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THE ANALYTIC SCIENCES CORPORATION

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1. INTRODUCTION

The TASC Magsat Investigation covers an area in the eastern Indian Ocean that contains several major bathymetric and tectonic features (Fig. 1-1). The overall objectives of this investigation are:

- Determination of the optimum resolution of Magsat anomaly maps of the study region.
- Production of magnetic anomaly maps from Magsat data covering the study region (0-50 deg S, 75-125 deg E).
- Comparison of Magsat and satellite altimeter (geoid undulation) data in this area, and quantification of their relationships.
- Interpretation of the Magsat data using satellite altimeter and other geophysical data in order to determine the origin and sources of the observed magnetic anomalies.

The investigation area contains a variety of tectonic and physiographic features shown in the figure.

The work during the past quarter has focused on three main areas: 1) new equivalent source inversions to produce improved maps of anomaly and magnetization; 2) production of color displays of Magsat anomaly and other maps to aid interpretation; and, 3) verification of the technique of spectrum estimation used previously with Magsat along-track data. Details of the results obtained in these areas are given in Sections 3.1 through 3.3.

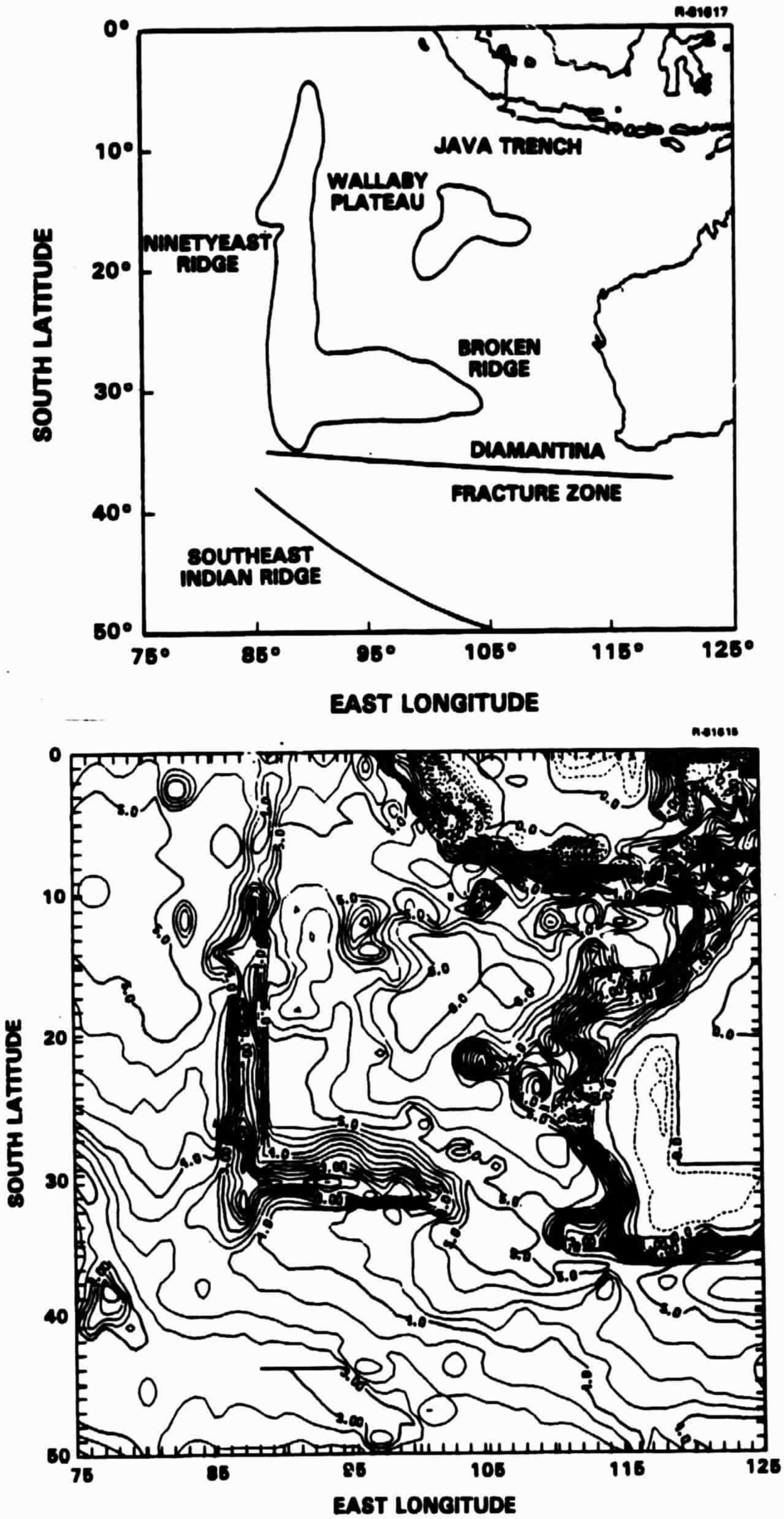


Figure 1-1 Tectonic Features and Bathymetry of Investigation Region

2. SUMMARY OF PROGRESS

The investigation produced four main products during this quarter:

- NEW EQUIVALENT SOURCE ANOMALY MAP. Based on 676 dipoles, and 16 separate runs of the ESMAP software, this map is reduced-to-the-pole and covers the entire investigation region. It has more dipoles and better resolution than the previous maps, and edge effects were reduced by using overlapping sub-regions for the equivalent source inversion.

- MAGNETIZATION MAP. Shows relative magnetization for the investigation region, based on the 676 dipole values obtained by the 16 equivalent source inversions.

- COLOR CONTOUR DISPLAY OF RESULTS and data in the investigation region. Gravity anomaly, bathymetry, and Magsat magnetic anomaly maps were contoured in pseudocolor display using the TASC Image Processing Laboratory. These products facilitate geophysical interpretation.

