field models in an attempt to determine the relative strengths of crustal sources from oceanic and continental areas. A surprising result is that the average vertical dipole moment per unit area (equivalent to the vertically integrated sum of vertical magnetization per unit volume over the thickness of the magnetized layer) is almost the same under continental and oceanic areas. Thus the continental crust must have a lower magnetization than the oceanic crust in the same ratio as the continental crust is thicker than the oceanic crust. We shall attempt to study this equality further by looking at the continent/ocean ratio of individual degrees of spherical harmonic, and by looking at groups of spherical harmonic terms, to see which harmonic terms give significan differences between oceanic and continental areas.

1. Spring Meeting

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5. Special Session:
MAGSAT Studies.

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9. Contributed

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EQUIVALENT SOURCE SOLUTIONS FOR LONG WAVELENGTH MAGNETIC ANOMALIES OBSERVED BY MAGSAT IN THE NORTH CENTRAL PACIFIC AND NORTH ATLANTIC OCEANS

C.G.A. Harrison, H.M. Carle and K. Hayling

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We have used the maagnetic anomalies observed by Magsat to learn something about the magnetization of the oceanic crust. Since the satellite flew with a perigee which was originally 350 km above the Earth's surface, only long wavelength signals are seen. In some oceanic areas, the signals can be as large as ± 10 nT. We have studied two areas which have larger than normal signal amplitudes, and have calculated the crustal magnetizations which are necessary to explain the observed anamalous field by using equivalent source technique. Our sources are tesseral caps, which give better results than dipoles placed within the crust. The height of the satellite gives a minimum resolution of only 300 km.

The least squares solution with spacings between the centers of each tesseral cap of 300 km gives a good representation of the observed field at satellite altitudes. The R.M.S. value of the magnetization of the oceanic crust for a region centered around the bend in the Hawaiian-Emperior seamount chain gives a value of more than 2 A/m. The result for the North Atlantic is somewhat less than this. These results were calculated assuming that the magetization is along the direction of the main field of the Earth. If the long wavelength magnetization is induced, then negative magnetizations are not allowed, and a correction for this produces R.M.S. magnetizations which are larger. These results will be discussed in terms of our knowledge of the magnetic properties of the oceanic crust.

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CONTINENT-OCEAN BASIN MAGNETIZATION CONTRASTS CALCULATED FROM LONG WAVELENGTH MAGNETIC ANOMALIES

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The residual magnetic anomaly produced by MAGSAT, represented by degrees of spherical harmonic above degree fourteen, has been studied to determine the difference between continental and oceanic magnetizaiton. This residual field has been shown by Cain, Schmitz and Muth to be very similar to the residual field produced by Langel, Phillips and Horner. It has been suggested several times that there does not seem to be any large difference between the size of long wavelength magnetic anomalies produced over oceanic basins and over continents, which is surprising considering the very large differences between the rock types within the continental and oceanic crust. We have investigated this difference by determining from the spherical harmonics the magnetization contrasts necessary to produce the observed residual magnetic fields. The source function is that of a vertically polarised thin magnetic shell, whose magnetization is very simply related to the spherical harmonics of magnetic potential. Although this source function is not physically realistic, in that the direction of magnetization is probably not vertical except possibly at very high latitudes, it should serve to indicate the overall differences between the magnetization of the continental and oceanic crust.

It has been found that the lower degrees of harmonic indicate that the vertically integrated magnetization over the oceanic and continental crust are almost precisely the same. In other words, the average dipole moment per unit area for continental crust is within 4% of that of the oceanic crust. It is suggested that in reality much of this signal must have a source not within the crust, but either in the upper mantle, or within the core of the Earth.

We have also looked at different numbers of spherical harmonic components in order to learn more about the continent-to-ocean contrasts in magnetization.

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MAGNETIC ANOMALIES

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Abstract. Without a doubt, the main event concerning the study of magnetic anomalies to have happened during this quadrennium was the successful deployment of a low elevation satellite which measured the scalar and vector magnetic field of the Earth. This satellite, called MAGSAT, was launched from Vandenberg Air Force Base on October 30, 1979 into a twilight, sun-synchronous orbit of apogee 561 km above the Earth's surface, perigee 352 km and inclination 96.76°. It remained in orbit until June 11, 1980, well exceeding its designed lifetime. Many preliminary results have been presented at various meetings (AGU, IAGA in Edinburgh, SEG) and a significant number of results have been published, mostly in a special issue of Geophysical Research Letters (volume 9 number 4, April 1982). But it should be emphasized that these are preliminary results, and there will be much more analysis done during the next quadrennium on the extensive data sets gathered by the satellite. With the acquisition of more surface data further steps were made in describing the tectonic history of the oceanic basins, but several problems remain. In particular, there seems to be considerable disagreement on the timing of the break up of Gondwanaland, and on the history of the various plates of the Pacific ocean basin. Major events in the study of continental magnetic anomalies have been the publication of magnetic anomaly maps of the conterminous United States, and of Alaska and the Hawaiian Islands. Further work has been done using continental magnetic anomalies to constrain models of various geological and geophysical features. Some useful advances have been made in modelling sea surface magnetic anomaly data. Problems in separating core and crustal field signals have been discussed by several authors.

MAGSAT

Much of the preliminary work in the interpretation of MAGSAT data has gone into producing magnetic anomaly maps. Langel et al. (1982a) discuss the derivation of a scalar map for latitudes less than $\pm 50^{\circ}$. They point out several of the pitfalls which need to be circumvented if reliable maps are to be produced from satellite data, such as correction for external field effects, and along track filtering. This along track filtering apparently results in an anomaly pattern elongated perpendicular to the tracks (i.e. approximately EW). One shortcoming of the method used by Langel et al. (1982a) is that no correction is made for the altitude of the satellite. Since the satellite also measured component data it was possible to produce component anomaly maps (Langel et al., 1982b). The number of data points which were available was much smaller for each of the component maps than for the scalar maps. The north component map shows the same EW lineation of anomalies as did the scalar anomaly map, whereas the eastward and vertical component maps do not seem to have this peculiarity.

