Summary of the Results of MAGSAT Investigations in Japan

Naoshi FUKUSHIMA

Chairman, Japanese MAGSAT Team,
Geophysics Research Laboratory, University of Tokyo, Tokyo, Japan

A. Crustal Structure near Japan and Its Antarctic Station

The team objective is to study the crustal structure near Japan and its Antarctic base by constructing a model of the regional magnetic field and investigating the local magnetic anomalies and their origin.

A.1 Regional magnetic charts

Construction of a model of the regional geomagnetic field over the Japanese islands and their neighborhood for the epoch 1980.0 has been attempted by means of MAGSAT data (NAKAGAWA and YUKUTAKE) and the aeromagnetic survey data obtained by the Hydrographic Department in 1980 (UEDA et al.). The original plan was to make a model by incorporating the MAGSAT data; however, incorporation of the MAGSAT data is for future work. The field synthesized by the model of the third degree polynomials was compared with the existing reference field, IGRF 1980.0 and MGST(4/81). Better agreement is seen with MGST(4/81) than with IGRF 1980.0 (UEDA et al.). This seems to arise from the difference in the number of terms included in the models. Poor approximation of IGRF is perhaps due to lack of terms higher than degree 10 which also represents contribution of the core field.

A.1.1. Spatial properties of the regional geomagnetic field

For the magnetically quiet period of $Kp\leq 2$, three component data $X$, $Y$ and $Z$ from MAGSAT Investigator-B tapes along individual paths over the area of $120^\circ$–$160^\circ$E and $18^\circ$–$58^\circ$N were subjected to the polynomial fit, by means of Legendre functions, by varying the maximum degree of series $N$ from 1 to 9 (NAKAGAWA and YUKUTAKE). It is known that the magnitude of the coefficient decreases rapidly from degree 1 to 6, and beyond degree 6 the rate of decrease becomes small. If the magnitude of the coefficient is regarded as represen-

1) This summary is taken from the Final Report to NASA from the Japanese MAGSAT Team (dated March 15, 1983), which was compiled with the collaboration of T. YUKUTAKE and T. IIJIMA. The text is modified so as to explain the results of investigation without illustrations. References are shown as footnotes.
2) The details are described in the paper by I. NAKAGAWA and T. YUKUTAKE published in this issue, pp. 443–453.
3) See the details in a paper by Y. UEDA et al. in this issue, pp. 471–482.
4) I. NAKAGAWA and T. YUKUTAKE, this issue, pp. 443–453.
ting the amplitude spectrum, it would indicate two distinct structures in the spatial spectrum of the observed field: one is the lower degree terms of large amplitude, and the other is the higher degree terms of small amplitude with a low decreasing rate.

The difference in the spectrum between the higher degree terms and the lower ones is more clearly seen in the residual field after removal of the fitted polynomials. The rms residuals decrease sharply from degree 1 to 5, and become almost constant beyond degree 5.

The above feature in the spatial spectrum is very similar to the spectrum structure obtained from the spherical harmonic analysis of the global data, suggesting that these structures are of the origin of the core and the crust, respectively. The two types of field become comparable at degree 13, corresponding to the wavelength of about 3000 km, as Langel and Estes\textsuperscript{5} (1982) reported.

In the present analysis, however, the overlap of the spectrum of the core and the crustal field does not always occur at the same degree. The overlap degree for the individual orbit paths was averaged in each region, and the frequency distribution of the average overlap degree was studied for 10 different regions. For the $X$ component, the overlap degree was either 5 or 6 in 9 regions. For the $Y$ component, the critical degree concentrated at 5. On the other hand, for the $Z$ component, it spread toward higher harmonics up to degree 7.

From the degree of the polynomial one may roughly estimate the wavelength of the field. The degree $n$ was related to wavelength $\lambda$ by the equation

$$\lambda = \frac{L}{[(n-1)/2]}$$

where $L$ is the length of the path used for the analysis, which is taken as 7000 km. The overlap degrees of 5 and 6 corresponded to the wavelength of 3500 to 2800 km. This agrees with the overlap wavelength 3000 km derived from the spherical harmonic analysis of worldwide data.

A.1.2. Regional magnetic charts\textsuperscript{6}

Aeromagnetic surveys were conducted by the Hydrographic Department of the Maritime Safety Agency in 1980 with fluxgate magnetometers for the three components (Hydrographic Department, 1982). Accuracy of the measurement was about 10 nT for the $Z$ component, and somewhat less precise for the other components, mainly controlled by the accuracy of orientation of the instrument. Total intensity was computed from the component data.

A.1.3. Comparison of the regional model with that derived from MAGSATE data

The regional field model expressed in a polynomial series was compared with the MGST(4/81) model (Ueda et al.\textsuperscript{6}). Field values at the grid point of


\textsuperscript{6} The geomagnetic survey results mentioned here are given in the paper by Y. Ueda et al. in this issue, pp. 471-482.
every 1° of longitude and latitude were synthesized from two models, the regional field model and MGST(4/81). The difference of the regional model minus MGST(4/81) is small; its absolute value is less than 20 nT almost all over the Japanese islands, except for the area near the border of the surveyed area, where the difference becomes -40 nT. Comparison was also made for the vector data. Discrepancy is insignificant in the central part, less than 20 nT for the X and Z components. Regarding the Y component, however, it becomes -80 nT; this large discrepancy might be caused by poorer orientation of airborne magnetometers. Hence, it may be said that, except for the Y component, agreement between the regional model and MGST(4/81) is satisfactory.

A similar comparison was made with the field values computed from IGRF 1980.0. Although a zero line passes through the central part of the surveyed area, the difference becomes as large as -80 nT toward the west, which is much larger than in the case of MGST(4/81).

Better approximation of the model MGST(4/81) in comparison with IGRF seems to stem from the difference in the number of spherical harmonic terms involved (up to the degree and order of 13 in MGST(4/81), and 10 in IGRF 1980.0). As was discussed earlier, the regional model contains fields with wavelengths of 2500 km, which roughly corresponds to degree 16 in terms of the spherical harmonic series. The IGRF 1980.0 model seems insufficient to approximate the field of this wavelength. It is perhaps due to this same reason that the past IGRF models (IGRF 1965.0 and 1975.0) have given rather poor approximation to the geomagnetic field over Japan and its vicinity.

