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RESULTS FROM THE MAGSAT MISSION

This article summarizes results obtained by the Magsat spacecraft mission of 1979-80 in modeling the geomagnetic field and in studying the earth's core, mantle, and core-mantle interface; crustal magnetic anomalies; and fields resulting from external current systems.

Magsat was the first near-earth spacecraft totally dedicated to the measurement of magnetic fields. The July-September 1980 issue of the *Johns Hopkins APL Technical Digest* (Vol. 1, No. 3), henceforth called "the earlier issue," was devoted to a description of the Magsat spacecraft, which the Applied Physics Laboratory designed, developed, and tested. There I gave a broad outline of the scientific investigations that were under way, listed the principal scientists involved, and described the very earliest results of analysis of the Magsat data. In the intervening two years, there has been substantial additional analysis, culminating in the April 1982 issue of *Geophysical Research Letters*, in which 36 papers relating to Magsat data analysis appeared.

Data from Magsat were acquired through the National Aeronautics and Space Administration (NASA) Space Tracking and Data Network and transmitted to the Goddard Space Flight Center (GSFC), where the Information Processing Division sorted and time-tagged the measurements and forwarded them to my (project scientist's) office. The satellite was tracked by the Defense Mapping Agency Doppler network, whose data were analyzed by personnel at APL to precisely determine the ephemeris.

Measurement of the vector field direction to 20 arc-seconds was a major challenge. The instrumentation to accomplish this was described in the earlier issue. Attitude data were analyzed by the Mission Support Computing Analysis Division at GSFC and then sent, through the Information Processing Division, to my office. Completion of the attitude determination to 20 arc-seconds required about eight months after data acquisition, so analysis of the vector data did not commence until some time after launch. When the data were received in the project scientist's office, we checked them for quality and consistency, used the data from the cesium-vapor scalar magnetometer to calibrate the fluxgate vector magnetometer, and converted the data to a form easily used by investigators.[1] The data were then (and are now) distributed by the National Space Science Data Center at GSFC. The full data set became available in September 1981. After that time, several special data sets and data plots have also been made available.

Investigations using Magsat data fall into four relatively distinct categories:

1. Geomagnetic field modeling;
2. Investigations of the earth's core, mantle, and core-mantle boundary;
3. Crustal magnetic anomaly studies;
4. Studies of fields from external current systems.

The next four sections summarize the results obtained to date in each of these areas. Much analysis is still in progress, and the results presented here are preliminary in nature.

GEOMAGNETIC FIELD MODELING

In 1839, Gauss showed that, in a region free of electric currents, the magnetic field can be represented by a scalar function, known as a potential function. The space near the earth is, for practical purposes, current-free, so Gauss' result applies. Gauss himself derived such a model, using a spherical harmonic expansion as his potential function. In the years since, spherical harmonic expansions have been the usual form of such models, although occasionally a different form is chosen.

A geomagnetic field model, then, is a potential function representing the measured field, usually in a best least-squares sense. Most such models represent only the field originating within the earth and, indeed, only the portion of that internal field originating in the core. The so-called core, or main, field is actually the major portion of the measured field. Its magnitude is between 30,000 and 50,000 nanoteslas at the Magsat altitude. Fields from external sources are generally between 0 and 1000 nanoteslas and fields from crustal sources, from 0 to 50 nanoteslas. Accurate main-field models are thus crucial to the study of the other field sources.

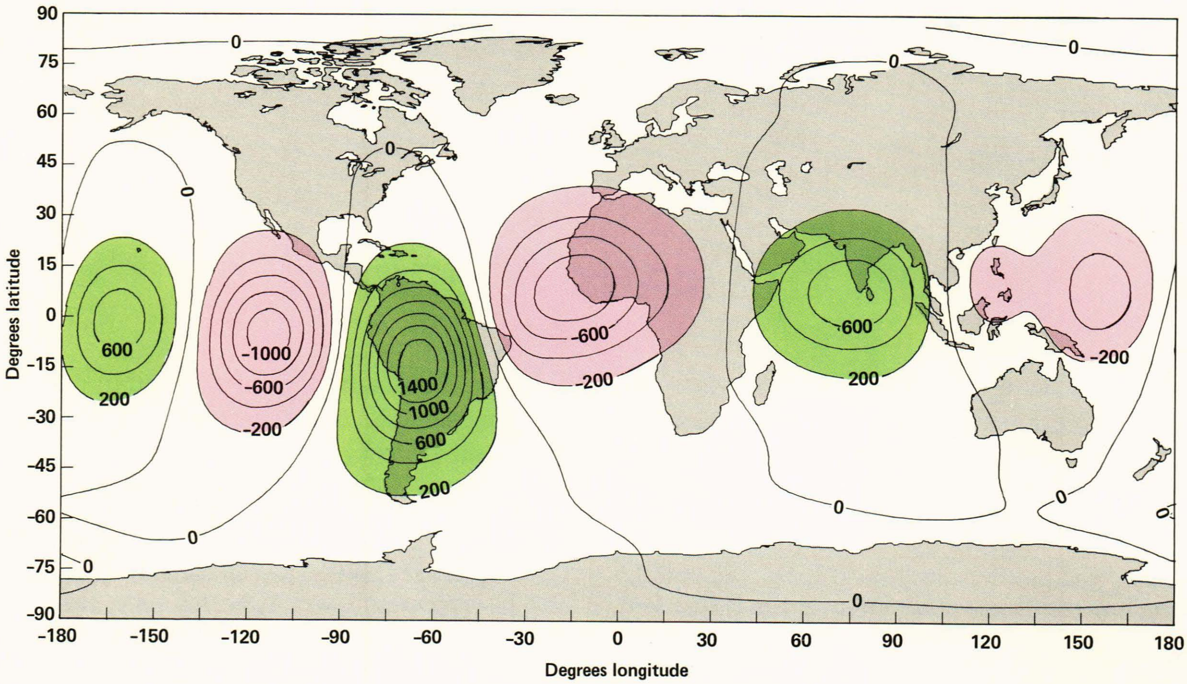

Figure 1 — The difference in the radial magnetic component at the earth's surface between a model derived from vector and scalar data and a model derived from scalar data only. The contour interval is 200 nanoteslas. Adapted from Stern *et al.*[6]

In addition to their role in identifying fields from the different sources, field models are used in preparing charts for navigation and in predicting charged-particle paths in the earth's magnetosphere. They also provide a useful tool for understanding the earth's liquid core. The basic limitations on model accuracy have been the limited accuracy and poor distribution of the data. Surface data fall short mainly because of the presence of high-amplitude crustal fields of very short (less than 10 kilometers, say) wavelength, combined with a woefully inadequate spatial and temporal data distribution. Only satellites provide a truly accurate global data distribution. Magsat was the first satellite to measure the vector field direction as well as the field magnitude.

The first published result from Magsat was the spherical harmonic model designated MGST(6/80).[2] This was also the very first model based on truly global vector data. Previous satellites, e.g., the POGO (Polar Orbiting Geophysical Observatories) series, collected global scalar data, and high quality magnetic field models have been derived from those data.[3-5] However, it became apparent that such models were probably subject to systematic errors in the vector components computed therefrom. This was dramatically verified by Stern *et al.*,[6] using Magsat data. They compared predicted vector components from two models (see Fig. 1), one derived from scalar data alone, the other using vector and scalar data. Differences greater than 1000 nanoteslas occur in the components between the two models, even though the scalar fields from the two models are identical to within a few nanoteslas. Thus the highly accurate Magsat vector data have made possible the determination of main-field models having unprecedented accuracy for representation of the vector field.

Two main-field models derived from Magsat data, one from NASA's Goddard Space Flight Center[7] and one from the United States Geological Survey,[8] were submitted to the International Association of Geomagnetism and Aeronomy as candidates for the 1980 International Geomagnetic Reference Field. The adopted 1980 Reference Field[9] was an average of the two models, and thus it was based entirely on Magsat data.

One source of inaccuracy in models of the core field is the presence of unmodeled external fields. In the past, the available data were not of sufficient quality to permit the determination of such fields. This situation has changed with the availability of the Magsat data. The MGST(6/80) model incorporated a solution for the three lowest-degree and -order external spherical harmonics.

More recently, we[10] have sorted the Magsat data according to the Dst index and have derived spherical harmonic models as a function of that index. Dst is a measure of the temporal variation of long-wavelength external fields — presumably dominated by the equatorial ring current, but also containing contributions from magnetopause and magnetotail currents. Dst is measured *relative* to magnetically quiet days. These models include a solution for the low-degree and -order external terms. Figure 2 shows the relationship between the predominant external term, denoted q_1^0, and the Dst index. Figure 3 shows the

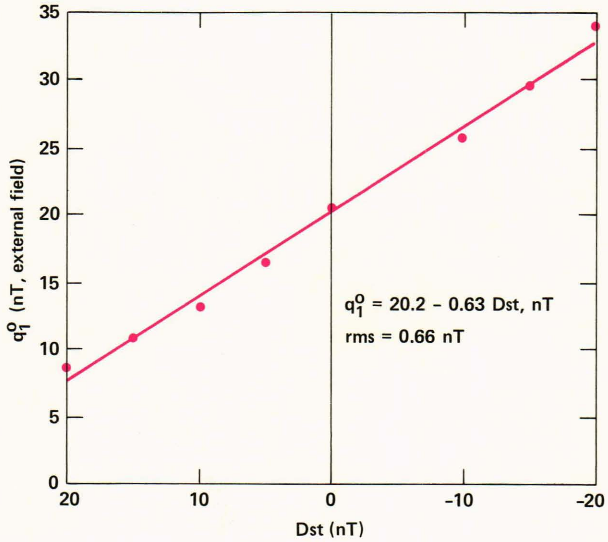

Figure 2 — The coefficient of lowest degree and order describing the field originating external to the earth as a function of the Dst index used to describe temporal variations of the equatorial horizontal field relative to magnetically quiet days.