Anomaly maps at higher latitudes are much more difficult to produce, because of the larger external field effects seen at these latitudes, such as field aligned currents and auroral effects. Therefore careful screening of the data prior to use is necessary in order to produce adequate anomaly maps for these regions. Scalar and vector maps of the Arctic have been produced by Coles et al. (1982) and a scalar map of the Antarctic is shown by Ritzwoller and Bentley (1982).

There have been several studies in which the accuracy and reliability of the satellite measured anomalies have been checked by comparison with other data such as aeromagnetic surveys. Won and Son (1982) compared the MAGSAT data with aeromagnetic data collected over the United States, and upward continued to approximately satellite altitudes. A striking feature of the upward continued data is that they are much smoother (i.e. of longer wavelength) than the satellite data, although the authors claim that there is an overall resemblance between the two anomaly maps. Another noticable feature is that the aeromagnetic upward continued map has much larger anomalies (total variation 55 nT) compared to the satellite data (total variation 22 nT). There is not only a problem with comparing upward continued surface data with satellite data, but also with different representations derived using the same data. Although the MAGSAT anomaly maps of the United States produced by Won and Son (1982) and von Freze et al. (1982) look moderately alike, the upward continued aeromagnetic maps produced by these authors are radically different. The reason for this difference should be investigated. Sailor et al. (1982) compared closely spaced tracks crossing the SE Indian Ocean using spectral techniques, and came to the conclusion that signals had some positive coherence at wavelengths greater than 700 km. In order to achieve a coherence greater than 0.5 however, the signal had to have a wavelength greater than 1000 km. This can be thought of as representing positive and negative magnetic signals of width 500 km, and so a natural question is what is the relationship between this number and the 220 km spacing of the data used to generate the MAGSAT anomaly maps described above.

Obviously, the use of the anomaly maps is to determine something about the structure and tectonics of the underlying regions, by determining what sort of magnetization models will adequately explain the anomalies, and how the regions came to be so magnetized. These studies are still in a preliminary stage, and undoubtedly the major thrust of effort will take place in future years, but some interesting pieces of information have already emerged. It is now a matter of routine to be able to produce a magnetization model which adequately explains the observed anomalous field. Mayhew and Galliher (1982, for MAGSAT data) and Mayhew et al. (1980, for POGO data) explain this technique. As the number of sources over a given area is increased, by placing them closer together, two things occur. The fit between observed and computed anomalies becomes better up to a certain spacing and

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then scarcely changes. And the variation in magnitude between sources starts to increase very rapidly for source spacing less than this spacing. What these observations tell us is that the resolution of the satellite data is limited to a certain spacing of sources. This phenomenon has been seen before, most notably in interpretations of marine magnetic anomalies. The spacing of the sources for North America was found to be 220 km, whereas the spacing of sources for Australia was found to be 300 km, consistent with the fact that the Australian data were collected at a higher altitude. The source functions used so far are predominantly dipoles located within the crust of the Earth, which are then transferred to magnetizations per unit volume by dividing by the area represented by each dipole and by a uniformly thick crustal region. Models achieving exactly similar agreement to the observed anomalies could be calculated by assuming a uniform magnetization, and having the magnetized layer of variable thickness. This technique is explained by Mayhew (1982) using the data from the western United States. He found that in some places there was a good inverse correlation between the thickness of the magnetized layer and the heat flow. The reason for this is thought to be due to the fact that higher heat flows will produce more elevated temperatures at depth, causing the magnetic minerals to be above their Curie temperatures at shallower depths, and hence causing the thickness of the magnetized layer to be less. An additional factor which should eventually be included in such models is the variation in the strength of magnetization from area to area. This depends very much on the rock type, which is unfortunately not well known for the deeper portions of the continental crust. The models also assume that the magnetization is in the direction of the core field (represented by a spherical harmonic function up to about degree twelve), and so might be thought of as induced magnetization except for one problem, which is that some of the magnetizations so generated are negative, representing directions opposite to the core field. If induced magnetizations are indeed responsible for the long wavelength anomalies seen at satellite altitudes, it is probable that an acceptable solution (i.e. one in which all magnetizations are positive) could be obtained by determining the annihilator function for a tesseral cap and adding as much of this annihilator function to the calculated magnetization variations as is necessary to remove all of the negative magnetizations. The annihilator is simply a magnetization function which gives no external field, and it was originally developed for use in sea floor spreading magnetic anomalies.

However, the problem still remains to determine the directions of magnetization within the crust from the magnetic anomalies themselves. Although there have been statements made that the acquisition of vector data will help in determining the direction of magnetization in a body (e.g. Langel et al., 1982b) it is not obvious to what extent component data will allow this to be done better than magnitude (scalar) data. What is really necessary in order to do this is to be able to specify the shape of the body to be investigated, in terms of its having a finite magnetization compared with the surrounding regions in which the magnetization is small enough to be negligible. For instance, it is perfectly possible to determine the magnetization vector in a seamount using field magnitude data, because the seamount topography delineates the region of positive magnetization from the sea water with no magnetization. Galliher and Mayhew (1982) suggest that in fact it may be exceedingly difficult to determine directions of magnetization from satellite magnetic anomaly maps. By inverting scalar data to obtain equivalent source models, they were then able to generate component data from these source models and compare them to the observed satellite component data. They tried this with the dipole sources in three different directions and found that the ability to model successfully the component data was not impaired by constraining the dipoles to point in peculiar directions. This is the sort of thing that we would expect from fields whose potential obeys Laplace's equation. Obviously, much further work needs to be done on the applications of vector data in the solution of geological problems.