- VERIFICATION OF ALONG-TRACK MAGSAT DATA PSD ESTIMATION TECHNIQUE. The TASC autoregressive spectrum estimation technique was verified with synthetic data and shown to be capable of resolving exponential power spectra using small samples of data. Interpretations were made regarding the relationship between Magsat data spectra and crustal anomaly spectra.

Production of the new (and final) equivalent source anomaly map required considerable computing effort. This map is now available in gridded, contoured, and color formats.

Further equivalent source inversions may be performed to improve the understanding of the magnetization output, but emphasis for the remainder of the investigation will focus on geophysical interpretation of the present anomaly map. The procedure for computing the new equivalent source maps is described in Section 3.1.

The color map products will aid the display and interpretation effort. These maps are presented in Section 3.2. Additional color displays will also be produced to show the correlations between the magnetic anomaly map and other geophysical quantities.

Numerical studies of the autoregressive spectrum estimation technique used for Magsat analysis led to a better understanding of the possible relationships between the Magsat data spectra and the spectrum of crustal magnetic anomalies. A previous progress report (Ref. 1) showed that spectrum estimates of Magsat along-track anomaly data were not consistent with a model based on upward continuation of a white noise spectrum from the crust. This raised the questions of whether: 1) the spectrum estimation technique was sensitive enough to resolve the properties of such short time series; 2) noise may have distorted this view of the nature of the crustal anomaly spectrum; or, 3) the actual behavior of the field is in fact different from the attenuated white noise (AWN) model. The preliminary results of numerical experiments with synthetic data indicate that the spectrum estimation technique is sensitive enough. Results of the computations relating to these questions are given in Section 3.3.

Other activities during this reporting period included upward continuation of the gravity field to Magsat satellite altitude. This output will be correlated with the new Magsat crustal anomaly map.