While the past IGRF models have always given 100 to 300 nT higher values for the total intensity than observation over the area of the Japan islands, the MGST(4/81) model has been confirmed to approximate the observed field even better.

A.2 Local magnetic anomalies and their origin

The objective here is to extract local magnetic anomalies and to investigate their origin. There are abundant data so far accumulated by surface surveys, not only on land, but also on the sea surface. Along with the MAGSAT data, these surface data were originally planned to be integrated into a single data set to generate the local magnetic anomalies. For this purpose it would be necessary to reduce all the data to a common altitude. A downward continuation program by use of a Fourier analysis technique has been completed, but not yet used practically for extraction of the short wavelength anomalies; accordingly, MAGSAT data were analysed independently from the surface data, and reported separately. However, the downward continuation method will be described here.

Two approaches were made for extraction of the local anomalies. The MGST(4/81) model was subtracted from the observed values, and residuals were computed (NAKATSUKA and Ono7). The second approach was to apply a

7) In this issue, pp. 455-462.
polynomial series approximation to a limited segment of the MAGSAT data and to compute the residuals (NAKAGAWA and YUKUTAKE\textsuperscript{8}). Both analyses revealed interesting features in the crustal anomaly, but many of the detailed structures still remain unresolved. A three-dimensional Fourier analysis technique was explored with local Cartesian coordinates (NAKAGAWA and YUKUTAKE\textsuperscript{8}). A computer program for the downward continuation was tested with lower order harmonics up to 3, giving only long wavelength features.

Total intensity data in the oceanic area surrounding the Japanese islands were compiled and analysed (FUJITA and KAWAMURA\textsuperscript{9}). Data acquisition covers such a long period, from 1961 to 1979, that correction of the secular variation was necessary to compare the data of different epochs. Definitive International Geomagnetic Reference Field (DGRF) models were used for the correction. The analysis is still under way. The results obtained so far were consistent with those of MAGSAT analysis. The surface data reinforced new findings only vaguely defined by the analysis of MAGSAT data.

Investigation of the origin of the magnetic anomalies is the most retarded part of the project. Equivalent source procedure is one method employed to infer the distribution of magnetization in the crust (YANAGISAWA et al., 1982). Several factors are conceivable causes of the observed magnetic anomalies; however, the preliminary study seems to suggest that either the varying thickness of the crust or its thermal structure plays an important role in generating long wavelength anomalies.

**A.2.1. Local magnetic anomalies derived from MAGSAT**

\textbf{A.2.1.1 Anomalies as the residual field from MGST(4/81)}

Anomaly maps of total intensity and vector components were drawn for the residuals of the observed field values from those computed by the MGST(4/81) model (NAKATSUKA and ONO\textsuperscript{10}).

(a) Data selection: Only half orbit (ascending or descending) paths passing through the area in the vicinity of Japan (15°–60°N, 115°–164°E) were picked up. In order to eliminate magnetic disturbance effect, the data for the period of $Kp \geq 2_+$ were excluded. Attitude quality words (refer to NASA Technical Memorandum 82160) were checked and data points of poor quality in attitude ($\geq 4000$) were excluded.

(b) Data processing: Every orbital series of data points was tested if it has sufficiently uniform distribution in dipole latitudes, and non-uniform series were dropped. After the subtraction of the reference field of MGST(4/81), the magnetic field data still included external (magnetospheric and ionospheric) disturbance fields. A trigonometric function form $[a \cdot \sin \phi + b \cdot \cos \phi + c]$ of dipole latitude ($\phi$)

\textsuperscript{8}) In this issue, pp. 443–453.
\textsuperscript{9}) In this issue, pp. 483–486.
\textsuperscript{10}) In this issue, pp. 455–462.
was fit within the dipole latitude range of 15°–55°N, and the residual between the two was assumed to be the crustal anomaly field. This operation was applied to each component and total intensity. A statistical process was then required to draw a two-dimensional anomaly map; we took a local Cartesian coordinate system around Japan, the origin of which is located at the point of 37.5°N (geocentric), 137.5°E, and at a geocentric distance of 6800 km. In order to find mesh point value, a 3-dimensional linear regression formula was applied to all data within 160 km in horizontal separations from the mesh point to be reduced, and the mesh point value at the mean elevation of these points was determined. This regression analysis was conducted at every 40 km mesh point, to get 2-dimensional mesh distribution of the magnetic field.

(c) Results: The data processing described above was applied to four kinds of data subsets, namely A (ascending dusk-side paths only, 7587 points), D (descending dawn-side paths only, 10488 points), H (high-altitude paths of >6800 km geocentric distance, 9745 points) and L (low-altitude paths of <6800 km geocentric distance, 8330 points), and to the set of all available data (namely B, total of 18,075 data points).

(d) Discussion

In respect to the large scale anomaly, similar patterns are obtained irrespective of the data subset. This implies that the reproducibility of anomaly patterns of this scale is good. Also, the amplitude of anomalous field at lower altitude L is larger than at higher altitude H. This results is consistent with the fact that the average elevational difference between these two data subsets is about 100 km, if we consider the crustal anomaly decreases its amplitude in proportion to the inverse square to cube of the distance.

On the other hand, there are some minor disturbances with shorter wavelength, which appear only in some data subsets. As the data processing step effectively includes a low-pass filtering operation, this process may be inadequate to reveal smaller-scale anomalies of shorter wavelength of a few hundred kilometers or less and also there may be problem in the retrieval of the external field. In any case, we cannot distinguish reliable magnetic anomalies.

The anomaly maps for the three components have also been made; they are more noisy than the total intensity. However, if all the available data are analysed together, the noisy character is strongly reduced. It is concluded that anomaly patterns with wavelengths longer than about 500 km can be sufficiently reproduced by the present analysis.

A.2.1.2 Anomalies computed by the polynomial series

It has been confirmed that polynomial approximation for the limited area is useful to separate the crustal field from the core field (NAKAGAWA and YUKUTAKE9). An anomaly map was drawn for the area of 18°–58°N and 120°–160°E, by means of the data on all the satellite paths passing through the area of 8°–68°N and 110°–170°E for the magnetically quiet period Kp≤20. Since it was known that the core field becomes comparable with the crustal field
at degrees from 5 to 7, the 5th degree polynomials of latitude were used to subtract the core field, and the residuals were assumed to represent the magnetic anomaly of crustal origin. Anomaly charts were drawn at an altitude of 430 km, which is an approximate mean of the satellite paths. Besides short wavelength anomalies, some of which are still seriously contaminated by noisy data contained in the original data set, an east-west trend of long wavelength is noticeable. There are two conceivable causes for this trend. One is the nature of the filtering process. Although the polynomial fitting process filters out the long wavelength anomalies along the orbital path (i.e., the anomalies in the north-south direction), those with a strike in the east-west direction perpendicular to the path remain unfiltered. The second is the possibility that the core field is not completely removed by the 5th degree polynomials, and that the core field contained in the 6th degree term dominates over the crustal field expressed by the rest of the polynomial series.