There have also been attempts to correlate anomaly features with large scale geological structures. A number of papers appear in the special issue of Geophysical Research Letters. For instance Hinze et al. (1982a) suggest that there is a correlation between aulacogens in South America and negative magnetic anomalies, while the shield areas appear to be marked by positive anomalies. This is discussed in greater detail by Longacre et al. (1982). Other results have been presented for Africa, Asia and North America. Also of interest in deriving geological models to explain the long wavelength magnetic anomalies is an ability to place limits on the vertical extent of the source areas. Wasilewski and Mayhew (1982) and Wasilewski and Fountain (1982) suggest that the lower continental crust, which they suppose to be formed of granulite, may be the source of intermediate wavelength magnetic anomalies. They do not believe that there is any necessity for having significant source regions below the Mohorovicic discontinuity (see also Wasilewski et al., 1979). However, these arguments depend to some extent on the necessity of extrapolating data from zenoliths to a representation of the whole lower crust, and also on the lack of knowledge of mantle material. Thus, the possibility still remains that serpentinite bodies beneath the regional Moho depth may still cause long wavelength anomalies, especially in oceanic regions where the temperature at the base of the crust is still quite low, especially for older oceanic crustal regions. Note however that Haggerty (1978) has suggested that partially serpentinized ultramafic bodies may contain metal alloys, whose Curie temperatures can be in excess of $1000^{\circ}C$, if Co or Cu are predominant in the alloy. If this is the case, then significant thicknesses of mantle material could be below the Curie temperature and hence could contribute to magnetic anomalies. The alloys studied by Haggerty (1978) have saturation moments which can be in excess of that for pure magnetite. For instance the saturation moment for CoFe is 232.1 $emu.gm^{-1}$. This fact also makes partially serpentinized ultramafic bodies with metal alloys a possible source for magnetic anomalies. One problem which has not been adequately studied is how the serpentinization process, which requires temperatures lower than about $500^{\circ}C$, can have taken place in rocks which are currently at much higher temperatures.

Core Magnetic Field

The ability to produce good anomaly maps depends critically on the ability to model and remove the core magnetic field of the Earth. Thus, the recent decision of Working Group I Division I at the IAGA meeting in Edinburgh to update continuously the International Geomagnetic Reference Field at five year intervals must be viewed positively. Since the main field for any epoch is best determined by data equally spaced in time around the epoch, a Definitive International Geomagnetic Reference Field (DGRF) for any epoch can only be established about five years after the epoch has passed. But since it is necessary to remove core field from data before the DGRF has been established, it is required to have an IGRF for 1980, which with secular variation terms can be used until 1985, and a Provisional International Geomagnetic Reference Field (PGRF) for the period 1975 to 1980, being a linear interpolation between the DGRF for 1975 and the IGRF for 1980. Thus, for any epoch not coinciding with one of the five yearly evaluations of the data, there will be three different fields used to remove the core sources, depending on whether the epoch during which the data were gathered occurred since the last evaluation (IGRF plus secular variation), within five years prior to the last evaluation (linear interpolation between a DGRF and an IGRF), or further back in time (linear interpolation between two DGRF's). This may cause confusion, but with the extreme ease of applying the corrections to digitally stored data, the three corrections can easily be applied (Peddie, 1982a,b; IAGA Division 1, Working Group 1, 1981).

But the theory behind the removal of the core field using spherical harmonics has been questioned by Carle and Harrison (1982) who point out that an arbitrary cut off at a certain degree of spherical harmonic does not produce a clean separation of long wavelength anomalies from the signal, since high degrees of spherical harmonic have long wavelength signals associated with them. They also suggested (Harrison and Carle, 1982) that the signal left in the MAGSAT data set after having removed the core field, usually thought of as being associated with the first thirteen degrees of spherical harmonic (Langel and Estes, 1982) is too large to be caused by crustal magnetizations. The additional along track filtering used prior to development of anomalous magnetic fields maps (see above; Langel et al., 1982a) may remove much of the unwanted long wavelength component, but may also be responsible for the lack of correlation between satellite data and upward continued aeromagnetic data, and may also be responsible for the EW trend of the satellite anomalies. It is clear that the problem of filtering, or what to leave in and what to take out, needs to be studied in far greater detail than has heretofore been done. Unless one is just interested in magnetic anomalies for such things as dating the ocean floor, it is simply not good enough to pretend that the core field may be removed by a degree 13 spherical harmonic expansion plus a little bit more, if necessary. This tends to obscure the intermediate wavelength signal, which may be trying to tell us something interesting about the crust.

The intermediate wavelength signal in marine magnetic anomalies was the subject of two papers published in a special issue of the Journal of Geophysical Research in honor of Sir Edward Bullard. Harrison and Carle (1981) showed that the shape of the power spectrum of marine magnetic anomalies was not what would be expected from completely lineated sources plus a core field, because there was no minimum in the power spectrum for wavelengths appropriate to mantle sources. They also indicated that the magnetization contrast necessary to explain the intermediate wavelength features was quite large. Shure and Parker (1981) on the other hand, had an explanation for the shape of the power spectrum at intermediate wavelengths. They suggested that the lack of a minimum in the power spectrum at intermediate wavelengths was because the "lineated" anomalies were not perfectly lineated. Thus any profile crossing the sea floor spreading anomalies would have intermediate wavelength power added by the non-linearity of the sources. They did not however tackle the problem of the intensity of magnetization necessary to explain the suite of anomalies. However, McLeod (1983a) has shown that the model used by Shure and Parker (1981) requires a considerable magnetization of r.m.s. value 1.95 $A.m^{-1}$ within the whole oceanic crust. Thus, the problem of intermediate wavelength anomalies and their causes is still a subject worth further investigation.