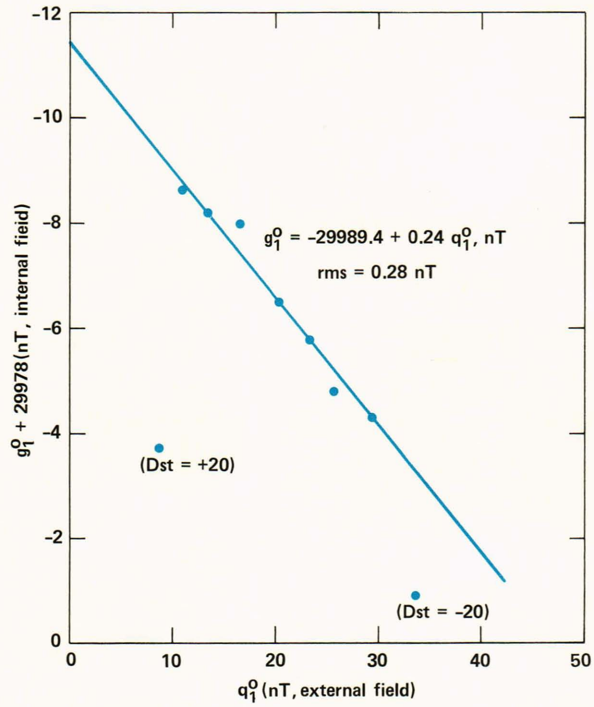

Figure 3 — The coefficient of lowest degree and order describing the field originating *within* the earth as a function of the lowest degree/order field coefficient describing the field originating *external* to the earth.

relationship between the main internal dipole term, g_1^0, and q_1^0. The term g_1^0 depends on external fields because the time-varying external fields induce currents within the earth's mantle. The induced fields are then "absorbed" into the g_1^0 internal term and cause erroneous estimates of the core field. This analysis permits identification of both the external part and its corresponding induced component.

A shortcoming of this analysis of external fields is that it applies only to external fields that are spherically symmetric. Extension to nonsymmetric fields, which certainly are present, is under way.

Although Magsat has provided an excellent model of the main geomagnetic field at 1980, it is also important to measure and model the temporal change (secular variation) of that field. The lifetime of Magsat was a little over seven months. Though long enough to detect the secular change, this may not be sufficiently long to measure it accurately. Cain and his colleagues[11] derived a secular variation model from Magsat data alone. Their model was in moderate agreement with models based on observatory data except for a major difference in the northern polar regions that they attributed to the seasonal change in external fields.

An alternative approach to representing the core field over a period of time is to combine Magsat data with other data for the time period of interest. The GSFC(9/80) model,[7] described in the earlier issue, covers the period 1960-80. The data used include those available from magnetic observatories, selected repeat stations (locations at which measurements are repeated once every 3 to 8 years), selected marine surveys, and the POGO spacecraft. This model uses the technique described in the earlier issue to solve for local fields at magnetic observatories as part of the least-squares solution parameters and permits a more accurate model of the observatory data, as illustrated in Fig. 4. In a recent progress report, Benton indicates that the GSFC(9/80) model preserves fluid-dynamic properties predicted to be constant at the core-mantle boundary better than do earlier models. This attests to the validity of the techniques used to obtain the model.

Alternative approaches to main-field modeling have also been investigated as part of the Magsat program. Gibbs and Estes[12] divided the pre-Magsat data for 1950-76 into five shorter time periods and derived standard spherical harmonic expansions (including linear time terms) over each period. These five models were then combined using a recursive information filter. The resulting estimate of the field was extrapolated to 1980 and compared with the Magsat data and with other pre-Magsat models. The accuracy of the propagated model was considerably better than that of most other pre-Magsat models. Further improvements should result from a more accurate estimation of the statistics of unmodeled errors.

A completely different approach was followed by Mayhew and Estes.[13] Their models used sets of equally spaced dipoles located at a fixed radius from the center of the earth to represent the field, rather than spherical harmonics. A group of such models was derived with various numbers of dipoles. Some solutions include only the dipole magnitudes, with their orientation fixed, while others solve also for the dipole orientation. These models were successful in accurately representing the Magsat data. Solutions

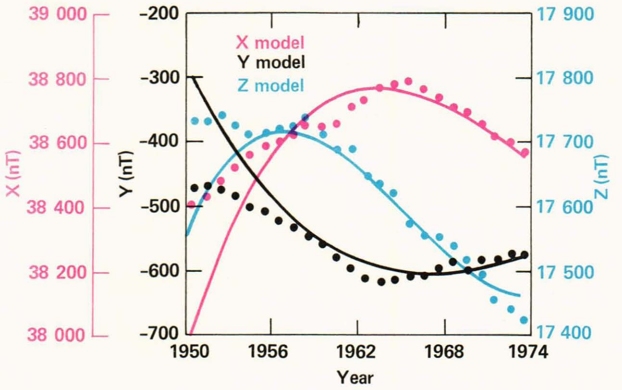

Figure 4 — Comparison of annual means for the north (X), east (Y), and down (Z) magnetic field components at Alibag with values computed from the GSFC(9/80) spherical harmonic model. (Latitude, 18.64 north; longitude, 72.87 east; altitude, 0.01 kilometers.) From Langel *et al.*[7]

were also obtained for the secular variation by allowing the dipole parameters to vary linearly with time. However, the secular variation solutions were difficult to obtain because of the short time interval of the data. The advantage of this technique is that it is computationally faster than the standard spherical harmonic representation.

Although not strictly a result of geomagnetic field modeling, the results of Newitt *et al.*[14] are worth mentioning. They derived regional charts of the geomagnetic field from both Magsat data and Canadian aeromagnetic data. The overall rms difference between the two is 150 nanoteslas, which is regarded as good agreement. They conclude that "vector and scalar regional charts comparable with those produced primarily from aeromagnetic data may be produced from Magsat data." Langel[15] suggested that the differences might be due to the effects of crustal anomaly fields in the aeromagnetic data.

One of the applications of spherical harmonic models is to remove the main-field influence from the field measurements and thereby isolate the crustal and external fields. Langel and Estes[16] determined that the core field dominates spherical harmonic models up through degree and order 13 and that the crustal field dominates for harmonics of degree and order greater than 14. However, Carle and Harrison[17,18] show that substantial fields of long wavelength remain in the data even after subtraction of fields from a 13th-degree and -order model from the data. They suggest that models based on radial dipoles will help eliminate this problem.

INVESTIGATIONS OF THE EARTH'S CORE, MANTLE, AND CORE-MANTLE BOUNDARY

Information regarding the core and mantle of the earth comes in very few forms. Because its origin lies in the motions of the core fluid and because changes in the main field must travel through the mantle, the main geomagnetic field is one of the sources of data for these regions. When a spherical harmonic analysis is projected to the core-mantle boundary, the higher degree and higher order terms become increasingly more important. Unfortunately, it is these terms that are least observable in the data and, hence, less accurately determined. The Magsat data have provided perhaps an order-of-magnitude improvement in some of these higher degree/order terms, and thus they provide a significant new tool for probing the inner earth.

Some of these studies are based on a result of Bondi and Gold,[19] who showed that the magnetic pole strength

$$P(S,t) = \iint_S |\vec{B} \cdot \hat{n}| \, dS \qquad (1)$$

is constant if the closed surface, S, separates a perfectly conducting fluid from an insulating exterior. Hide[20] pointed out that if a planetary core is very highly conductive while the surrounding mantle is an insulator, the radius at which $\dot{P}(S,t)$ is zero should be the radius of the core of the planet. Using this concept, Voorhies and Benton[21] compared magnetic field models from several earlier epochs with MGST(6/80) to determine the radius at which $\dot{P}(S,t)$ is zero. The radius they found agrees with the seismic radius to within 2%. More recently[22] they have redone the calculation using GSFC(9/80) at 1960 and 1980 with a result only 0.63% different from the seismic radius. This supports the approximation of a perfectly conducting core and a perfectly insulating mantle, at least for these time spans.

Another use of the constancy of P at the core-mantle boundary has been to estimate probable upper limits for some of the spherical harmonic coefficients.[23] This is done by assuming that P is constant at the value found by Magsat and then determining the maximum value the coefficient would have if it were the only contributor to that P. One result of this analysis is that the main dipole term is only 28% lower than its probable upper limit.

One would like to be able to infer core fluid motions from magnetic field measurements and thereby study properties of the geomagnetic dynamo. Backus[24] has shown that it is not possible to determine uniquely the fluid velocity from knowledge of the magnetic field. However, Benton[25] has shown that some properties of the core fluid velocity can, in principle, be determined by investigating the intersections of those curves, at the core-mantle boundary, along which B_r and its derivatives in the meridional ($\partial B_r/\partial\theta$) and azimuthal ($\partial B_r/\partial\phi$) directions vanish. In a preliminary application of this method, Benton[22] concluded, contrary to Whaler,[26] that significant vertical fluid motion exists at some of these locations. This means that the core is not stably stratified but that the dynamo includes vertical motions.

One of the difficulties in extrapolating the field to the core-mantle boundary is that the higher degree/order terms assume a much greater importance there than at the earth's surface. Unfortunately, the terms above degree and order 13 due to the core field are virtually unknown because of the dominance of crustal fields in the measurements.[16] This is a severe restriction on our ability to know the field at the core. Benton *et al.*[27] examined properties of the field at the core-mantle boundary and concluded that, for existing models, significant contamination from crustal fields sets in above degree and order 8. More recent[22] results suggest that the GSFC(9/80) model may be usable up to degree and order 10 at the core-mantle boundary.

CRUSTAL MAGNETIC ANOMALY STUDIES

When estimates of the core and external fields have been removed from the data, the remaining field is attributed to sources in the crust of the earth. As pointed out in the earlier issue, not only the short-wavelength but also the long-wavelength (greater than 100 kilometers, say) crustal fields are of interest for geologic and tectonic studies. These fields are most efficiently mapped by satellite measurements; however, at satellite altitudes, the anomaly amplitudes are extremely small (0 to 50 nanoteslas for Magsat) compared with the main field of 30,000 to 50,000 nanoteslas. Also, the time-varying external fields can be of large amplitude and can also be of the same spatial wavelength as the anomaly fields. Thus, in the early days of near-earth field measurements by satellite, the anomaly fields were considered negligible. While studying the equatorial electrojet using POGO data, Cain and his colleagues noticed a field variation very much like the electrojet signature but at local midnight, when the equatorial electrojet is absent or negligible. This ultimately led to the publication of the global scalar anomaly map from POGO in 1975,[28] a refinement of which appeared in the earlier issue. Magsat was better suited for such measurements because its lower altitude gave closer proximity to the anomaly sources and because it measured the field direction as well as its magnitude. Studies of the anomalous magnetic field at this spatial scale have only commenced in recent years; it remains a young science with many unanswered questions.