3. TECHNICAL RESULTS

3.1 NEW EQUIVALENT SOURCE INVERSIONS

3.1.1 Production of New Anomaly Map

Two previous equivalent-source anomaly maps were presented in earlier progress reports (Refs. 1 and 2). These maps had certain limitations resulting from use of the ESMAP software, which restricts the number of dipoles to a maximum of 150 in each inversion. One of these earlier maps covered the entire investigation region, but used a 7.5-degree dipole spacing. Another map focused on the 16 × 36 deg region near Broken Ridge and used 2 deg dipole spacing.

The analysis of individual tracks of Magsat data showed that crustal anomaly features with wavelengths greater than 700 km were repeatable between nearly coincident tracks of data (Ref. 3). Anomaly features with wavelengths between 300 and 700 km were not coherent between closely-spaced tracks, but may have enough power to be above the noise level in the data. Thus, reasonable grid spacings for constructing Magsat anomaly maps would range between 1.5 and 4 degrees. A spacing of 2-deg was chosen for maps of the eastern Indian Ocean since it represents a lower bound on the resolution of the data, and since 2-deg spacing was also used by NASA in constructing a global Magsat anomaly map.

The new equivalent source anomaly map covers the central 40 × 40 deg portion of the investigation region using more than 400 dipoles. This map is based on multiple runs of

ESMAP using 16 overlapping 20 × 20 deg subregions. Multiple runs were necessary to achieve the desired 2-deg dipole spacing and to minimize edge effects. Figure 3.1-1 shows the pattern of the 16 subregions that form the final anomaly map. Each of these regions is the central 10 × 10 deg square from the 20 × 20 deg square used in each inversion. The results in the outer 5-deg edges of each 20 × 20 deg square were ignored because of obvious edge effects.

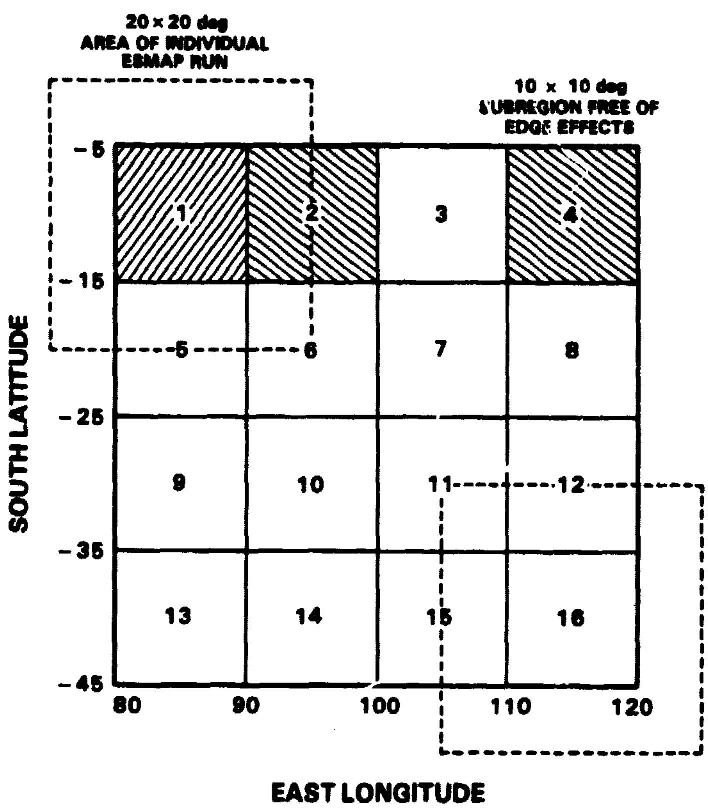


Figure 3.1-1 Diagram of 16 ESMAP Runs Used to Produce New Anomaly Map. Dashed Lines Indicate Regions Ignored Because of Edge Effects