The intermediate wavelength field was also studied by Alldredge (1981) who pointed out that spherical harmonic analysis of fields of limited areal extent was extremely cumbersome in that so many spherical harmonic terms were needed to represent shorter wavelength signals of the field. His solution was to use a rectangular harmonic analysis. The advantage of this analysis is that far fewer coefficients are needed unless the whole of the Earth is to be covered. For instance, in order to represent wavelengths of magnetic potential down to 100 km using spherical harmonics a total of 160,800 coefficients need to be used. But if an area approximately square shape with a side of length 2300 km, representing 1.0% of the Earth's area, needs to be evaluated at the same resulution the number of rectangular coefficients is only just over 1000. One problem which does not seem to have been adequately studied when using sperical harmonic analysis or rectangular harmonic analysis is that of aliasing. This problem is well known in one dimensional Fourier analysis but seems scarcely to have been tackled in spherical harmonic analysis. We know that there are distinct magnetic anomaly signals in the deep oceanic areas with significant signal down to wavelengths of ten km or so. Therefore, any data from the oceanic regions which are used to determine spherical harmonic coefficients must sample spatially at half this wavelength; otherwise some of the real signal at small wavelength will be spuriously transformed into longer wavelength signals. Some attempt to deal with this problem has been made by allowing observatory data to be offset by some amount to be determined in the spherical harmonic solution, this amount being then equivalent to the local magnetic anomaly at the observatory. But this method depends on having a large quantity of other data such as satellite data, in which local anomalies are much less important due to the elevation of the satellite.

Oceanic Basins

The study of the plate tectonics of ocean basins is still proceeding, largely with the help of marine magnetic anomalies. In some cases, preliminary models are being revised by a more careful and detailed study of the anomalies and other tectonic features, whereas in other cases major reevaluations of the existing plate tectonic models have been carried out. Major reevaluations of Pacific plate tectonics occur more frequently than in other ocean basins, mainly because there is no good starting model for the Pacific Ocean basin. As we go back in time, the area of the Pacific Ocean basin increases, but the area in existence then, which remains today, decreases, due to the fact that the basin is surrounded on most sides by subduction zones.

Pacific Ocean

Klitgord and Mammerickx (1982) produced a new model of spreading in the NE Pacific, involving the Pacific, Guadalupe, Rivera and Cocos plates from 25 m.y.B.P. to the present, using the magnetic anomalies and bathymetric observations. A more limited study was done by Schilt et al. (1982) on the evolution of the Cocos plate during the past fifteen million years. One interesting feature of their model is that the rotation pole for Cocos-Pacific motion over this time interval is much closer to the northern margin of the Cocos plate, with the result that the curvature of the Orozco fracture zone can be produced simply by the proximity of the rotation pole.

Further south, a new interpretation of the absolute motion of the Nazca plate was made by Gordon and Izmirian (1983). They proposed that at the time of breakup of the Farallon plate into the Nazca and Cocos plates (which they think occurred at 25 m.y.B.P.) a major shift in the absolute motion of the Nazca plate over the hot spot frame of reference took place. Reconstructions of earlier tectonic history in the Southern Pacific have been hampered by the lack of data. But a cruise by R/V Conrad added significantly to the amount of data in this region and enabled Cande et al. (1982) to arrive at a new interpretation of one area in the SE Pacific. They suggest that a ridge jump (or a rapidly propagating spreading center) 50 m.y.B.P. (anomaly 21 time) separated a portion of the ocean crust from the Pacific plate and added it to the Aluk plate. Their model does not require relative motion to occur along the Eltanin fracture zone system, except between the active spreading centers. In other words they suggest that such motion, which has been used to explain the discrepancy in paleomagnetic measurements between the North and South Pacific, has probably not occurred although their data do not absolutely forbid it. In another study of great detail, the interaction of the Chile Ridge with the Chile trench has been documented (Herron et al., 1981). This is one of the two areas in the world where zero age crust is being subducted, the other being at the opposite end of what was originally the Farallon plate, now called the Juan de Fuca plate. The surprising thing about this interaction is that neither the trench nor the ridge seem to be modified except where they are very close to each other. The reason may be that this situation of a ridge entering a trench has only existed for a few hundred thousand years. Prior to this time, the interaction was between a fracture zone and the trench.

A general synthesis of Tertiary and Upper Cretaceous magnetic anomalies in the eastern Pacific ocean has been produced by Whitman and Harrison (1983). This is apparently the first attempt to deal with all of the tectonic problems within the scope of a single study. While in any one area there will be details not covered by their model, in general the major plate changes, reorientations, ridge jumps etc. have been satisfactorily dealt with. One major problem was to explain the data concerning hot spot traces, paleo-equator crossings and other paleogeographic evidence. This usually calls for an additional plate boundary, which is sometimes placed between East and West Antarctica, sometimes along the Eltanin fracture zone or some other lineation in the southern Pacific. Whitman and Harrison chose to use the model of Farrar and Dixon (1981) to explain most of the paleomagnetic and paleogeographic discrepancies. This calls for an additional plate boundary between the NW Pacific basin and the rest of the Pacific plate, with a fracture zone running along the Emperor trough, and an extinct spreading system running to the north of Australia. Further work is necessary to determine which of the additional plate boundaries explains the observed features better.