$\Delta X, \Delta Y$ and $\Delta Z$ residuals were computed into gridded values at 1.25° intervals in longitude and latitude without altitude correction, and expressed in a double Fourier series of longitude and latitude. In order to filter out the east-west trend, the first order harmonics were excluded from the series synthesized up to the order of 31. Then the east-west trend was almost completely removed. Instead, a weak tendency appeared, running in the northeast-southwest direction. It is not known at the present whether this tendency is partly of artificial origin or not; sometimes these tendencies are real, such as the positive belt along the Kuril islands from Kamchatka to Hokkaidō. Although there are many anomalies of short wavelength, anomalies smaller than 500 km are supposed artifacts created by erroneous data.

A.2.1.3. Results derived from MAGSAT data

A positive anomaly of total intensity and the vertical component seems to exist along the trench. An anomaly along the Kuril islands is particularly intense, which corresponds to a narrow belt of positive anomaly observed at the surface running along the Kuril Islands on the land side of the trench. On the other hand, another positive belt that is also remarkable at the surface in the north-south direction along the east coast of Northern Honshu is not clearly recognizable at the satellite altitude. This may suggest that the positive belt of Northern Honshu is of shallow origin in the crust, decaying rapidly with height, while that of the Kuril Islands has deeper roots.

It is also interesting to point out that, over the Izu-Mariana trench, a positive area extends north-south. This agrees well with the result of analyses of the marine data as will be discussed later, where the positive anomaly runs north-south in the west of the trench. These results seem to imply that it is a general feature of the magnetic anomaly in the subduction zone that the positive anomaly runs parallel to the trench on its island side. If this is true, it would become an important key in disclosing the evolution process of the island-arc and the trench structure.
It is thought, from evidence in the surface survey, that the Japan Sea is covered with a negative anomaly of \( \Delta F \) and \( \Delta Z \). However, it is negative only in the northeastern part of the Japan Sea, whereas it is rather positive in the southwestern half. This is possibly related to the fact that the oceanic basin extends in the northeastern part of the Japan Sea, while in the southwestern part there are submarine rises such as the wide Yamato-tai rise. A similar feature is seen in the Okhotsk Sea, where negative anomaly is more conspicuous. This seems to suggest an important nature of the back-arc basin.

Another feature to be noted from the surface survey is a negative anomaly of \( \Delta Z \) that covers the Korean peninsula. This forms a pair with a positive anomaly in the south. In the \( \Delta Y \) anomaly chart, we note a quadrant structure at the place of the pair of \( \Delta Z \) anomalies, where \( \Delta Y \) is positive in the northeast and southwest quadrants, and negative in the northwest and southeast quadrants. These are typical patterns of the anomalies caused by a dipole beneath the ground with its magnetization in the direction of the present magnetic field. The \( \Delta X \) anomaly is also consistent with this model. All this suggests that a highly localized magnetic material with extremely intense magnetization is buried, perhaps at a shallow depth, near the southwest tip of the peninsula.

A.2.2. Three-dimensional Fourier analysis of MAGSAT data

The treatment in the previous section ignored changes in field values caused by the change in the satellite altitude from 350 km to 500 km. This increase in altitude is one of the causes generating the noises that conceal the detailed structure of the anomalies. The altitude correction is an important step in refining the anomaly map.

When the data are given by geodetic coordinates, it is practical to expand the field values into a Fourier series of longitude and latitude. However, this method cannot be used for altitude correction, because the Fourier series in longitude and latitude does not satisfy the Laplace equation in a strict sense.

In this section, we employed a local Cartesian coordinate system with its origin at 35°N, 140°E. The z-axis was taken vertically downward, and the x- and y-axis toward the north and the east, respectively, on the plane tangent to the earth. The coordinates of the satellite position were transformed into the local coordinates, and the observed field was decomposed into \( X \), \( Y \) and \( Z \) components or the Cartesian coordinates. The decomposed values were then subjected to a three-dimensional Fourier analysis (NAKAGAWA and YUKUTAKE\textsuperscript{11}).

Among the data on the paths over the area of 8°–68°N and 110°–170°E, only those with high accuracy of satellite attitude control were selected, although this process resulted in reducing the data set to about a quarter of its original size. The data thus selected were subjected to the polynomial fit. Since the core field is likely to remain in the residuals even after the trend was removed by the 5th degree series, we employed the 7th degree polynomials to compute the

\textsuperscript{11} In this issue, pp. 443–453.
residual anomaly field. Of the residuals obtained in this way, those inside the space $-L/2 \leq x \leq L/2, -L/2 \leq y \leq L/2$ were Fourier analysed, taking the maximum order of harmonics as 3.

From the Fourier series determined in this way, it has become possible to compute the anomaly field at any point in the three-dimensional space, and the anomalies at the altitude of 300 km were thus synthesized. Since only the lower harmonics were used for the analysis, the anomaly charts delineate only the long wavelength features. Upward and downward continuation was made and the magnetic anomalies at the altitude of 100 km and 500 km were computed.

Even in this crude approximation with only the lower harmonics, one may see the magnetic features revealed in the previous section. $\Delta Z$ anomaly shows that the northeastern part of the Japan Sea is weakly negative, while the southwestern part is positive. A positive anomaly is noticeable from the Kuril Islands to Hokkaido. A second positive anomaly, which runs along the Izu-Mariana trench, is not easily recognizable. In order to see this second relatively short wavelength anomaly, it is necessary to include higher harmonics in the series. On the other hand, a negative anomaly covering the Korean peninsula is very remarkable in the present case. Another feature to be mentioned is, though weak, a trend in the direction of ENE to WSW of alternating positive and negative anomalies. Further investigation is needed to confirm whether or not this trend is real.