The output from the separate runs of ESMAP was expressed as a magnetic anomaly map at 350 km altitude, sampled at 1-deg uniform grid spacing (even though the dipoles for each run were spaced at approximately 2-deg and located according to separate equal-area projections). To form the final map of the entire area, the 5-deg boundaries from each 20 × 20 deg sub-map were deleted and the sub-maps were placed together. The sub-maps still overlapped along one row or column of grid points at the edges, and at those locations, the anomaly values were averaged (discrepancies were all <1 nT). A contoured version of the final anomaly map is shown in Fig. 3.1-2. Figure 3.1-3 compares the new map, which was reduced-to-the-pole by the ESMAP runs, with the NASA Magsat anomaly map derived by averaging observations in 2-deg bins. The two maps agree in general, but the TASC map shows more definition of the Ninetyeast Ridge. Also, the TASC map shows more clearly the presence of a magnetic high trending NE-SW near the NE corner of the investigation region. This magnetic anomaly ridge seems to be correlated with bathymetric trends (see Figs. 1-1 and 3.1-2).

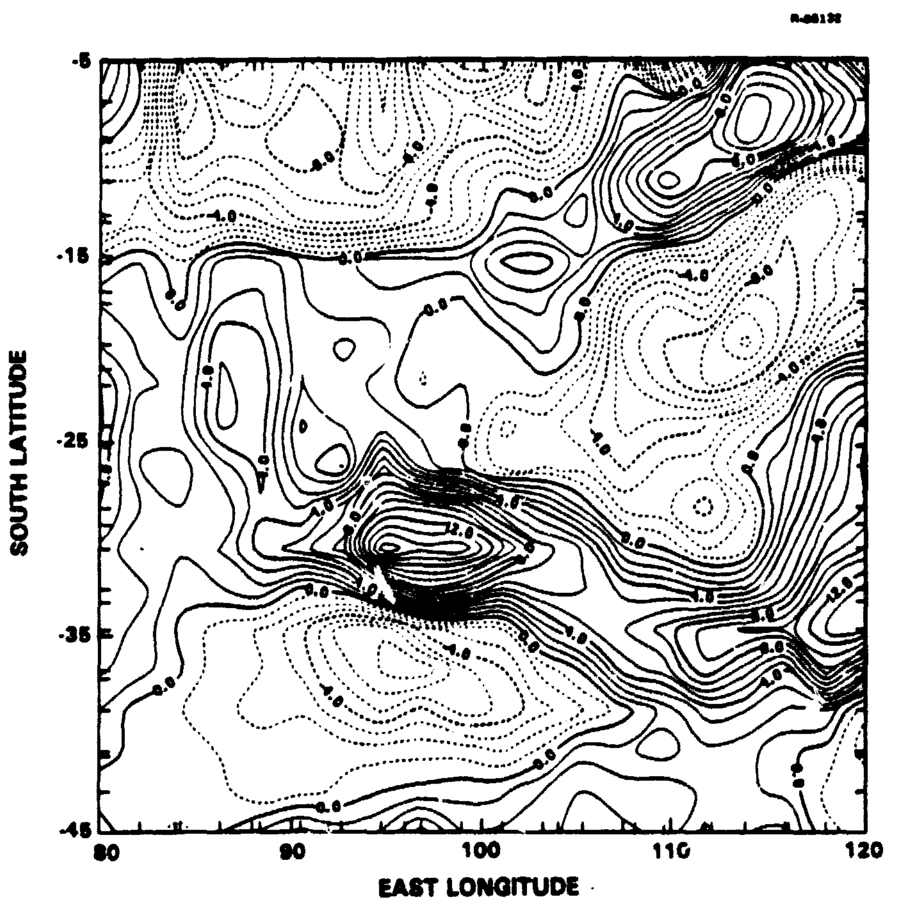
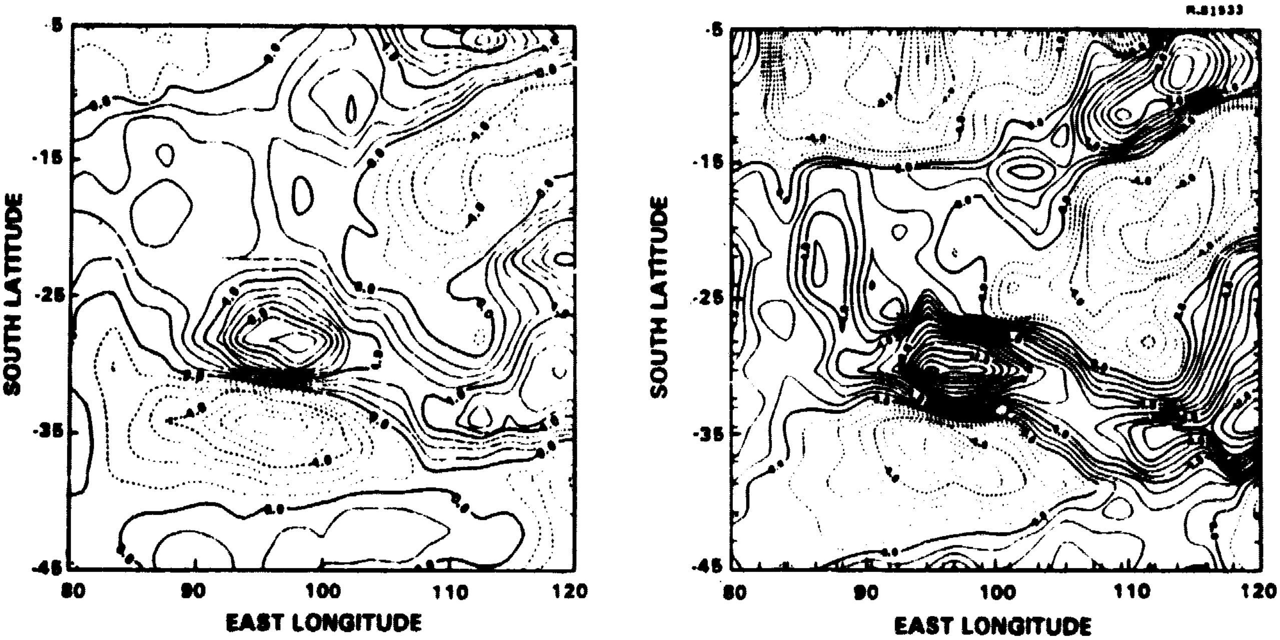