Atlantic Ocean

In the North Atlantic Ocean, most of the effort has gone towards refining the fits of the continents shortly after opening took place in the early Mesozoic. Many of the data used in these studies were aeromagnetic. In addition, there has been some effort in using magnetic data to refine geophysical models of the continental margins. Schouten and Klitgord (1982) showed that closely spaced magnetic data could be used to delineate fracture zones, without the need for any bathymetry. Indeed, the fracture zones may in some cases be located more easily using magnetic anomalies, because the topography tends to become obscured by the thick sediment cover of the older NE Atlantic ocean floor. They also suggested (see also Schouten and White, 1980) that in some cases there are breaks in the magnetic anomaly pattern, marked by changes in amplitude, rather than by offsets, and suggest that the spreading process is organized into cells of finite length running along the ridge crest, each cell acting independently of the others, and eventually producing a distinctive magnetic pattern which can be distinguished from that of the adjacent cells. The nature of the J anomaly in the NE and NW Atlantic was studied by Rabinowitz et al. (1979). This anomaly was shown to be isochronous wherever these authors studied it. Their explanation for it is a zone of much greater magnetization intensity centered on crust of MO age, but extending into normally magnetized crust on either side of MO. An alternative explanation could be a thicker magnetized layer. The maximum magnetization necessary to model the J-anomaly successfully was six times the magnetization of normal crust on either side. No explanation was given for the large increase in intensity of magnetization.

Klitgord et al. (1983a,b) used magnetic anomalies amongst other types of information to constrain models of the early tectonic development of the southeastern United States continental margin. Ancient fracture zones can be mapped in the western North Atlantic using magnetic anomalies, and divide the continental edge into zones having slightly different tectonic styles. Klitgord and Behrendt (1979) and Behrendt and Klitgord (1980) used magnetic anomalies in a slightly different way, to determine depth to basement for the US Atlantic continental shelf, slope and rise. It is not clear, however, that these measurements represent independent estimates, because they were chosen out of a much larger number of calculations, in order to match the information from seismic data. In any case, their analysis showed that the magnetic evidence was consistent with other geophysical data.

Talwani et al. (1981) used aeromagnetic data collected from the Norwegian margin to infer that the shallow region of steeply dipping reflectors seen in the Outer Voring Plateau is of the same age as normal oceanic crust seen in the Lofoten Basin because of the continuity of anomaly 24 through both regions. They surmised that the steeply dipping reflectors consist of basaltic flows and volcanigenic sediments formed about 4 million years after the oceanic crust on which they are placed.

A somewhat revised analysis of the opening of the South Atlantic was produced by Rabinowitz and LaBrecque (1979). Their time of opening of the South Atlantic is about 130 m.y.B.P., in agreement with some earlier work. But their initial poles of rotation are considerably further south, resulting in extension in the south of the region while the equatorial South Atlantic basin was under some compression. Thus, the observed difference in timing of the beginning of marine sequences between the south (Upper Valanginian) and the north (Albian) is satisfactorily explained by their model. On a more detailed level LaBrecque and Hayes (1979) used magnetic anomalies and bathymetry to study the sea floor south of the Agulhas-Falkland fracture system in the South Atlantic. The ridge crest jump which must have occurred here is thought by them to have taken place in the Late Maestrichtian. Another small plate was in existence between the ridge crest and the Falkland Plateau but disappeared after the ridge crest jumped to its new position.

Several studies have been done on critical regions in the Southern Ocean, where data are still very sparse. For instance, the data interpreted by LaBrecque and Barker (1981) from the Weddell Sea indicate that the age of this basin is older than previously thought. The earliest ocean crust in their model is 162 m.y.B.P. But as they point out, the new data, while suggesting that some of the earlier models are incorrect, have not yet allowed workers to choose between the different proposed models for the reconstruction of Gondwanaland. One thing that the new data in the Southern Oceans allows us to do is to refine the sea floor spreading rates between Antarctica and South Africa (LaBrecque and Keller, 1982).

Indian Ocean

Several major papers on the reconstruction of the Indian Ocean have appeared within the past four years. Norton and Sclater (1979) have presented a complete history of the opening of the Indian and South Atlantic Oceans, starting from a reconstruction of Gondwanaland in which Madagascar is placed in a north position against the coast of Kenya, and in which relative motion has to occur between East and West Antarctica. East Antarctica fits against the eastern side of South Africa and from poorly developed magnetic anomalies (Simpson et al., 1979; Harrison et al., 1980) in the Mozambique basin appears constrained to separate from Africa at M22 time. Yet more recent work by Rabinowitz (1982) constrains Madagascar to move away from the coast of Kenya in a southerly direction considerably earlier than this, presenting a space problem. The earlier breakup of Gondwanaland proposed by Rabinowitz (1982) and LaBrecque and Barker (1982, see above) removes one of the problems of placing Madagascar to the north, which was the sediment history seen in DSDP hole 241 and seismic reflection records connecting the sediments in this region to those dated by shallow water drilling. An alternative model for the spreading in the Indian Ocean and South Atlantic has been presented by Barron and Harrison (1980), who place Madagascar to the south and who require no separation between East and West Antarctica. Obviously, this area needs considerably further work. Collection of data close to Antarctica would be of immense help, and as has been discussed above, could be done by aeromagnetic surveys, which not only can be used to identify magnetic anomalies, but also can help in showing the directions of fracture zones provided that the flight lines are closely spaced.