A.2.3. Local anomalies derived from maritime data

A large amount of data has already been accumulated from the surface surveys and can be compared with the MAGSAT data. Unfortunately, however, these surface data are not well compiled nor analysed in a form ready to compare with the satellite data except for a very few works (Nomura12), 1979). Among the data accumulated in the Oceanographic Data Center of the Hydrographic Department, Maritime Safety Agency, total intensity data obtained by ship-borne proton precession magnetometers covering the region of $120^\circ$E–$160^\circ$E and $15^\circ$N–$50^\circ$N were analyzed (Fujita and Kawamura13). The total number of data amounts to about 600,000, which was acquired between 1961 to 1979.

Since the observation covers such a long period, a certain kind of correction for the geomagnetic secular variation is necessary to reduce the data to a common epoch for computing the magnetic anomalies. For this correction, we used the Definitive International Reference Field (DGRF) for 1965.0, 1970.0 and 1975.0, together with the International Geomagnetic Reference Field (IGRF) for 1980.0. To begin with, comparison was made of these reference field models with the observed fields at Japanese magnetic observatories, Memambetsu (MMB), Kakioka


13) In this issue, pp. 483–486.
(KAK), and Kanoya (KNY). The reference field values were linearly interpolated between 1965-70, 1970-75, and 1975-80. The total intensity of the reference field is larger than that observed in Japan by about 100 nT, and the differences are almost constant for the two periods 1965-70 and 1975-80, but from 1970 to 1975 the differences increase abruptly by more than 50 nT at Memambetsu and at Kakioka. Therefore, the adopted reference field may be taken to represent the secular variation in total intensity in Japan with an accuracy of about 50 nT. Since the amplitude of magnetic anomalies in total intensity around Japan is about 300 nT, the magnetic anomaly chart based on these reference fields may not be seriously influenced by the correction of the secular variation.

The anomaly was obtained by taking the difference between the observed values and those synthesized from the reference models. At each observation point, the difference was computed (i.e., observed total intensity minus reference total intensity), and averaged every 0.25° × 0.25° area. Using all the data from 1965 to 1979, the averaged anomalies were demonstrated.

For the two stable periods of the secular variation (i.e., the periods 1965-70 and 1975-80), the anomalies were computed separately and compared. Although there is a tendency for the anomalies computed from the data in 1966-70 to have larger values than those in 1976-79, the general patterns of the anomalies are similar in each period. The following features are noteworthy.

1. There are positive anomaly belts running parallel with trenches on their continental side, such as the anomaly along the Kuril trench, the one associated with the Japan trench, and the anomaly parallel with the Izu-Mariana trench. As has already been described, the anomalies along the Kuril trench and the Izu-Mariana trench were visible at the satellite altitude, whereas the anomaly running north-south in parallel with the Japan trench was not recognizable in the MAGSAT data. (2) The southwestern part of the Japan Sea is covered with a positive anomaly, and an area of negative anomaly spreads to the north; this feature was confirmed by the MAGSAT data. However, the marine data suggests existence of a positive area again further to the north. (3) A strong positive anomaly is clearly seen near 40°N and 155°E. This has not been confirmed by the satellite data.

On the other hand, the positive anomaly region in the Pacific Ocean is not clearly established. In the Pacific Ocean it is difficult to draw a clear anomaly pattern, due either to complex superposition of small scale magnetic anomalies or to sporadic distribution of the regions where data are not observed. The number of data used in the calculation of average anomaly in each unit area amounts to several hundreds near Japan, while only a few data are available in the Pacific Ocean far from Japan.

A.2.4. Possible causes of the magnetic anomalies

Applying an equivalent source procedure, distribution of magnetization in the earth's crust was determined to generate the observed total intensity anomalies
at the MAGSATE altitue (YANAGISAWA et al., 14) 1982). In comparison with the other geophysical data, possible causes of the anomalies were investigated. Lateral variation in the thickness of the crustal layer was found to be one possible cause. The other was the difference in geothermal structure revealed by heat flow measurements. These were determined to be the most likely sources for the magnetic anomalies.

By placing magnetic dipoles at the surface of the earth with their axes parallel to the main field calculated from the MGST(4/81) model, an attempt was made to interpret the observed anomaly of total intensity at a satellite altitude, which was derived by the method described in Section A.2.1.1. by subtracting the MGST(4/81) field from the observation. The dipoles were placed at every 3° × 3° latitude-longitude mesh points. The magnetic moment of each dipole was determined by means of an equivalent source procedure proposed by MAYHEW15) (1979), so as to fit the observed anomaly. The magnetic moment thus obtained was then converted to a magnetization of the earth's surface layer on the assumption that the layer has a uniform thickness of 30 km.

A zone of high magnetization runs almost north-south near the center of the Japan Sea. Most of this high magnetization roughly coincides with the location of the Yamato-tai, a sea platform with a shallow depth of less than 2,000 m. Except for this high, the magnetization in the Japan Sea area is lower than that on the Japan Island by 1 × 10⁻¹ to 2 × 10⁻¹ A/m. The weak magnetization is most pronounced in the northeastern part of the Japan Sea, i.e., most of the Japan Basin and the Yamato Basin, where the depth of the bottom is typically 3,000 to 3,500 m.

We assumed a layer of 30 km thickness for the source of magnetic anomalies. The anomalies in this figure can, therefore, be interpreted as representing either the lateral variation of susceptibility in the magnetized layer or the lateral variation of the thickness of the magnetized layer. If the thickness of the layer is assumed constant, variation of its thickness causes the magnetic anomalies. From comparison with other geophysical data in this area, this second interpretation appears more plausible.

It was tentatively assumed that the crustal material had a uniform susceptibility of 4 × 10⁻³ in SI unit (= 3.2 × 10⁻⁴ emu/cc). Then the crustal material was magnetized by 1.6 × 10⁻¹ A/m (1.6 × 10⁻⁴ emu/cc) per unit volume under the geomagnetic field of 40 A/m (= 0.5 Gauss). The magnetization contrast of 1.3 × 10⁻¹ A/m between the Japan Sea and the Japan Island corresponded to the 24 km difference in the thickness. This value certainly depends on the assumed susceptibility, but suggest that the magnetized layer is substantially thinner

in most parts of the Japan Sea.

According to the seismic data, crustal thickness is about 30 km beneath the Japan Island and about 10 km beneath the Japan Sea (YOSHI16), 1979). If the Curie point isotherm is deeper than the crust/mantle boundary, the crust must be magnetized, but the mantle would not be magnetized at all (WASILEWSKI et al.,17) 1979). If this is the case in this area, the thin magnetized layer in the Japan Sea may be explained by the thin crust.