Crustal anomaly maps from Magsat are now available, not only of the scalar field[29-31] but also of the field components.[31-33] These maps have not yet been reduced to a constant elevation but are averages over areas equivalent to 2 by 2° at the poles. Figures 5 and 6 show the maps at low latitudes and Figs. 7 through 10 those from northern high latitudes.

Comparison of the scalar maps from Magsat data with those derived from the POGO data shows good agreement in the general anomaly pattern over most of the world, although there are a few regions with unexplained differences. This agreement provides a general confirmation of the physical reality of the anomalies. As expected, the resolution of the Magsat data is considerably better than that of the POGO data. For example, Sailor *et al.*[34] confirm the reliability of isolation of the anomaly fields and conclude that resolution down to 250 kilometers is probably possible at a 0.5 nanotesla level.

As reported in the earlier issue, the POGO anomaly map for western Canada was verified by comparison with aeromagnetic data. This type of verification has also now been carried out for the United States both for POGO data[35] and for Magsat scalar data.[35,36] The agreement is not as good as was found for Canada, although the authors regard it as satisfactory. Won[37] has recently redone the comparison after filtering east-west trends from the Magsat data. He claims a much closer agreement between the resulting Magsat map and the aeromagnetic survey. In an unpublished comparison, Taylor continued scalar aeromagnetic data in the vicinity of the Alpha Ridge upward from the surface in order to make a compari-

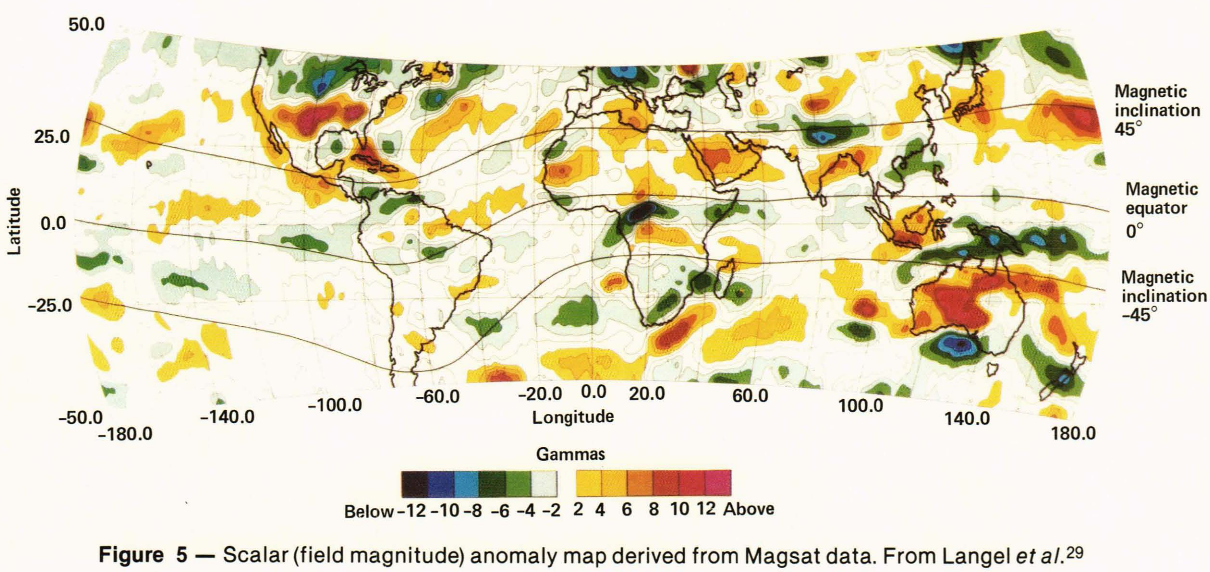

Figure 5 — Scalar (field magnitude) anomaly map derived from Magsat data. From Langel *et al.*[29]

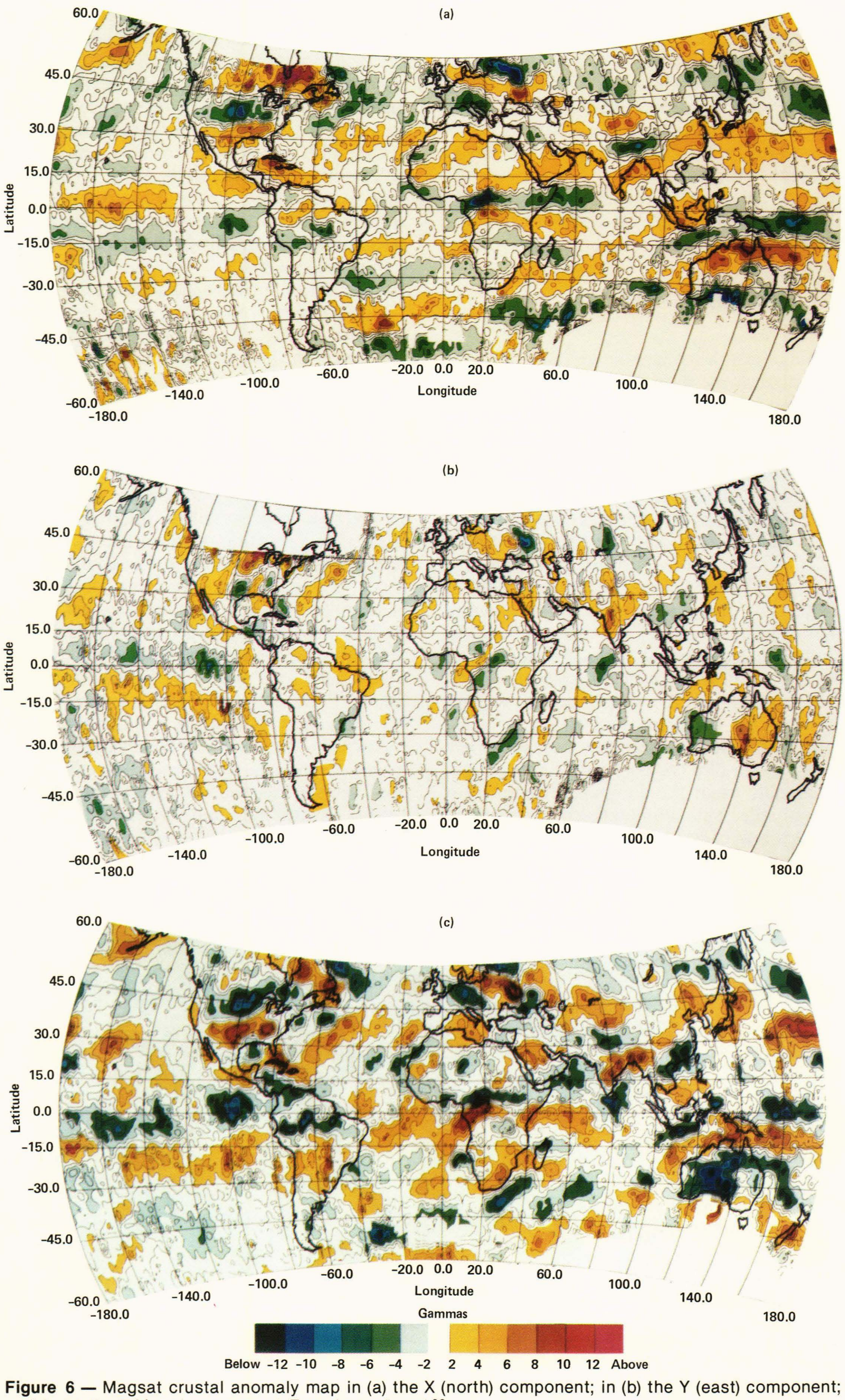

Figure 6 — Magsat crustal anomaly map in (a) the X (north) component; in (b) the Y (east) component; and in (c) the Z (down) component. From Langel *et al.*[32]

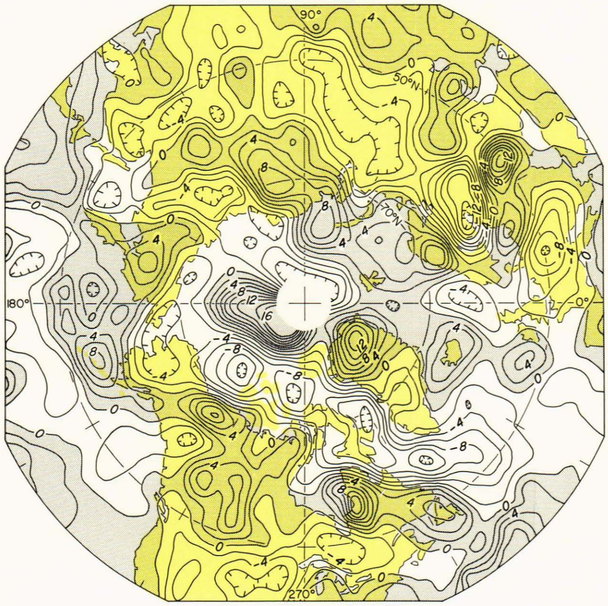

Figure 7 — North polar scalar anomaly map from Magsat data. Units are nanoteslas. From Coles *et al.*[31]