Several studies in the Gulf of Aden and Red Sea have made use of magnetic anomalies. Cochran (1981a,b, 1982a, 1983) has presented studies of both areas, which appear to be consistent with respect to the timing of the initial opening. He believes that the data do not indicate periods of quiescence which had been proposed previously. Rather, the spreading has been continuous since sometime during the Miocene. The change from the deep axial valley to the shallower structures on either side, observed in the southern Red Sea, is considered to mark the change from continental extension by rotational faulting and dyke intrusion to genuine sea floor spreading concentrated in an area only a few km wide. The diffuse continental extension seen in the Red Sea is also believed to exist along the northern margin of the Gulf of Aden, where it forms a magnetic quiet zone. But see Girdler and Styles (1982) and Cochran (1982b) for further discussion of this matter.

Sea floor spreading anomalies have formed the basis for determining the movement of Australia away from Antarctica, which was thought to have commenced about 55 m.y.B.P. However, a new interpretation of these anomalies by Cande and Mutter (1982) suggests that the separation occurred much earlier. They were able to recognize anomaly 34 as being the first anomaly seaward of the quiet zone off both coastlines. When allowance is made for the crust produced during the quiet zone, the age of breakup appears to be about 100 ± 10 m.y.B.P. A corollary of this early breakup is that there has to be very slow spreading between the time of breakup and about 45 m.y.B.P. Sea floor spreading west of Australia was studied by Larson et al. (1979). They indicate that greater India started to separate from this region of Australia at about 120 m.y.B.P. These results and others described above all relate to the timing of the breakup of Gondwanaland. It appears that there are significant discrepancies of these timings, which need further study to bring them together into a consistent model of Gondwanaland dispersion.

Arctic Ocean

Further aeromagnetic data from the Arctic gathered by the U.S. Navy has been interpreted during the past four years (Vogt et al., 1979, 1981; Taylor et al., 1981b). The Lomonosov Ridge, a continental sliver running through the North Pole along meridians 140°E-60°W separated from the Eurasian margin somewhat earlier than 55 m.y.B.P. The oldest magnetic anomaly recognized for the Nansen-Gakkel Ridge, the sea floor spreading center separating the Lomonosov Ridge from Eurasia is anomaly 24, but there is an area about 75 to 150 km wide between this anomaly and shelf edge where no recognizable anomalies could be seen, suggesting that the time of breakup was earlier than anomaly 24 time. Magnetic anomalies in the Canada Basin, which is the basin immediately north of Alaska, with the Queen Elizabeth Islands to the east and the Northwind Ridge to the west, have been interpreted as being caused by Mesozoic spreading (Taylor et al., 1981a). The magnetic anomalies fan out into the Canada Basin appearing to come from an apex just south of the Beaufort Sea. The timing of the spreading is from 153 m.y.B.P. (anomaly M25 time) to 127 m.y.B.P. (anomaly M12 time). The model calls for the rotation of Alaska away from the Canadian Arctic during this time, about a pivot point coincident with the area from which the anomalies appear to fan out. The authors emphasize that this model is quite tentative, due to the small amount of data available. The third Arctic area studied was the Alpha Ridge and Makarov Basin. The origin of the Alpha Ridge remains obscure, but these authors do not think that it was formed by sea floor spreading. They do believe however that the Makarov Basin was formed by sea floor spreading during which time the Alpha Ridge separated from the Lomonosov ridge. The timing of this separation was between the Late Cretaceous and Paleocene (anomalies 22 to 34), which correlates well with the timing of the separation of Greenland from North America.

Marginal Basins

The geological history of the marginal basins has been enigmatic for many years. Significant work on

Table 1. Marginal basins of the western Pacific and their ages (adapted from Weissel, 1981).

Probable back arc spreading	Possible back arc spreading	No back arc spreading
Bismarck Basin (m. Plio.-)	South Fiji Basin (Olig.)	Woodlark Basin (M. Plio.-)
Fiji Plateau (l. Mio.-)	West Philippine Basin (Eocene)	Coral Sea Basin (Pal.)
Shikoku Basin (m. Olig.-e. Mio.)	Caroline Basin (Olig.)	Tasman Basin (l. Cret.-Pal.)
Parece-Vela Basin (Olig.-e. Mio)	New Hebrides Basin (l. Pal.-l. Eocene)	South China Basin (Olig.-e. Mio.)
Lau Basin (l. Mio.-)	Andaman Basin (m. Mio.-)	Aleutian Basin (l. Jur.-e. Cret.)
Mariana Trough (l. Mio.-)	Celebes Basin (Eocene)	Solomon Sea Basin (?)
Havre Trough (Plio.-)	Kamchatka Basin (Olig.)	
Japan Sea Basin (Olig.-e. Mio.)	Sulu Basin (Olig.)	
Okinawa Trough (Plio.-)	Banda Basin (?)	
Okhotsk Basin (?)		

Some of the ages are uncertain.

elucidating the problems of these basins has been accomplished during this four year period. A useful review of the basins of the western Pacific has been published by Weissel (1981). Table 1 summarizes in slightly different form Weissel's table 1, listing basins which were probably formed by back-arc spreading, those which were possibly formed by back-arc spreading, and those which are believed not to have formed by back-arc spreading. In this table, the basins are listed according to the quality of the marine magnetic anomalies used to determine their geologic history. Weissel also made some comments about back-arc spreading compared to mid-oceanic ridge spreading. Although the zone of crustal accretion in back-arc basins appears to be similar to that from mid-oceanic ridges, the duration of spreading from any one back-arc spreading center tends to be quite short, on the order of 10 m.y., compared with c.100m.y. for major ridge systems. The placement of a basin into the category of No back-arc spreading is based on the timing of events largely. If the spreading which produced the basin is not related to subduction of the surrounding ocean floor (i.e. it is in the wrong direction, or it pre-dates subduction) then it is placed in this category. Back-arc spreading then means spreading in response to subduction. Other marginal basins have also received some study during the past four years. In particular, the Andaman Sea (Curray et al., 1979) was shown to have formed by extension and to have produced a moderately good magnetic anomaly signature.