On the other hand, the heat flow through the sea floor of the Japan Sea is about 100 mW/m², and about twice the value observed on the Japan Island (YOSHI16), 1979). The Japan Sea area is characterized by low surface wave velocities, which means a hot upper mantle in this area (ABE and KANAMORI18), 1970); the large negative residual gravity anomalies also indicate that the upper mantle is light and hot (YOSHI19), 1972). These facts suggest that the Curie point isotherm is shallow beneath the Japan Sea and only the shallower part of the crust is magnetized.

From the heat flow values and geothermal gradients measured at the surface, the depth of the 500°C isotherm is estimated to be about 30 km beneath the central part of Japan (WATANABE20), 1968). If this can be regarded as the thickness of the magnetized layer in central Japan, the 24 km difference of the thickness leads to a 6 km magnetized layer beneath the Japan Sea. This is smaller than the Japan Sea crustal thickness (about 10 km). Therefore, this seems to suggest that the lower crust is not magnetized because of high temperature.

Study of the origin of the magnetic anomaly is still in its initial stage. Although two highly possible causes were investigated, there is no decisive evidence to determine whether the anomaly is created by the lateral variation of the thickness of the crust or by that of the depth of the Curie point isotherm; further investigation is necessary.

A.3 Crustal structure in the Antarctic

The ultimate goal of the team is to clarify the crustal structure in an area near the Japanese Antarctic base stations, Syowa Station at 69°00'S, 39°35'E and Mizuho Station at 70°42', 49°20'E, incorporating the geomagnetic data with gravity and seismic data. The aeromagnetic survey was the central program related to the present investigation. The aeromagnetic surveys were conducted under severe

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16) YOSHI, T., A detailed cross-section of the deep seismic zone beneath northeastern Honshu, Japan, Tectonophysics, 55, 349-360, 1979.
conditions, and the data are now being analysed (KAMINUMA and SHIBUYA\textsuperscript{21}).

With a proton precession magnetometer, the aeromagnetic survey was carried out around Syowa Station in 1980 and 1981. In 1980, the survey was executed along the 20 flight lines over the eastern and central part of Lützow-Holm Bay, 3 hours each, with a flight elevation of 1500 feet over the ground surface in 1980. The survey was also carried out in the Yamato Mountain area, which was located 200–300 km south from Syowa Station, and in the area between Syowa and Mizuho Stations.

The aeromagnetic survey was conducted in 1981 at 5000 feet and the total flight distance was 1685 km. Surveys at 1500 feet and 3000 feet were also carried out, and the total flight distance were 1120 km and 1325 km, respectively. The total intensity of the geomagnetic field was measured at three different flight elevations of 3000, 5000 and 8000 feet. These surveys were carried out along the longitude of 39°25′E from 68°50′S to 69°40′S in latitude. As the surveys were completed within a few days, during a magnetically quiet period when $K$-index was 0–1, no correction was made for the intensity value.

Using the data obtained above, an isomagnetic chart of the total intensity is being made, and the analyses are in progress.

B. Electric Currents and Hydromagnetic Waves in the Ionosphere and Magnetosphere

The objective in this section is to investigate ionospheric and magnetospheric contributions to geomagnetic variations, field-aligned currents, geomagnetic pulsations and hydromagnetic waves by analysis of MAGSAT data, and if necessary also through comparison with ground magnetic variations.

B.1 Ionospheric and magnetospheric contributions to geomagnetic variations

The MAGSAT data proved very useful in studying the ionospheric and magnetospheric contributions to geomagnetic field variations from various standpoints. The main results obtained so far are summarized below.

B.1.1. External field correction for satellite magnetic data

A new conventional method was introduced to learn the features of external and internal contributions to the data obtained by MAGSAT (YANAGISAWA\textsuperscript{22}), 1984). Let $\Delta B$ denote the difference between the magnetic field $B$ observed by MAGSAT and that given by the MGST(4/81) model. $\Delta X_{\text{mag}}$ and $\Delta Z_{\text{mag}}$ of the residual field in geomagnetic coordinates were subjected to a harmonic analysis with Legendre functions in the latitude range of ± 55°, by means of the equation

\textsuperscript{21} In this issue, pp. 487–491.

$W = a \sum_{n=1}^{6} \left\{ E_n \left( \frac{r}{a} \right)^n + I_n \left( \frac{a}{r} \right)^{n+1} \right\} P_n(\cos \theta)$

(1)

where $W$ is the magnetic potential for $\Delta B$. The analysis was carried out separately for the dawn and dusk sides. The calculated values of external and internal coefficients ($E_n$ and $I_n$) of the magnetic potential $W$ are shown for four classes of $Dst$ values.

It is clear that $E_1$ increases with the absolute value of $Dst$, whereas $E_2-E_6$ are negligible in comparison with $E_1$ in all cases. This means that the magnetic field of origin external to the MAGSAT level is well approximated by a simple southward magnetic field along the geomagnetic dipole axis. A noticeable dawn/dusk asymmetry of this southward field is discussed in the next section.

The internal component of $\Delta B$ consists of the induction current within the earth and the electric current flowing in the ionosphere below the MAGSAT level. $I_1$ seems to increase in approximate proportion to $E_1$, but $I_2-I_6$ do not change much with $E_1$ value. We may assume here that the magnetic field originated from $E_1$ and $I_1$ terms represents the ring current field and its induction effect, and the remaining fields (especially those from $I_2-I_6$) the ionospheric current as a first approximation.

The worldwide $Z$-anomaly maps were dawn separately from the MAGSAT data on (a) the dawn side and (b) the dusk side, after removing the MGST (4/81) model and the contributions from $E_1$ and $I_1$ terms. The two maps for the dawn and dusk sides differ considerably from each other because of the contamination from the ionospheric current. The latitudinal profiles of $Z$-anomaly thus obtained for the dawn and dusk regions were averaged for all longitude range, and the average is denoted as delta-$Z$. The mean delta-$Z$ curve is thought to represent the contribution to $Z$ along the dawn and dusk meridians from the ionospheric current dependent on local time. Subtracting delta-$Z$ from the $Z$-anomaly maps, we obtain the maps where the two maps for the dawn and dusk meridians are nearly the same.