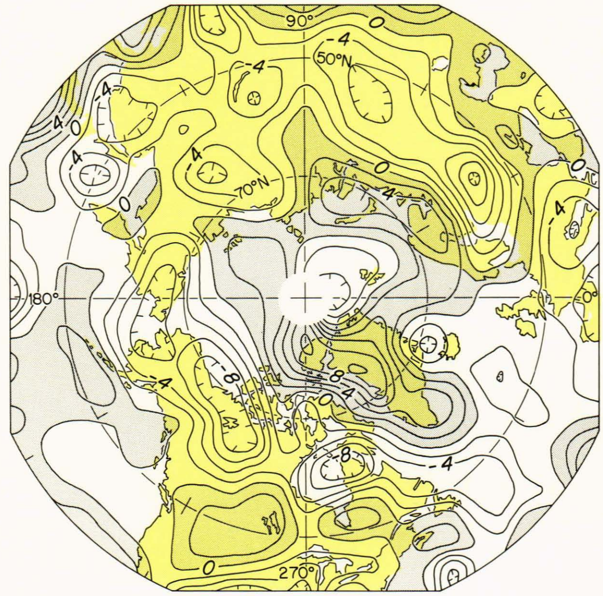

Figure 8 — North polar Magsat crustal anomaly map in the X (north) component. Units are nanoteslas. From Coles *et al.*[31]

Figure 9 — North polar Magsat crustal anomaly map in the Y (east) component. Units are nanoteslas. From Coles *et al.*[31]

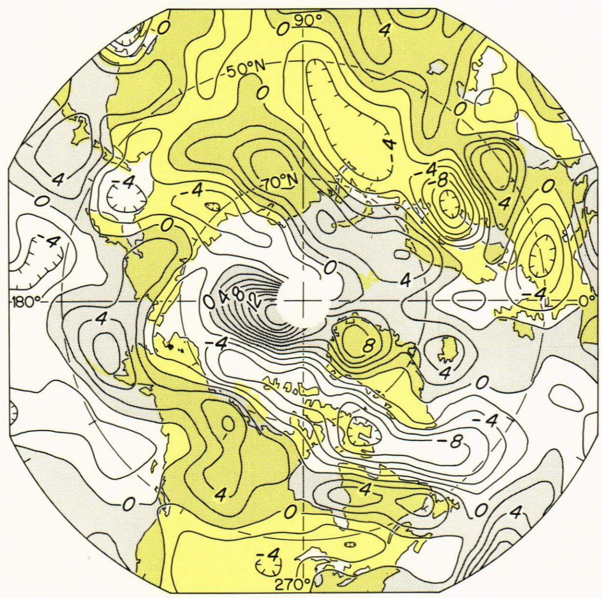

Figure 10 — North polar Magsat crustal anomaly map in the Z (down) component. Units are nanoteslas. From Coles *et al.*[31]

son with the Magsat scalar map of Coles *et al.*[31] He found good agreement.

A similar verification was carried out by LaBrecque and co-workers,[38] using all the digital marine data available to them, for the northern Pacific. Anomalies of less than 300 kilometers wavelength were filtered from the profiles. The filtered values were assembled into 2 by 2° bins and corrected for Dst and Sq (the quiet day external field variation). Because the data spanned a significant time period, the secular variation was also determined. After making these corrections, they derived the anomaly map of Fig. 11. Comparison with the Magsat scalar map, Fig. 5, shows satisfactory agreement. Both maps show very broad anomalies such as that which they denote as the "Emperor" anomaly (30°N, 175°E), associated with the Hawaiian-Emperor Seamount chain. Correspondence between the two maps is generally poorer in the western Pacific island arc system. They note that this may be due to the directional sensitivity of the Magsat data, which are acquired along nearly north-south tracks and subsequently filtered along-track. This emphasizes the cross-track (east-west) anomalies at the

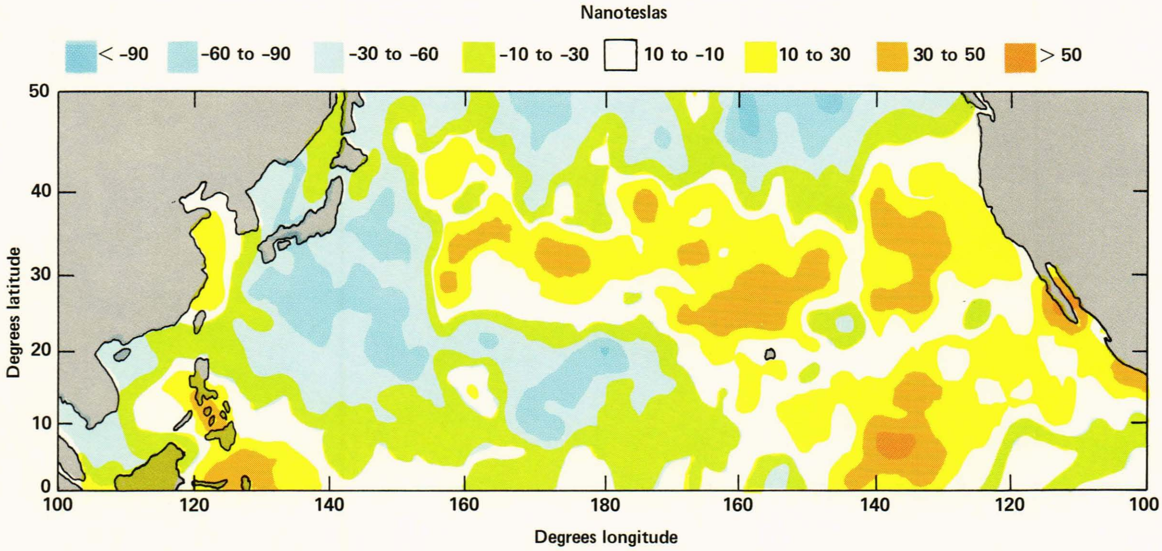

Figure 11 — Long-wavelength magnetic anomalies derived from the sea-surface data. The data were corrected for Sq, Dst, and secular variation. Wavelengths less than 300 kilometers were removed. From LaBrecque *et al.*[38]

Geologic Tectonic Features Graphically Coincident With Magsat Scalar Anomalies

Ocean Basins/Abyssal Plains

Southwest Pacific Basin (SW),[1] *Canadian Basin* (CB), *Bellinghausen AP* (BE), *Argentine Basin* (AR), *Gulf of Mexico* (GM), *Hatteras AP* (H), *Sohm AP* (S), *Labrador Sea* (LS), *Baffin Bay* (BB), *Weddell AP* (W), *Cape Basin* (CA), *Enderby AP* (E), *Madagascar Basin* (MB), *Somali AP* (SO),* Arabian Sea (AS),* *Wilkes AP* (WI), *Australian Bight* (AB), Melanesian Basin (ME),* *East Mariana Basin* (EM),* *Sea of Okhetsk* (OK), *Bering/Aleutian AP* (BG)

Submarine Plateaus/Rises

[*Chatham Rise* (CT)],[2] Falkland-Scotia Ridge (F), Santos Plateau (SP),* Rio Grande Ridge (RG),* Jan Mayen Ridge (JM), Walvis Ridge (WR), Maud Rise (MR), Agulhas Plateau (A), Mozambique Plateau (M), Crozet Plateau (CZ), Seychelles-Mascarene Plateau (MS),* Kerguelen Plateau (KR), Broken Ridge (BR), [Tasman Plateau (TS)], Lord Howe Rise-Norfolk Ridge (LH), Campbell Plateau (CD), Shatsky Rise (SR)*

Trenches/Subduction Zones

Tonga Trench (TT), Kermadec Trench (KT), Aleutian Trench (AT), Middle America Trench (MD),* Amirante Trench (AM),* *Diamantina Trench* (DT), Java Trench (JT),* Izu Trench (I), Japan/S. Kuril Trench (JT), [Philippine Trench (PH)*], New Guinea (NG),* New Hebrides Trench (NH)*

Shields/Cratons/Platforms

Bear Slave (B), Churchill (CH), N. Superior (Su), *S. Superior* (Su), Guiana Shield (Gu),* *Guapore Craton* (GC),* S. Greenland (SG), N. Baltic Shield (BS), *S. Baltic Shield* (BS), E. European Platform (EE), Ukrainian/Voronez Massif (KU), Bohemian Massif (BO), Mauritania Craton (MT),* W. African Craton (WA),* *Liberian Craton* (SL),* [Tanganyika Shield (T)*], Saudi Arabian Shield (SA),* *N. Russian Platform* (RP), S. Russian Platform (RP), Siberian Platform (SP), Anabar Shield (AN), Aldan Shield (AL), Kolyma Massif (K), Dharwar Craton (DH),* Pilbara Block (P), Yilgarn Block (Y), Musgrave Block (MU), Gawler Block (G), Mt. Isu (IS)

Basins/Troughs

Alberta Basin (AL), Michigan Basin (MC), W. Texas Basin (WT), Amazon Valley (AZ),* Benue Trough (BN),* Congo Basin (C),* *Kalahari Basin* (KL),* *Karoo Basin* (KA), *W. Siberian Basin* (WS), Dzungarin Basin (DZ), Tarim Basin (TA), Szechuan Basin (SZ),* Moma-Zyryanka Basin (MZ), *Eromanga Basin* (ER)

Other

Kentucky (KY), *Bangui* (BI),* *Himalayas* (H)*

[1] Negative anomalies shown by italics.
[2] Less certain coincidences in brackets.
*Indicates features at low geomagnetic latitudes.