Seamounts

After a pause of a few years, there has been increasing activity concerning the magnetic anomalies produced by seamounts. A survey over Suiko seamount, part of the Hawaiian-Emperor seamount chain, was analysed by Kodama et al. (1978), who found a direction of magnetization consistent with the seamount having formed at the same latitude as Hawaii is today within rather broad errors. The agreement between the observed and computed anomalies was not very good, but the interest in this seamount is that it was drilled during leg 55 of the Deep Sea Drilling Project. Inclinations of magnetization of basalts collected during this leg (Kono, 1980) suggest however, that Suiko was formed at a slightly higher latitude than Hawaii is today, giving some support to the idea that the hot spot reference frame is not fixed with respect to the geomagnetic field reference frame (Harrison and Lindh, 1982).

A survey of a much smaller seamount in the Pacific (Watkins seamount) showed agreement with previously published material (Keating and Sager, 1980). Small seamounts tend to give much simpler magnetic anomaly patterns which are capable of being fitted by a uniform magnetization of the bathymetric shape of the seamount. The goodness of fit parameter for Watkins seamount is one of the highest ever achieved. Nagata seamount, close by to Watkins seamount, also gave an acceptably high goodness of fit parameter, and a pole position consistent with other seamounts in the same general area (Sager et al., 1981).

In contrast to the paleomagnetic inclination data from Suiko seamount, the magnetic anomaly data from Abbott seamount (Sager, 1983), located close to the bend in the Hawaiian-Emperor seamount chain, suggests a latitude of formation close to that of Hawaii today, indicating little movement between the hot spot reference frame and that of the geomagnetic field. A new technique used in this paper was upward continuation of the magnetic anomaly, which allowed the fit between computed and observed anomalies to become very close.

Magnetic Anomalies in the United States

Magnetic Anomaly Maps

A major event in the study of continental magnetic anomalies was the publication of a composite magnetic anomaly map of the United States (Zietz et al., 1982). This map was put together from a wide variety of sources (but mostly total field aeromagnetic surveys), which are well documented in the accompanying description of the map. The map is colored and published at a scale of 1:2,500,000, and is of the total field from which has been removed a regional field, usually represented by the IGRF. Almost all of the conterminous United States is covered, along with some portions of the adjacent marine areas. The compilers have done an excellent job at putting together the data from such a wide variety of sources, in which flight path separations and altitudes can vary by as much as an order of magnitude. But as the compilers point out, the map must be used with caution, as many of the changes of magnetic character are due to the juxtaposition of data from different sources. Wider line spacings and higher flight paths will tend to produce a magnetic anomaly map with less character to it. Thus the map should only be used with the accompanying description, which indicates flight path elevations and spacings. The change from one data type to another is marked on the map itself. The data are contoured every 200 nT with some subsidiary contours at 100 nT intervals. The map will be particularly useful when used in conjunction with the geologic, tectonic, basement rock, and Bouguer gravity anomaly maps of the United States.

Notable features which can be recognized on this map include the following. The Appalachian system is recognizable as a series of narrow, elongated anomalies running sub-parallel to the main trends of the mountain system. These anomalies are better shown in a more detailed map of the region (Zietz et al., 1980). There is a group of more-or-less equidimensional positive anomalies centered around the Kentucky-Tennessee border (the so-called Tennessee anomaly). The region of the mid-continent gravity high is marked by some elongate positive anomalies. More detailed discussion of anomalies in the mid-continent region, plus a more accurate magnetic anomaly map of this area, can be found in Hildenbrand et al. (1983). There is a large elongated positive magnetic anomaly running parallel to the Sierra Nevada but to the west, along the San Joaquin Valley. Various portions of the Cascades give rise to significant positive anomalies. The largest positive anomaly on the map is located just south of the Canadian border, close to the Rocky Mountain Thrust Belt. In the oceanic areas, the east coast magnetic anomaly is recognizable, as are the lineated sea floor spreading anomalies off the west coast of the United States.

One peculiar feature about the map is that the average level of the anomalies is about 900 nT above the regional field used, which was the IGRF suitably updated for the epoch of each survey. The reason for this very large offset over such an extensive area is unknown. In oceanic areas there are often offsets of long wavelength, but they rarely become greater than 300 nT.

A composite magnetic anomaly map of Alaska and Hawaii will also be available soon (Godson, 1982). The preliminary version is not in color and so is less easy to understand. All the remarks made concerning the magnetic anomaly map of the conterminous United States also apply to the map of Alaska. It appears as though some portions of Wrangellia, an allochthonous terrane normally considered to be oceanic in structure, are characterized by short wavelength, high amplitude magnetic anomalies. It is possible that the map of Alaska might be of use in determining more about the tectonics of the displaced terranes which make up the whole of this sub-continent. The map of the Hawaiian Islands and surrounding oceanic areas should have fewer of the problems associated with the other maps, since the data were collected at a fairly constant elevation, except over the peaks of Mauna Loa and Mauna Kea. The data over the islands were flown at a close line spacing, whereas the oceanic data were collected using a line spacing from 3 to 9 times as large. It is possible that this increase in spacing is responsible for the much smoother aspect of the magnetic anomalies over the oceanic areas compared with those over the islands. But it is more likely that this is the true state of affairs, in that the islands would tend to give higher amplitude anomalies due to their elevation compared with that of the surrounding oceanic areas. The anomalies in this map are described in detail by Malahoff and Woollard (1968).