Figure 3.1-2 New Equivalent-Source Anomaly Map at 350 km From 16 Runs of ESMAP

Figure 3.1-4 compares a portion of the new anomaly map (in the vicinity of Broken Ridge) with gravity and bathymetry maps. This figure is updated from one presented in the previous progress report (Ref. 2).

3.1.2 Magnetization Map

Figure 3.1-5 is the map of relative magnetization based on the equivalent-source dipole solutions described above. To construct this map, the central dipoles from each of the 16 ESMAP runs were saved. These were regridded by Lagrange interpolation to form a uniformly spaced 2-deg grid. The contour map is of relative magnetization in the arbitrary units used in the ESMAP software. It is rather "noisy," indicating that the dipole spacing may be too close. Broken Ridge, the coast of Australia, the Java Trench area, and part of the Ninetyeast Ridge have relatively high magnetization.



(a) (b)

Figure 3.1-3 (a) NASA 2×2 deg Anomaly Map, and (b) New Equivalent Source Map Reduced-to- Pole (Same as Fig. 3.1-2)

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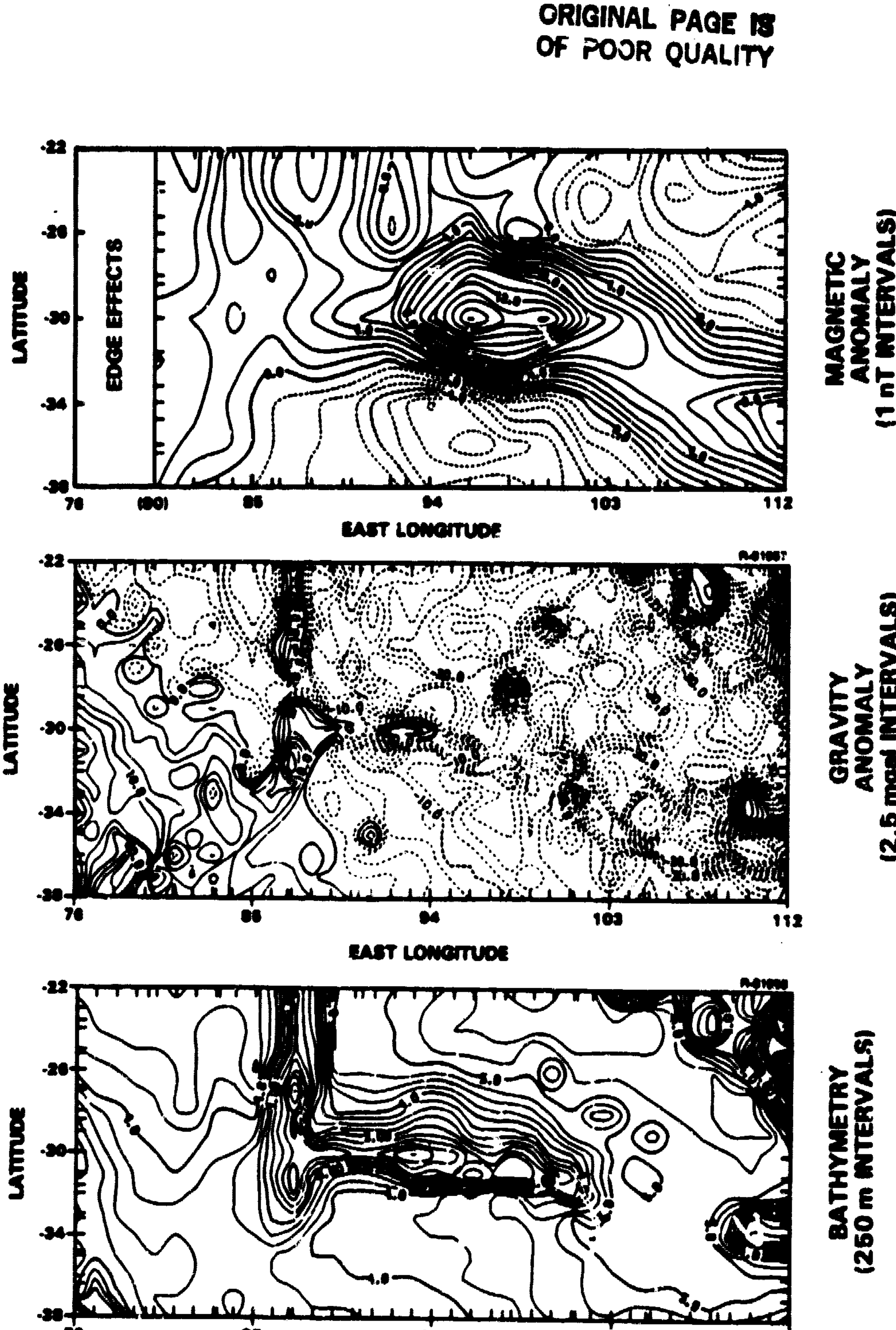