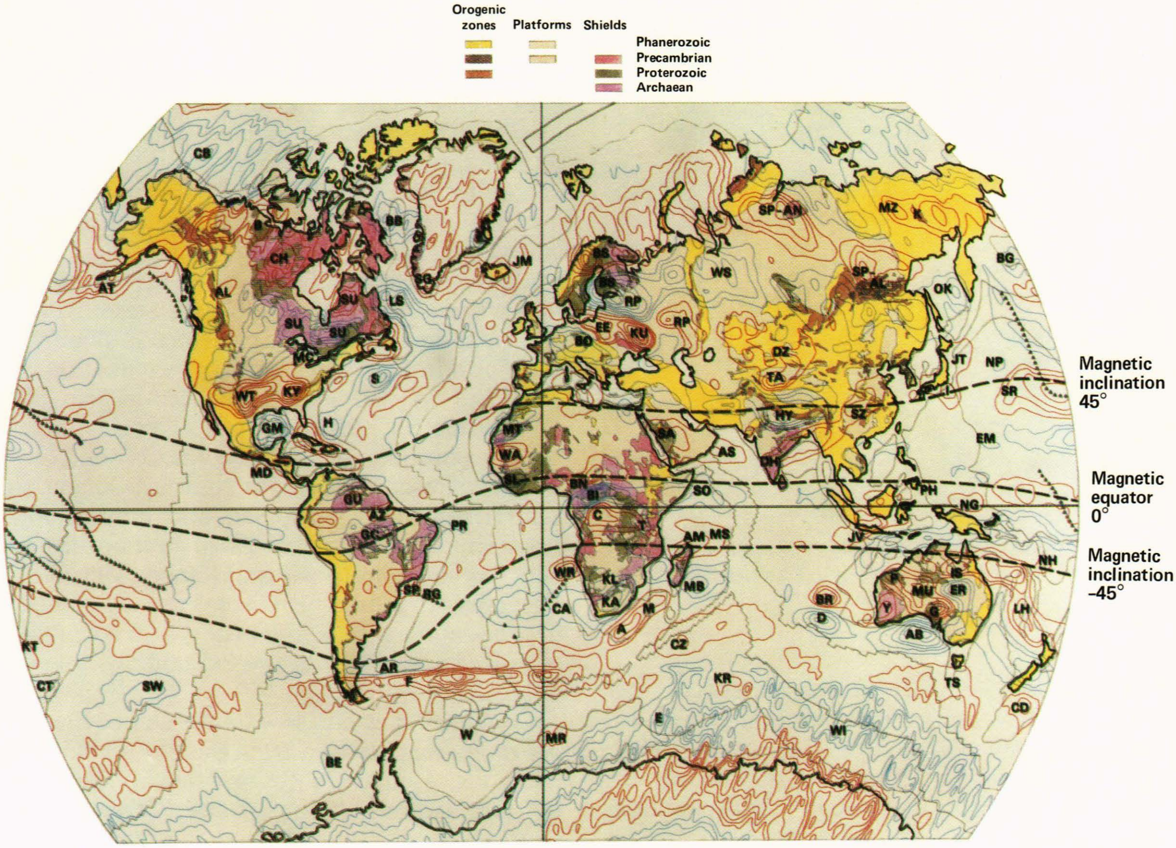

Figure 12 — Magsat scalar anomalies superimposed on a simplified tectonic province map; positive anomalies in red, negative anomalies in blue. Contour interval is 2 nanoteslas. Adapted from Frey.[39]

expense of the along-track (north-south) trends. Future work should include a more quantitative comparison of an upward continuation of the sea-surface data with the Magsat map.

An initial step in geologic studies using such maps is to investigate their gross correlation with known geologic or tectonic features. Figure 12, from Frey,[39] shows Magsat scalar anomalies superimposed on a simplified tectonic map. The insert opposite lists the spatial coincidences noted by Frey. He describes a tendency for positive anomalies to be coincident with some continental shields, platforms, and subduction zones and for negative anomalies to be associated with oceanic basins and abyssal plains. The location of an anomaly relative to its source depends on its geomagnetic latitude. For this reason, the coincidences discussed above are very preliminary. Also, they are applicable at higher latitudes and, in fact, would be expected to *reverse* near the magnetic equator. This reversal is consistent with some of the low-latitude coincidences pointed out in the box insert and is also in agreement with the similar analysis of Hastings[40] for the African continent.

Figure 13, from Frey,[41] seems to me even more thought-provoking. Here are seen the Magsat scalar anomalies for Asia, together with the locations of known tectonic boundaries. In almost every case, major tectonic boundaries are also boundaries of major magnetic anomalies or are coincident with a shift in the pattern of the anomaly. Frey (personal communication) has seen this same pattern elsewhere in the world and concludes that the tectonic boundaries between discrete blocks of different crustal character appear to be the boundaries for the magnetic anomalies that represent these blocks and whose signatures can be used to constrain the deep crustal properties of these blocks.

Comparisons such as those by Frey and Hastings must be regarded as preliminary because the character of the anomaly pattern changes with geomagnetic latitude. This occurs because the strength and, particularly, the inclination of the inducing field vary with latitude. Because Fig. 13 is entirely at relatively high magnetic latitudes, it will be largely unaffected. The solution to the problem is to reduce the anomaly map to the form it would take if the main geomagnetic field were everywhere the same. Most often, the polar field (strictly vertical) is chosen, and the process is known as "reduction to the pole."

An alternative representation is to compute an equivalent magnetization, i.e., a hypothetical magnetization distribution that would result in the observed anomaly values. Usually the same computational procedure yields both forms of representation. Meth-

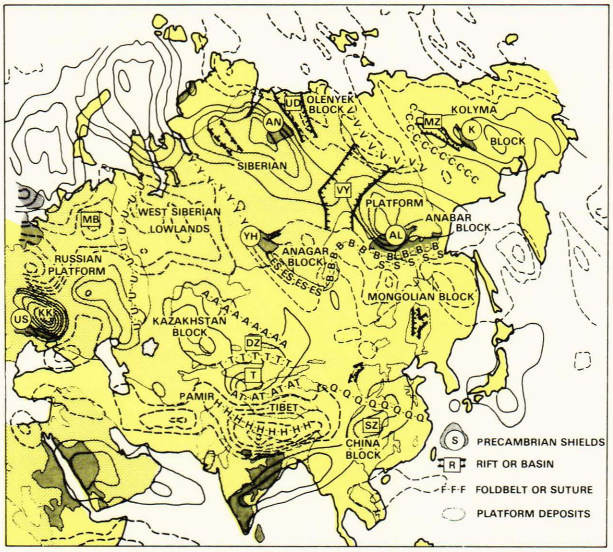

Figure 13 — Magsat scalar anomalies over Asia compared with major tectonic boundaries. Negative anomalies shown dashed, positive anomalies solid. Contour interval is 2 nanoteslas. From Frey.[41]

ods for accomplishing this with aeromagnetic and shipborne data have existed for some time. However, because of the limited area covered by such surveys, these solutions assumed a flat earth and a constant main geomagnetic field. Extension of these results to satellite data was begun by Bhattacharyya[42] and by Mayhew *et al.*[43,44] Mayhew's method[44] has proved most useful, except that near the equator the solution becomes unstable. Using basically the same method but with 2° average data as input, von Frese and his colleagues[45] have been able to obtain reductions to the pole both at middle[45] and low[46] latitudes. However, for results with more resolution, it is desirable to use the measurements themselves rather than averages. The stability problem near the equator may be overcome by the use of an eigenvalue decomposition scheme suggested by von Frese *et al.*[45] and, independently, by Slud and Smith.[47] The latter method is being used at GSFC for final reduction of both POGO and Magsat data.

Mayhew and Galliher[48] have derived a relative magnetization map for the United States from Magsat scalar data; the map is presented in slightly modified form in Fig. 14. A cursory examination of that map and of von Frese's reduced-to-pole map of South America[45] confirms Frey's[39] observations concerning coincidences; namely, shields and platforms (Sierra Nevada, Colorado Plateau, Guiana shield, central Brazilian shield, San Luiz craton, and San Francisco craton) are associated with positive anomalies, while basins (Basin and Range, Amazon River, Parnaiba, Parana, and Chaco) are associated with negative anomalies. Hinze *et al.*[46] also note that aulacogens appear to be associated with negative anomalies.

Comparison of Fig. 14 with the United States magnetization map derived from the POGO data (earlier issue, Fig. 4; also see Ref. 49) quickly demonstrates the increased resolution of the Magsat data. The clear correspondence of anomalies with known tectonic features gives confidence that these anomalies are truly of crustal origin.

Figure 14 shows a "belt" of magnetic highs extending from New Mexico and Texas in an arc

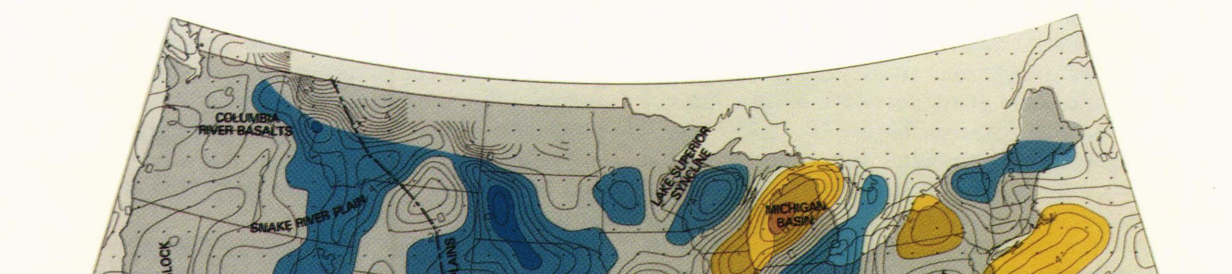

Figure 14 — Apparent magnetization for the United States in a 40-kilometer-thick layer, as derived from Magsat data. Contour interval is 0.1 ampere/meter. Some tectonic features are indicated. Adapted from Mayhew and Galliher.[48]

toward the Michigan basin. This also appears in the reduced-to-pole map of Black[50] and Carmichael,[51] who note that a pronounced gravity low (free air anomaly) is coincident with the magnetic high. The trend of the anomaly follows the trend of the Mazatzal[52] age province belt and the supposed northern boundary of the granitic rhyolite terrain to the south of the Mazatzal belt. They have speculated, and are investigating the possibility, that the positive anomaly is associated with the granitic rhyolite region whose northern boundary, particularly in the northeastern Missouri, southeastern Iowa, and northern Illinois regions, should perhaps be farther north than has been postulated.[52]

Sailor and Lazarewicz[53] have derived a reduced-to-pole map for a portion of the eastern Indian Ocean (−5 to 45°S latitude, 80 to 120°E longitude). That region includes several tectonic features, including the Ninety-East Ridge, Broken Ridge, and the Wallaby Plateau. In general, the anomaly patterns seem to correlate with bathymetric trends. Positive anomalies overlie both Broken Ridge and Ninety-East Ridge, although that over Ninety-East Ridge is a factor of 3 or 4 below that of Broken Ridge. The reason could, conceivably, be that Ninety-East Ridge trends north-south, the direction in which the data are selectively filtered.