Continental United States Studies

Magnetic surveys have played a useful part in understanding ancient continental rifts. Keller et al. (1982) studied a linear feature running through Kentucky and Tennessee and came to the conclusion that it was an ancient rift, formed during the Keweenawan orogeny. The magnetic anomalies over the rift area are of high amplitude and very short wavelength, suggesting that the causative bodies are shallow and have a large magnetization or susceptibility. Thus the rift represents an area where mafic or ultramafic rocks come closer to the surface than in the surrounding regions. This rift may be related to the rift which causes the mid-continent gravity high. The Mississippi Valley embayment is another area for which continental rifting has been postulated (Kane et al., 1981; Hildenbrand, 1982). In this case the rifted area is marked by weak magnetic anomalies compared with the surrounding regions. It has been calculated that basement is 2 km deeper under the rift than in the flanking areas. It is thought that this rift started to be active in the earliest Paleozoic. It is not known why these two rifts have produced opposite effects on the level of the basement. One would normally think that any rifting process would cause thinning of the crust, and that after the thermal anomaly produced during the rifting process had been dissipated the resulting structure would have a depression over the rift. If this depression then becomes filled with sediment, the resulting isostatic adjustment would cause the basement beneath the rift to become depressed with respect to that on either side, provided that the infilling sediment is less dense than the basement material. If however the sediments are more dense than basement rock, the basement will be elevated with respect to the surrounding regions, as in the model proposed for the Kentucky-Tennessee lineation. In this respect, the Lake Superior basin (Hinze et al., 1982b) represents an area with thicker sedimentary cover than normal, resulting in more subdued magnetic anomalies. Strangely enough, the Rio Grande Rift does not appear to give any significant signal visible on the magnetic anomaly map (Zietz et al., 1982). Nor is there any mention made of magnetic anomalies in the monograph volume on this feature (Riecker, 1979).

Magnetic Modeling

There have been significant advances in this field over the past four years. Generally they have been designed to investigate the nature of the magnetization responsible for marine magnetic anomalies. Blakely and Hassanzadeh (1981) attempted to determine the depth to the source of marine magnetic anomalies on either side of the Peru-Chile trench by determining the negative slope of the maximum entropy power spectrum of magnetic field as a function of wave number. This slope should be directly dependent on the depth to the source. Their results on synthetic anomalies were excellent, but they raised some doubts as to the utility of the method when applied to observed magnetic field signals. Blakely (1973) studied the effect of "noise" in the tape recorder on magnetic fields, and found that the discrete magnetic units seen in the upper part of layer 2 will not seriously disrupt the observed signal unless these units are considerably wider than 0.1 km, which seems to be a typical observed width of an extrusive body. He also suggested that layers deeper than the upper part of layer 2 are necessary to generate the observed field signals. Blakely (1983) studied average power spectra of ensembles of magnetic anomalies of three different ages. After having allowed for varying ocean depth, changes in spreading rate and reversal rate between the three areas, and several other factors, he found that the younger anomalies tended to preserve their short wavelength signal much better than did the older anomalies. He suggested that the upper pillow basalt layer, in which much of the short wavelength signal resides, gradually loses its magnetization as it ages, with a time constant of about 30 m.y.

Schouten and Denham (1979) and Denham and Schouten (1979) developed a Monte Carlo model of the upper oceanic crust in order to study the likelihood of going through a reversal in a vertical drill hole, which has been demonstrated to have a high probability during the past few years of ocean crustal drilling. They found that this probability depended mostly on the spreading rate and the width over which lava flows are extruded onto the oceanic crust, and rather little on the number of units extruded per unit time. Critical tests of their model await drilling in areas of rapid spreading, where they predict that the probability of striking a reversal in vertical section would be small.

Macdonald et al. (1980) have produced the most exact picture of what a reversal in magnetization looks like within the oceanic crust. They inverted magnetic field data collected close to the ocean floor, taking topographic effects into account, and assuming nothing about the linearity of the source. The magnetization turned out to be extremely linear, and the width of the zone in which the magnetization changed from one polarity to the other was only just over 1 km, indicating a crustal emplacement zone of about 0.8 km width. But this conclusion was reached in a region of relatively well developed magnetic anomalies, just off the mouth of the Gulf of California. In the same area, a series of measurements of the polarity of faulted outcrops, lava flows and other features which gave measurable magnetic anomalies was made. The Alvin was used to get close to these features, and their magnetic field was measured using a three component magnetometer and a vertical gradiometer, which enabled the polarity of each feature to be determined. These polarities (a total of 280 determinations was made) also were arranged in a very coherent way, such that a single line separated the features formed during the reversed Matuyama interval from those formed during the normal Brunhes interval. This boundary line lay further from the ridge crest than did the zero magnetization line determined from the inversion of the deep tow field measurements. This is exactly what is to be expected from a model of overlapping lava flows coupled with spreading, for which the reversal boundary will slope downwards from the surface towards the spreading center. The two boundaries are separated by about 0.5 km. Wilson and Hey (1981) have also studied the problem of transition widths, and found that the transition width in the gabbro layer was much wider than in the upper layer, and also that the magnetization was offset away from the ridge crest in the lower layer, this being consistent with cooling curves showing where material passes through its Curie temperature.

Summary

Preliminary results from MAGSAT are encouraging. Much further work is needed before the significance of the results is fully understood. The possibility of obtaining satellite magnetic field measurements at a lower altitude (on the Geopotential Research Mission) should be encouraged. Interpretation of magnetic anomalies is still one of the best ways of sorting out difficult tectonic problems in the ocean basins. Past work on marginal basins is now paying off, but more effort is needed to unscramble the complex opening scenario of Gondwanaland. Further work on continental rifts will help in determining the depth to the basement in these features. Seamount magnetization studies are are making a comeback, and with the better results now being obtained, promise to be of use in determining Pacific Ocean Basin plate tectonics.

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