Figure 3.1-4   Comparison of Maps in Broken Ridge Area

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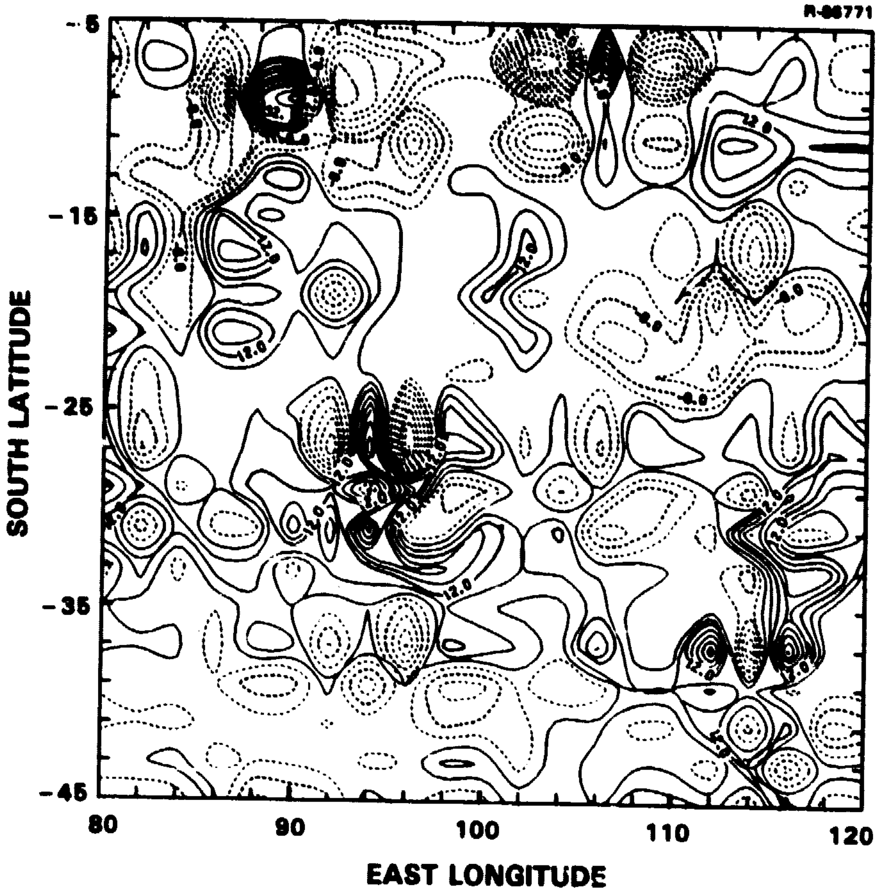

Figure 3.1-5 Map of Relative Magnetization from Equivalent Source Dipoles

3.2 COLOR DISPLAY OF MAP RESULTS

Maps of geophysical data can be usefully enhanced by presenting them as pseudocolored images. Compared to a contour plot (which smooths the data), more information is preserved in the color display, because the eye can distinguish subtle variations in color based on the mapped value at each grid point. The following steps describe the procedure used to produce the color maps (Figs. 3.2-1 to 3.2-5): 1) For each map, a linear scale with values from 1 to 255 was assigned to cover the range of values to be plotted (0 was reserved for

Figures 3.2-1 to 3.2-3

Color Display of New Equivalent Source Magnetic Anomaly Map, Gravity Anomaly Map, and Bathymetry Map of the Investigation Region