LaBrecque *et al.*[38] also note the delineation of tectonic boundaries by the long-wavelength sea-surface anomalies. Comparison of long-wavelength anomalies with bathymetry shows that linear negative anomalies are associated with the older seamounts (middle to late Cretaceous). They calculated simple models for several seamounts from which they deduce a strong remanent component, especially for the Emperor anomaly. The Emperor anomaly in the Magsat map seems to extend over the Shatsky and Hess Rises, which are zones of thickened crust. The greater resolution of the sea-surface map resolves them into separate positive anomalies. In the western Pacific, they find a moderate correlation between crustal thickness and magnetic-anomaly amplitude but only a weak correlation of anomalies with heat flow. In the eastern Pacific, they find a correlation between major fracture zones and the satellite magnetic anomalies. A crude susceptibility-contrast model reproduces the major anomalous features.

Mayhew[54] has developed a method of modeling the thickness of the magnetic crust from an apparent-magnetization model supplemented by calibration points from ground truth data. The method can be used to predict regional heat flow and Curie depths. He concludes from a POGO magnetization map that the southern extent of the Rio Grande rift into Mexico turns southeast at the Mexican border. It "appears to be closely associated with the Sierra Madre Oriental, suggesting a zone of elevated temperature beneath this tectonic province."

Detailed quantitative interpretation of satellite anomaly data will normally be carried out on a local or regional basis. Some first steps in this direction have been taken. Yanagisawa *et al.*[55] have modeled the magnetization near Japan. Concentrating particularly on the Japan Sea, they attribute a magnetic low to a thinning of the magnetic crust and note its association with high heat-flow values. Quantitative modeling has also been carried out for the Amazon River region of South America. Figure 15, adapted from Longacre *et al.*,[56] shows the measured anomalies (reduced to pole) compared with anomalies calculated by a block model. The principal conclusion is that the data and models for the anomalies over the Takatu and Amazon rifts are consistent with the fact that the anomalies are aulacogens, similar to the Mississippi Embayment, which they studied earlier[57] using the same techniques.

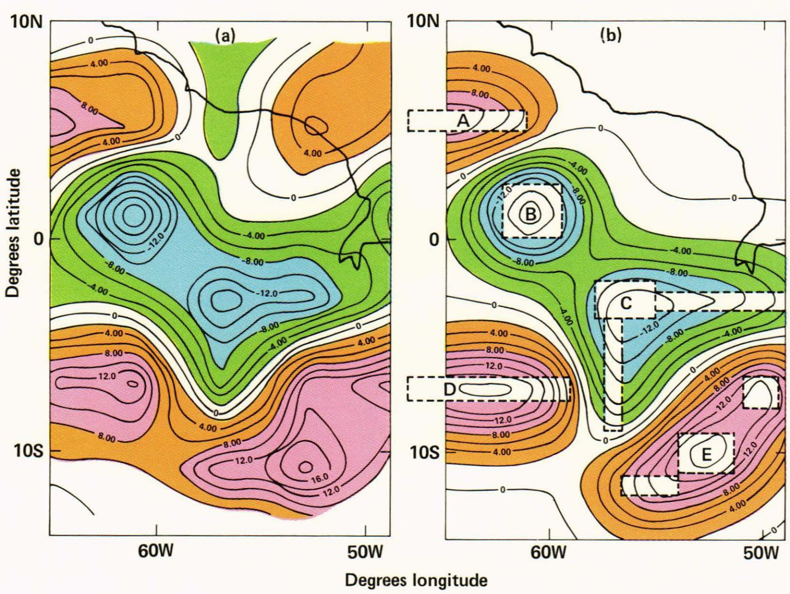

Figure 15 — Reduced-to-pole magnetic anomalies at 350-kilometer altitude derived from scalar Magsat data over northeastern South America (a) compared with magnetic anomalies computed from a crustal model (b). Contour interval is 2 nanoteslas. Adapted from Longacre *et al.*[56]

The Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM) is studying the Bangui Magnetic anomaly in central Africa.[58] Their main effort to date is the collection of gravity and seismic data. A gravity map of central Africa has recently been published,[59] and an analysis of seismic data has resulted in a preliminary model[60] in which the crustal thickness is estimated to be about 40 kilometers, and in which travel-time anomalies for teleseisms are modeled for six layers, down to 200 kilometers. Results will be used to refine the model of Regan and Marsh.[61]

Laboratory studies of suitable rocks have been an integral part of the Magsat program because of the need to constrain parameters in models of anomalous crust. These studies suggest that in the continental crust the Moho generally defines the lower boundary of the magnetic source region[62] and, further, that the mafic rocks of the lower crust are the principal source of the long-wavelength anomaly field.[63,64] This model of the origin of the lower crust agrees with several studies on the origin of long-wavelength anomalies as seen in aeromagnetic data.[65,66] Schnetzler and Allenby[67] have taken areas of the United States where the lower crustal thickness is relatively well-known and have calculated the magnetization necessary to produce the satellite anomaly field, assuming all the magnetization is in the lower crust. They have done this with the POGO[67] and the Magsat data (unpublished result). In each case, the values of apparent magnetization derived by Mayhew were converted to absolute magnetization using the assumption that the magnetic moment goes to zero as the thickness goes to zero. Figure 16 is a contour map of the resultant magnetization values from the Magsat data. On this map, if all anomalies were produced by variations in lower crustal thickness, the magnetization would be constant. Thus, regions in Fig. 16 where local variations occur (e.g., the Colorado Plateau) are regions where the magnetization, as well as the thickness, varies laterally. The magnetization values obtained are in general agreement with published estimates of magnetization in the lower crust and with laboratory measurements of the mafic rocks expected in the lower crust.

In an effort still in progress, Frey (unpublished) is studying continental rifts using both POGO and Magsat data. His preliminary results indicate that active rifts always result in a negative magnetic anomaly, presumably as a result of the thinned crust and elevated Curie isotherm associated with high heat flow. Failed or inactive rifts may show either positive or negative anomalies. A positive anomaly is present when extensive volcanism has been part of the rifting process and the heat flow is low. Negative anomalies frequently occur where extensive volcanics are not present in the rift but where the depressed, thinned crystalline crust is overlain by a sequence of thick sediments.

Returning to a more global viewpoint, Fig. 17[68] shows the magnetic anomalies from the POGO data as they would look in a reconstruction of Pangaea

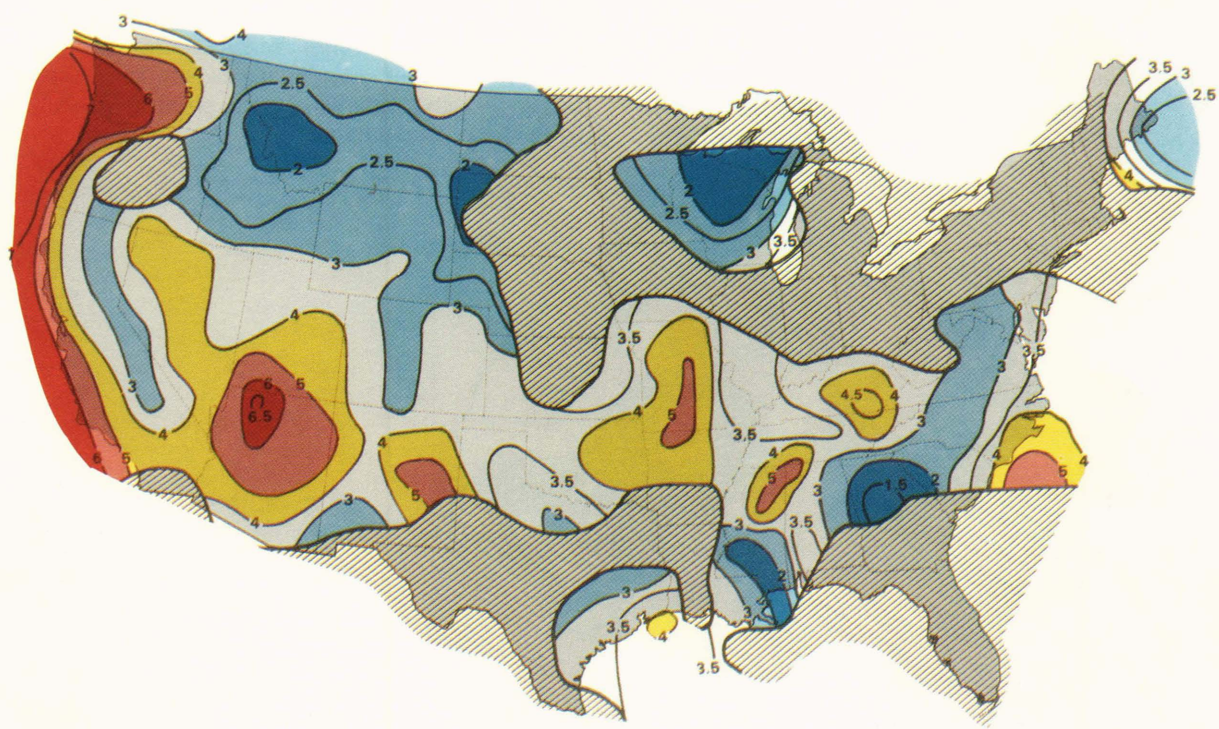

Figure 16 — "Absolute" magnetization over the United States computed assuming that all magnetization is concentrated in the lower crust. Shaded areas indicate lack of data regarding the thickness of the lower crust. From Schnetzler, personal communication.