In conclusion, it is shown that the magnetospheric contribution is represented by a simple southward field with a noticeable dawn/dusk asymmetry. The elimination of the ionospheric contributions (coming from below the MAGSAT level) gives a common anomaly map in the dawn and dusk regions.

B.1.2. Dawn-dusk asymmetry of the ring current field

The values of coefficient $E_1$ (which represents the southward magnetic field of magnetospheric origin) in Eq. (1) of the previous section are calculated for 26 days from November 2 to 27, 1979 (YANAGISAWA, 1984), together with the simultaneous $Dst$ and $Kp$ values. The $E_1$ values generally vary in close correlation with $Dst$, but they exhibit sometimes pronounced dawn/dusk asymmetry.

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(enhancement at the dusk side, and a reduction at the dawn side), especially when \( Dst \) and \( Kp \) values are great. The dawn/dusk asymmetry of \( E_1 \) values is noticeable for \( Kp \geq 3 \), but almost absent for \( Kp \leq 2 \).

Since the ground \( Dst \) also contains the contribution from the induced electric current within the earth, which is a main part of \( I_1 \) in Eq. (1), the comparison of \( E_1 + I_1 = -1.0 \ Dst + 24 \).

A comparison of the results observed by OGO-5 (SUGIURA\(^{24} \), 1973) and MAGSAT was made to infer the ring current flow in the magnetosphere. OGO-5 observed the minimum field depression at 2.3–3.6 \( R_E \). The empirical formulae are

\[
E_1 \text{ (at OGO-5 level)} = -0.83 \ Dst + 45 \text{ nT},
\]
\[
E_1 \text{ (at MAGSAT level)} = -0.74 \ Dst + 22 \text{ nT},
\]

so that

\[
E_1 \text{ (MAGSAT)} = 0.89 \ E_1 \text{ (OGO)} - 18 \text{ nT}.
\]

The factor 0.89 in the last equation is attributable to the difference in geocentric distance of the observation level of MAGSAT (\( \sim 1 \ R_E \)) and OGO (2.3–3.6 \( R_E \)). If we represent the ring current by a simple circular line-current, the factor 0.89 is obtained if the line current is assumed to be situated around 8 \( R_E \). On the other hand, the difference of 18 nT between \( E_1 \text{(MAGSAT)} \) and 0.89 \( E_1 \text{(OGO)} \) will be reasonably attributed to an eastward ring current, which must exist in the inner edge of the westward ring current region to keep the plasma pressure of trapped charged particles in the magnetosphere.

B.1.3. Electric current through the plane encircled by the MAGSAT orbit\(^{25} \)

It is possible to calculate the total amount of electric current passing through the plane enclosed by the MAGSAT orbit by means of Ampère’s theorem (or integrated form of a Maxwell equation). The electric current can reasonably be thought to flow as a field-aligned current in the magnetosphere, and as a horizontal current in the ionosphere.

Attention must be paid in this analysis to the fact that MAGSAT requires 94 minutes to complete the magnetic field measurement over a complete circular path, and the earth rotates as much as 23.5° eastward under the MAGSAT orbit. This condition will result in a spurious effect on the calculated current under the MAGSAT orbit, unless the effect of the earth’s rotation is corrected.

We dealt with two kinds of calculations: first, one in which \( B_t \) (the magnetic

\(^{24} \) SUGIURA, M., Quiet time magnetospheric field depression at 2.3–3.6 \( R_E \), J. Geophys. Res., 78, 3182–3185, 1973.

\(^{25} \) The work of this section is part of a paper by A. SUZUKI, M. YANAGISAWA, and N. FUKUSHIMA, Anti-sunward space current below the MAGSAT level during magnetic storms, and its possible connection with partial ring current in the magnetosphere, submitted to J. Geophys. Res., 1984.
field to be integrated) was taken to be tangential to the loci of MAGSAT orbits projected onto the earth (not parallel to the MAGSAT path in space), and second where $B_t$ was taken tangential to the MAGSAT orbit in space. The calculated total current $J$ is denoted here as $J(I)$ with MAGSAT data, $J(II)$ with MGST(4/81) model in the first case, $J(III)$ with MAGSAT data, and $J(IV)$ with MGST(4/81) model in the second case. A previous paper by SUZUKI and FUKUSHIMA\textsuperscript{26}) (1982) adopted the first case, which included a spurious effect due to the earth’s rotation. The correct result is given through the second calculation: $J(IV)$ is the integration for a static magnetic field derivable from a magnetic potential, so that $J(IV)$ must vanish theoretically. The actual result showed that the total current is less than $3\times10^5$ A on a quiet day, and such an amount can be produced from a very small error in the absolute magnetic field measurement and/or in the altitude determination of MAGSAT. For example, the accumulation of 1 nT error in the absolute value of $B_t$ results in a total current of $4\times10^4$ A. An altitude error of only 150 m will produce a total electric current of $10^5$ A.

In 1982, SUZUKI and FUKUSHIMA\textsuperscript{26}) published the preliminary results of their analysis. They compared the $B_t$-integrations with the actual MAGSAT data and with the MGST(4/81) model field; both integrals showed the total current of $4\times10^6$ A in magnitude with predominant semidiurnal variation, and the difference of these two calculations was assumed to indicate the electric current in space below the MAGSAT level. However, the authors would like to revise their conclusion in this report because of the criticism of the method of calculation described above.

The $J(I)-J(II)$ calculation for the quiet day of November 5, 1979, in the SUZUKI-FUKUSHIMA paper\textsuperscript{26}) (1982), contains a spurious effect of the earth’s rotation. The apparent semi-diurnal variations of the sunward or anti-sunward electric current in space below the MAGSAT level is now understood mainly as an effect from $g_{22}$-term of the earth’s magnetic field\textsuperscript{27}).

On the other hand, in the results of the $J(III)$ calculation on the same day, the total intensity of space current below the MAGSAT level is much smaller, i.e., less than $10^6$ A. We are continuing the calculation of $J(III)$ for many other days during the period of the MAGSAT flight in order to find or check the dependence of sunward or anti-sunward space current below the MAGSAT level on (1) universal time, (2) geomagnetic activity, (3) solar wind and interplanetary magnetic field conditions, and (4) season. The space current under the MAGSAT orbit is anti-sunward in the disturbed condition with its magnitude far exceeding $10^6$ A in approximate proportion to the geomagnetic $AE$-index.