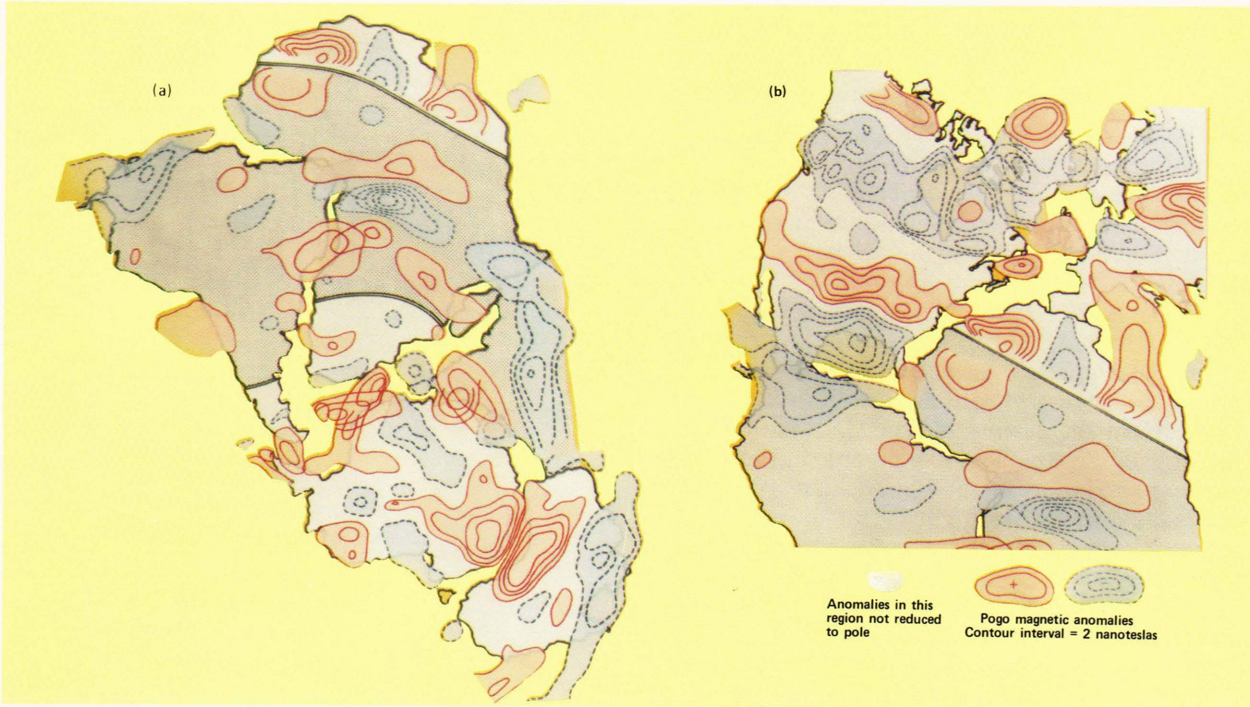

Figure 17 — (a) Reconstruction of Gondwanaland with magnetic anomalies superimposed. Negative anomalies are shown as dashed contours, colored blue; positive anomalies are shown as solid contours, colored red. The shaded region represents geomagnetic latitudes where the reduced-to-pole solution was unstable. Anomalies in this region are not reduced to pole. Comparison between South America and Africa is still valid because the geomagnetic latitudes are similar. (b) Reconstruction of Laurasia with magnetic anomalies superimposed. From Frey *et al.*[68]

(Gondwanaland and Laurasia). Anomalies in the areas with unshaded background have been reduced to the pole; those in the areas with shaded background have not. Of interest are the continental boundaries where anomalies, in the reconstruction, appear to cross the boundary. This may be seen, for example, in the following: the adjacent positive anomalies in Antarctica and Australia, in the United States and northern Africa, and in central Africa and South America; the adjacent negative anomalies in northern South America and northern Africa; and the belt of lows from Scandinavia across Greenland and into Canada. (A comparison between South America and Africa is valid even though not reduced to pole since those regions are at similar geomagnetic latitudes.) Such features indicate blocks of crust that were once contiguous and therefore may have had a common geologic history up to the time of continental breakup. The combined anomaly could then possibly be an indication of the location of a relatively homogeneous unit in the combined continent. This work is highly preliminary and requires verification but indicates the possibility of a significant new understanding of the Pangaean continental structure.

Modeling of anomalies in the component data is still in its early stages. Preliminary attempts to study the possible existence of a remanent component of the magnetization have given unclear results. Using the scalar data alone, Galliher and Mayhew[69] computed a series of equivalent source models for the United States, using arrays of dipoles at the earth's surface. The dipole directions were prespecified and varied from model to model. Each model not only reproduced the scalar anomaly data on which the model was based but also reproduced the measured anomalies in each component, regardless of dipole direction. This indicates that, at least for the United States, the vector anomalies can be determined analytically once the scalar anomalies are known. On the other hand, Langel *et al.*[32] derived a similar model for the Near-East Region, again based on scalar data alone, and found some areas where the vector anomaly measurements were not reproduced by the model. It appears that most of the crustal anomaly fields measured by Magsat, though not necessarily all, can be modeled as though they are induced.

Finally, it should be noted that alternative methods are being developed to represent the anomaly field. Schmitz *et al.*[70] have derived spherical harmonic models of degree/order 22 (POGO) and 24 (Magsat) and then computed the resulting residuals. One isolated anomaly, near Broken Ridge, was then modeled with a single dipole. The models fit very well, and the dipoles, derived independently from POGO and Magsat, were nearly equal in direction and magnitude. In a related approach, Cain *et al.*[71] have derived a degree/order 29 spherical harmonic model that represents most of the crustal features in the published maps.[29-32] Using the terms between degree/order 14 and 29, they are able to reproduce most of the features on those published maps, except for the east (Y) component.

STUDIES OF FIELDS FROM EXTERNAL CURRENT SYSTEMS

The environment of the earth is magnetically very active. Plasma from the sun (the solar wind) envelops and confines the magnetic field of the earth within a region known as the magnetosphere. As a result, the field of the earth is compressed in the direction toward the sun and stretched into a "tail" in the antisunward direction. Currents flow on the boundary of the magnetosphere (the magnetopause), across the center of the tail, and in an equatorial "ring" or "sheet" current inside the magnetosphere.

All of the currents mentioned are relatively distant ($\geq 2R_e$) from the earth's surface. In addition, currents flow in the conducting region of the earth's atmosphere known as the ionosphere. The ionosphere is generally a much better conductor during the day than during the night, except in the auroral regions. Dayside currents are apparently driven by tidal winds and are present every day. The large-scale dayside current system is known as Sq, for solar quiet day current. It is intensified at the geomagnetic equator into what is known as the equatorial electrojet.

The Magsat orbit was chosen so that it would always lie at local twilight, i.e., dawn or dusk. This was specifically done in order to avoid most of the effects of the equatorial electrojet and of the Sq current system because the electrojet tends to mask the fields from crustal anomalies. Nevertheless, the effects of these currents are still present in the Magsat data. This was predicted by Sugiura and Hagan[72] prior to Magsat launch. Maeda[73] extended this prediction by developing a formalism to analyze the data and separate it into ionospheric and magnetospheric contributions. Derivation of the magnetic anomaly maps involves filtering long-wavelength, time-varying fields from the data. We think this effectively removes the effects of the magnetospheric currents and of Sq. However, fields from the equatorial electrojet, though reduced in amplitude from their noontime magnitude, are plainly seen in the data from the dusk portion of the orbit. Equatorial electrojet effects are apparently either absent or below the noise level at dawn.

Analysis of the Sq current system is still very preliminary. The field from the equatorial electrojet has been seen clearly by us (GSFC) in the dusk data and has also been seen by the Indian and Japanese investigators. Of significance is a toroidal (meridional) current system discovered by Maeda *et al.*[74] It is associated in some way with the equatorial electrojet. Two alternative current systems are shown in Fig. 18. Meridional currents were predicted by Sugiura and Poros[75] but have not previously been verified because their fields are not apparent in surface data or in satellite scalar data (e.g., POGO) but only in near-earth, *vector*, satellite data. The magnitude of the current system depends on longitude; it also has a periodic variation of about 30 days that could be associated with either a solar rotation period (27 days) or a lunar orbital period (29.5 days).[76] Takeda and Maeda[77] have now shown that current system (b) of Fig. 18 is probably correct and that it is caused by neutral pressure gradients as part of the ionospheric F-region dynamo.

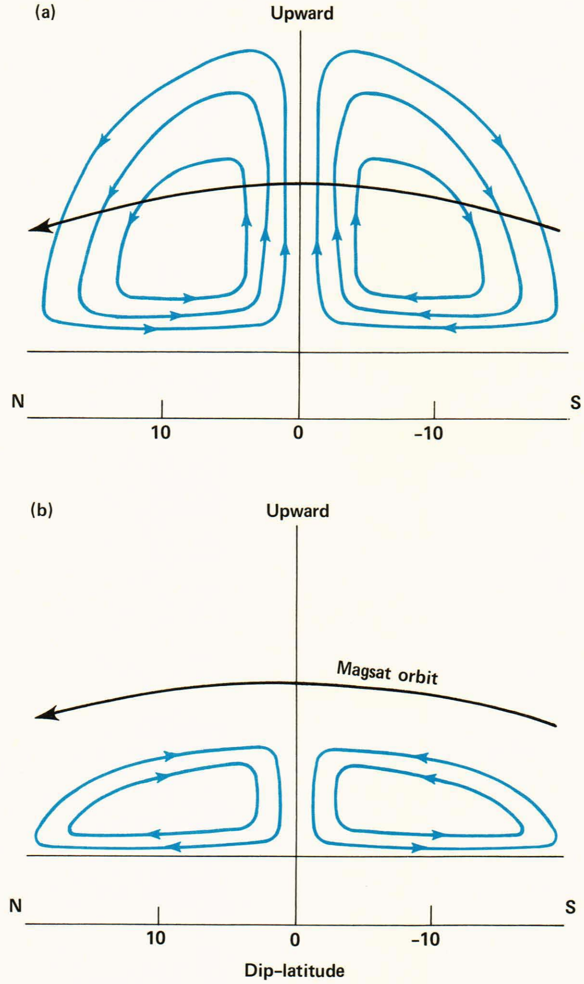

Figure 18 — Two models for the interpretation of near-equatorial variations in the Y (east) component at dusk. The source is modeled as a meridional current. The currents shown are in association with the equatorial electrojet. From Maeda *et al.*[74]

In the discussion of main-field models, it was pointed out that the simultaneous determination of the spherically symmetric portion of the external field was also accomplished. Further investigations of the long-wavelength external field, including its local time variability, are under way using individual pass data. After removal of the main field, the residuals are an approximation of the effects of external currents and crustal anomalies. At the very long wavelengths (greater than 4000 kilometers) associated with magnetospheric currents, the anomaly fields are assumed negligible and for each half-orbit a potential function

$$V = r_o[(r/r_o)e + (r_o/r)^2 i] \cos\theta \qquad (2)$$

is determined, where r_o is the radius of the earth, r and θ (and ϕ) are the standard polar coordinates, and *e* and *i* are coefficients determined by least-squares analysis of the measured field components. The coefficients *e* and *i* represent the external and induced contributions, respectively. After collecting the *e* and *i* values for the entire mission, we performed the following preliminary regression analyses of *i* versus *e* and of *e* versus Dst, separately for dawn and dusk:

$$e = a + b \text{ Dst} \qquad i = c + de . \qquad (3)$$

Table 1 summarizes the solutions for the coefficients *a, b, c,* and *d* for the case where Dst is limited to ±20 nanoteslas. The dawn-dusk asymmetry is apparent. Dusk is always more disturbed than dawn. Fukushima[76] and his colleagues have also examined independently derived *e* and *i* coefficients and have also found the dawn-dusk asymmetry and the dependence of *e* and *i* upon Dst. Similar results are found in an independent analysis by Kane and Trivedi.[78] They analyzed the residual horizontal component of Magsat data at the equator after subtracting a spherical harmonic main-field model. A high correlation of the residual horizontal component with Dst was found, and dusk was always more highly disturbed than dawn. When they look particularly at times of magnetic storm, they find that the field at dusk responds earlier in time to magnetic disturbance and that it also has greater values of disturbance. Variations in the east-west component give evidence of meridional currents. A direct comparison with ground data when the satellite was nearly overhead indicates that the satellite and surface variations are identical, and therefore the field variations are of magnetospheric rather than ionospheric origin.

The technique of simultaneously analyzing surface and satellite data to locate the source of a magnetic variation was also successfully used by Araki *et al.*[79] Often a magnetic storm begins with a sudden worldwide field increase, called a Sudden Commencement. This is particularly pronounced in the horizontal component at low latitudes. A Sudden Commencement may be accompanied by a superposed variation called a Preliminary Impulse. Using a combination of Magsat and surface observatory data, Araki *et al.*[79] demonstrated that, at least for one case, the Preliminary Impulse was ionospheric in origin.

By looking at the earth as a whole, Suzuki and Fukushima[80] directly applied the integral form of Maxwell's equations to the Magsat data in order to calculate the total current passing through the Magsat orbital plane. The direction of the current varied with Universal Time. It was sunward near 0^h and 9^h and antisunward near 3^h and 18^h. The total current was approximately 2.0×10^6 amperes at its maximum amplitude.

The ionosphere in the auroral regions of the earth has a highly variable conductivity. During periods of high conductivity, intense currents flow in these regions. The currents are now known to couple to magnetospheric currents by way of currents flowing along magnetic field lines. These field-aligned currents have a complicated structure. Nearly simultaneous data from Magsat (between 325 and 550 kilometers altitude) and Triad (at 800 kilometers altitude) enabled Zanetti and Potemra[81] to show that the field-aligned currents are nearly identical at the two altitudes and to demonstrate a persistence of major characteristics over a significant period of time. Display of Magsat data for an entire day in a color polar projection enables these authors to picture the general current distribution in the ionosphere and along magnetic field lines.[82]

The complexity of the high-latitude ionospheric current system and the field-aligned current system makes them extremely difficult to model. Two sophisticated models are under development (Hughes *et al.*;[83,84] Klumpar and Greer[85]), one of which includes a new coordinate system for better ordering of the data.[83] Both models predict similar features and, in fact, reproduce most of the large-scale features of the Magsat data. Much of the importance of these models is that their discrepancies with the data give indications of where an understanding of ionospheric and magnetospheric physics is deficient. For example, both models predict that an east-west disturbance should be present at latitudes significantly lower than the auroral belt. This is generally not seen in the data; this indicates that the actual latitudinal boundaries of the current systems (i.e., of the electric field or conductivity that defines the current system) are sharper than in the models. An important conclusion of Klumpar and Greer[85] is that magnetic pertur-

Table 1 — Regression analysis for external fields.

	a(nT)	*b*	*Standard Deviation (nT)*	*Correlation Coefficient*	*c(nT)*	*d*	*Standard Deviation (nT)*	*Correlation Coefficient*
Dawn	21.3	−0.62	3.9	0.82	−6.1	0.17	3.6	0.32
Dusk	22.4	−0.72	4.2	0.85	−0.34	0.21	3.9	0.39

bations poleward from the auroral belt arise naturally from a field-aligned current system, with the inward current and outward current in a meridian being balanced. Previous workers had suggested that either unbalanced field-aligned currents or cross-polar-cap currents were necessary.

Zanetti *et al.*[86] showed that the success of such models will depend partly on having a proper estimate of the undisturbed field. Inadequate spherical-harmonic models can give misleading results. They also examine several passes and attempt a quantitative model of the ionospheric portion of the current system. However, their model is unable to reproduce both the horizontal and vertical disturbance.

Disturbances parallel to the main field, $\delta B_{\parallel}$, are studied by Iijima *et al.*[87] A region of high negative gradient in $\delta B_{\parallel}$ is found to coincide with the location of field-aligned currents. Such a region is also suggested as the region in which ionospheric currents (Hall currents) are flowing. The ionospheric currents are modeled as a thin current sheet of infinite longitudinal extent.

Magnetospheric and ionospheric currents cause induced fields within the earth. Studies of the electrical conductivity of the crust and upper mantle are possible with such data. Conductivity changes are caused by variations in the temperature and composition of rocks and by changes in geologic structure. Langel[88] and Didwall[89] have pioneered satellite studies of the crust and mantle conductivity using the POGO data. Those studies, however, failed to distinguish lateral conductivity variations, which surely exist. Hermance[90] has shown, in a simulation study, that lateral differences in conductivity can, in principle, be detected in Magsat data. The fields produced by differences in conductivity may be similar to some of the fields from ionospheric currents and from crustal anomalies.

CONCLUSIONS AND A LOOK TO THE FUTURE

Significant advances in modeling and understanding the solid earth and its magnetic field have resulted from analyzing Magsat data in combination with other relevant data. The earth's main field for 1980 is already known with unprecedented accuracy. Further, new modeling techniques promise even more accuracy in the future.

The outstanding problem in main-field modeling is that of understanding the secular change of the field. Combining Magsat data with POGO data and with surface data has improved our representation of the *past* field, but the prediction of fields into the future remains grossly inadequate. Further development in modeling techniques is badly needed.

Studies of the core, mantle, and core-mantle boundary have progressed at a painfully slow rate because the inaccuracies in the models at the surface are multiplied manyfold when they are projected to the core. This is particularly true of the secular variation. In the absence of better models of the secular variation, future missions with accuracy comparable to Magsat will be required to address in detail the definition of fluid flow in the core. Such missions need to monitor the field both on a short-term basis (continuously for 1 or 2 years) and on a long-term basis (repeated about every 5 years for many years).

Crustal anomaly studies remain in their infancy. However, they have gained respectability for several reasons. First, Magsat has confirmed the earlier POGO results and has given us an improved resolution of the anomalies. Second, it has been shown that anomalies derived from satellite data are in substantial agreement with those derived from airborne or shipborne surveys. Finally, the identification of anomalies with tectonic features and the modeling of some of those features have indicated the potential usefulness of the data.

Qualitative analyses have demonstrated that the long-wavelength magnetic anomalies are associated with tectonic features. In some regions, the anomalies mainly reflect the undulations in the Curie isotherm, while in others they reflect changes in the structure of the lower crust. Quantitative modeling has begun for some regions (parts of the United States, South America, and Japan) and is already contributing to a detailed understanding of the geology of those regions.

Increased effort in quantitative modeling of the crust can be expected in the future. This modeling will be multiparameter, requiring not only satellite magnetic field data but also gravity, heat-flow, seismic, and other geophysical data. Such models can be expected to address the present state of the crust as well as its evolution and the relationship of that evolution to the occurrence of natural resources.

The role of remanence in these long-wavelength anomalies remains in doubt. Quantitative modeling of specific anomalies will probably be required in order to identify under what conditions remanence is important.

The resolution limits of the satellite data will soon assert themselves. Only features greater than about 250 to 300 kilometers can be resolved by Magsat data, and many tectonic features are much smaller than that. This fact may not be important in studying regions that have been well surveyed magnetically by aircraft (such as Canada), but data of such detail are not available for most of the world. Furthermore, patching together small-scale surveys to study larger regions usually distorts the long-wavelength features of interest. The solution lies in pushing the satellite technology to obtain lower-altitude measurements. The Geopotential Research Mission currently under study by NASA would orbit at an altitude of 160 kilometers, yielding anomaly resolution near 100 kilometers. Such resolution will permit the study of many sedimentary basins, shields, oceanic rises, rifts, foldbelts, and subduction zones that are too small to be seen in the Magsat data. NASA is also studying the feasibility of a tethered satellite system, either from the shuttle or a space platform. One can conceive of measurements as low as 120 kilometers with such a system.

It has become apparent that reduction techniques necessarily associated with the north-south tracks of the POGO and Magsat missions have selectively filtered out many north-south anomalous features. Measurements from a satellite at an inclination of 50 to 60° would remedy this situation, and we should consider such satellites for the future.

Although Magsat was not designed as a tool for investigating fields from external sources, it has proven useful in doing so. An estimate of the "absolute level" for Dst has been found and the existence of a current system discovered. New modeling capability is under development and has already been used to investigate properties of the high-latitude current systems. Future results will include studies of the fine structure of field-aligned and ionospheric currents and a better definition of the overall current flow in the inner magnetosphere.

It is apparent, even with these preliminary results, that the breadth of science involved in the Magsat project is great and that the research is being conducted with some measure of vigor. It is a privilege to be associated with this multidisciplinary community.

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