It was described in Section B.1.2. that the dawn/dusk asymmetry of $Dst$
is pronounced when the $AE$-index is large. Hence we may conclude that the increase in the $AE$-index is accompanied by both the dawn/dusk $Dst$-asymmetry and the intensification of anti-sunward space current below the MAGSAT level. For the disturbed condition, a schematic picture of the electric current in the earth’s environmental space emerges, which picture includes a partial ring current connected with the field-aligned currents in the magnetosphere and the Pedersen current in the ionosphere. Such a current system was proposed earlier by Fukushima and Kamide \(^{28}\) (1973a,b). Although the Hall current is important for the auroral electrojet, it does not contribute at all to the net space current below the MAGSAT level because of its divergence-free flow within the ionosphere. It must be emphasized here that the anti-sunward Pedersen current will contribute to the electrojet along the auroral oval, although the auroral electrojet is mainly due to the Hall current in the ionosphere.

**B.1.4. Geomagnetic perturbations at low latitudes due to electric currents in the ionosphere and magnetosphere** \(^{29}\)

The average perturbations ($\Delta H$, $\Delta D$, $\Delta Z$ and $\Delta F$; observed value minus the MGST(4/81) model) at low latitudes between 30°N and 30°S show a noteworthy difference in the observed results at dawn and dusk meridians, especially for $\Delta D$, which was discussed in detail in a paper by Maeda et al. \(^{30}\) (1982).

The average latitudinal profile of $\Delta D$ over 270°–320° meridians is studied here by means of the contours of equal $\Delta D$ values. We note that the peculiar $\Delta D$ at dusk exists at altitudes lower than about 450 km centered at 8°N and 8°S in dip latitudes. Another region of $\Delta D$ centered at dip latitude 5°N, at a height of about 500 km. If the contour lines of equal $\Delta D$ are approximately regarded as stream lines of the electric current in the ionosphere-magnetosphere, the electric current in the meridian plane flows upward at the equator across the geomagnetic field-lines, and northward and southward above the dynamo layer along the geomagnetic field-lines.

The latitudinal profile of $\Delta D$ at various longitudes and the double amplitude ($\Delta D_n + \Delta D_s$) are proportional to $1/B$, where $B$ is the magnetic field intensity at the dip equator. The $\Delta D$ range increases with decreasing altitude, from 8 nT at 500 km to 40 nT at 300 km.

The peculiar $\Delta D$ on both sides of the magnetic equator seems to be caused by a meridional current system in the ionosphere, upward at the magnetic equator.


The fact that the $\Delta D$ range is proportional to $1/B$ and to the sunspot number will support the ionospheric origin of $\Delta D$ anomaly. TAKEDA and MAEDA$^{31}$ recently carried out a calculation of $F$-region dynamo driven by pressure gradient in the evening, and they obtained a current system which produces the observed $\Delta D$ anomaly. The electric currents flowing above the dip equator are not field-aligned but flow across the magnetic field-lines. The meridional currents in the dusk region in the $F$ region have never been found in the past, in contrast to their detection by rockets in the noon equatorial $E$ region.

A shift of the base line in $\Delta D$ (positive at dusk and negative at dawn) may be due to field-aligned currents from the northern (winter) hemisphere to the southern (summer) hemisphere in the evening and in the opposite sense in the morning; a numerical calculation by TAKEDA$^{32}$ (1982) for a dynamo with NS-asymmetry seems to support this interpretation.

The dawn/dusk asymmetry of $\Delta H$ observed by MAGSAT shows good correlation with the $AE$-index. This seems to support the picture of current flow in the ionosphere and magnetosphere with the presence of partial ring current and the anti-sunward field-aligned current connected with the horizontal current in the ionosphere.

**B.1.5. Sudden commencement of magnetic storms observed by MAGSAT**

From the analysis of ground magnetograms, ARAKI$^{33}$ (1977) inferred the presence of the following three kinds of electric currents flowing in the ionosphere during a sudden commencement (SC) of magnetic storms: (1) a westward zonal current induced by a sudden compression of the magnetosphere associated with an eastward current at the magnetopause; (2) a twin-vortex current for the preliminary reverse impulse on the ground, attributable to a dusk-to-dawn electric field in the polar region; and (3) a twin-vortex type current due to a dawn-to-dusk electric field which develops after SC.

Since MAGSAT was making an accurate three-component measurement of the geomagnetic field above the ionosphere, it was expected to be easy to detect these currents flowing in the ionosphere by comparing MAGSAT and ground data, because the current flowing in the ionosphere produces a magnetic field in an opposite sense at the MAGSAT level and on the ground. This section describes the real existence of currents (1) and (2) reported by ARAKI et al., although it was already partly published in a paper by ARAKI et al.$^{34}$ (1982).

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Unfortunately, it was impossible to check current (3), because the MAGSAT records suffered from high-latitude disturbances soon after the SC's concerned.

Twenty-two SC's were observed, according to the Solar Geophysical Data (edited by J. V. Lincoln, published by WDC-A for STP, NOAA) during the MAGSAT observation period of November 2, 1979 – May 17, 1980. Of these ARAKI et al. examined 21 cases.

In low latitudes, MAGSAT detected SC mainly in $H$-component with a slightly greater amplitude (average value 1.3) in comparison with the ground SC data. In high latitudes, MAGSAT detected SC in both $H$- and $D$-components, but their amplitude was not always measurable (especially at latitudes higher than 60°) because of contamination from polar disturbance. The larger amplitude of the $H$-component SC at the MAGSAT altitude to that on the ground was due to a westward shielding current at the time of SC. The $Z$-component showed no significant change at the time of SC.

A detailed case study was made for two large SC's observed on November 30, 1979, at a low latitude, and on March 19, 1980, at a high latitude.

An SC was observed on November 30, 1979, by MAGSAT at the altitude of 550 km at 26.5°S, 30.3°W over the South Atlantic Ocean and on the ground (Hermanus in South Africa, Trelew in Argentina and its conjugate point San Juan in Puerto Rico). This SC showed a preliminary reverse impulse (PRI) in $D$-component, and MAGSAT recorded an eastward deviation with its maximum magnitude of 10 nT within 3 minutes after the SC. A worldwide equivalent overhead current-system for this PRI was drawn from the ground data for the northern hemisphere, assuming that the current flow is symmetric with respect to the geomagnetic equator. At Eusebio (3.9°S, 58.4°W) in Brazil (+5.6° geomag. lat.), a ground station in close proximity to MAGSAT at the time of SC, the overhead current responsible for $\Delta D$ of PRI was northward. If the symmetry of the PRI current is assumed, $\Delta D$ of PRI at the ground subsatellite point of MAGSAT must have been eastward. Since a westward $\Delta D$ of PRI was observed by MAGSAT, ARAKI et al.\textsuperscript{35}) (1982) concluded that the case of SC on November 30, 1979, was the first experimental evidence of the global ionospheric current-system of PRI of SC.

Another example of SC with PRI is on March 19, 1980, when MAGSAT was passing over Magadan (60.0°N, 151.0°E) in east Siberia. The $D$-component at MAGSAT first decreased by 43 nT in about 2 minutes and then recovered to the original level. A little later, the $H$-component increased by 52 nT in about 1 minute. After 0621 UT, irregular disturbances masked the SC variations. It is clear that the deviations above and below the ionosphere were approximately

opposite to each other. This case also supports the conclusion that PRI is caused by an ionospheric current.

B.2 Field-aligned currents

MAGSAT provides us with the best available data in the dawn and dusk regions for studying the field-aligned current distribution, because of its accurate measurement of the three-component geomagnetic field and its flight at lower altitudes in comparison with other previous satellites. Insofar as the field-aligned currents in high latitudes are concerned, there are the following three regions of large-scale field-aligned currents according to present knowledge:

1. Region 1: average invariant latitude 72–78° on quiet days and 68–75° on disturbed days; current into the ionosphere on the dawn side and out of the ionosphere on the dusk side; total current 3–5 \times 10^6 A without much influence from magnetic activity;

2. Region 2: invariant latitude 65–72° on quiet days and 62–68° on disturbed days, equatorial side adjacent to Region 1; current out of the ionosphere on the dawn side and into the ionosphere on the dusk side; total current 2–5 \times 10^6 A dependent on magnetic activity; and

3. Cusp Region: located poleward of and adjacent to Region 1 near local noon; total current 1.5 \times 10^6 A; pattern is modified by \( B_y \) of interplanetary magnetic field.

In a previous paper by Illima et al. (1982), they analyzed the MAGSAT record during a severe magnetic storm on November 13–14, 1979. In their analysis, the MGST(4/81) model field was first subtracted from the actual MAGSAT data, and the residual was illustrated for \( \Delta F \), \( \Delta B_\parallel \) and \( \Delta B_\perp \), where the latter two are the components parallel and perpendicular to the main geomagnetic field line of the MGST(4/81) model at each observation point. \( \Delta B_\perp \) was further decomposed into \( \Delta D \) (dusk-to-dawn component) and \( \Delta S \) (sunward component), or into geomagnetic north-south \( \Delta B_{XM} \) and east-west \( \Delta B_{YM} \) components. \( \Delta B_\parallel \) is very useful in discussing the contribution from electric currents flowing in the ionosphere of enhanced electric conductivity during magnetic storms, because the MAGSAT altitude is low enough to detect the influence of Hall current that attenuates steeply with height.

In this report a new result of analysis was described, which dealt with the field-aligned current distribution over the polar-cap region for an extremely quiet period when the interplanetary magnetic field was northward with a magnitude as large as 5–20 nT. Such an interesting case has never actually been reported, so that the present report introduces new knowledge on the dependence of field-aligned current patterns on solar wind conditions.

Looking at two examples of the latitudinal profile of the residual magnetic

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36) See also pp. 507–520 of this issue.
field in the northern hemisphere on May 10, 1980, the location of Regions 1 and 2 were several degrees higher in comparison with disturbed days, as is usual with quiet days. Region 1 currents were detected on the dusk side. The most striking feature on this quiet day was the large perturbations observed poleward of Region 1 with a fairly large amplitude of $\Delta B_1$ or $\Delta F$. Two examples of the observed characteristics during consecutive paths of MAGSAT show the presence of upward current in the morning region and downward current in the afternoon region. The intensity of this field-aligned current confined to the region above 80° latitude was 1.7 times the Region 1 current intensity, and the current direction was opposite to Region 1 current. The concurrent $\Delta B_1$ or $\Delta F$ observed by MAGSAT indicated the presence of a twin-vortex horizontal current confined to the polar-cap region, with an anti-sunward current over the geomagnetic pole that was opposite to the ordinary $S_q$ current (ARAKI et al. 1983; IIJIMA et al. 1985).

The results of analysis of ground magnetograms at 8 high-latitude stations also support the above conclusion. The overhead current arrows for the horizontal geomagnetic variation (deviation from the mean level between 2100–0300 MLT of May 10–11, 1980) in high latitudes clearly show the existence of a reversed $S_q$ current near the geomagnetic pole. This is further confirmed by the simultaneous geomagnetic variation of $\Delta Z$, namely positive in the region of a counter-clockwise ionospheric current, and negative in the region of a clockwise current near the northern geomagnetic pole.

Although the occasional appearance of a reversed $S_q$ current near the geomagnetic pole has been advocated by IWASAKI (1971), MAEZAWA (1976) and others from a comprehensive analysis of ground magnetograms at high-latitude observatories during the period of northward interplanetary magnetic field, the case on May 10, 1980 is the first evidence of such a current in the ionosphere revealed in the MAGSAT data.

**B.3 Geomagnetic pulsations and hydromagnetic waves**

When the Japanese MAGSAT Team presented its proposal in February 1979, it also intended to study short-period hydromagnetic waves in the earth's environmental space through spectral analyses of geomagnetic fluctuation observed by MAGSAT and simultaneous data on the ground. However, the team members

41) MAEZAWA, K., Magnetospheric convection induced by the positive and negative Z components of the interplanetary magnetic field; quantitative analysis using polar cap magnetic records, *J. Geophys. Res.*, 81, 2289–2303, 1976.
for this item had other obligations to fulfill during 1980–82, so that this subject remains a task for the future. We hope, however, that a number of interesting results will come out in the near future after comparing the MAGSAT data and other simultaneous data, such as geomagnetic VLF wave and auroral observations at various places in high latitudes.

All the investigations described in this report were conducted with the aid of MAGSAT data made available by NASA to the Japanese MAGSAT Team for the approved Statement of Work M-43. On behalf of the Japanese MAGSAT Team, the chairman wishes to express sincere thanks to NASA for the useful MAGSAT data.