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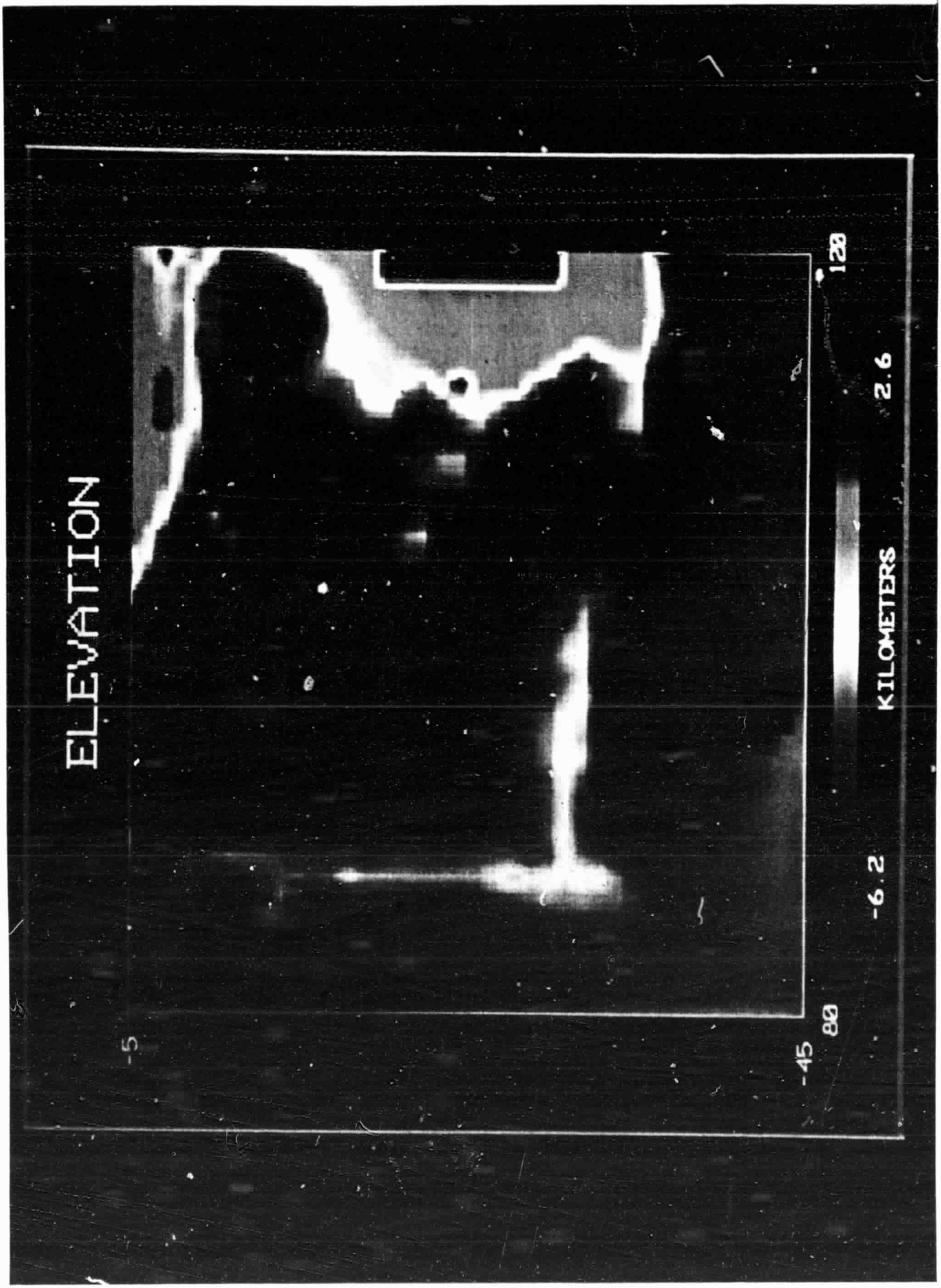
ELEVATION
-5
-45
80
120
-6.2
2.6
KILOMETERS

the absence of data); 2) An image was created using the TASC Image Processing Laboratory (IPL) using bilinear interpolation in order to increase the image size; 3) Colors were assigned to bit levels in a linear scale; 4) In the case of the gravity anomaly, there were a few very low gravity anomaly values in the trench, so an improved visual display was formed by a contrast stretch procedure, producing a non-linear mapping of colors to anomaly value.

The color map images of Figs. 3.2-1 to 3.2-3 are very useful products. Subtle variations in color show the texture of the magnetic anomaly, gravity anomaly and bathymetry features in the study region. Improved interpretation should result from the use of these maps and additional color maps that will be produced to show the correlations among these data types.

3.3 VERIFICATION OF ALONG-TRACK PSD ESTIMATION TECHNIQUE

Figure 3.3-1 is repeated from Ref. 1. It compares an observed Magsat along-track power spectrum with curves predicted by a simple attenuated white noise (AWN) model of the magnetic anomaly field. This type of model has been widely used to represent magnetic anomaly spectra (see Ref. 4). In this model, the anomaly field has a white-noise character at the surface of the earth, and its flat-earth two-dimensional spectrum is upward-continued by multiplication by an exponential. The along-track spectra at various altitudes are described by the modified Bessel function K_1, plotted as dashed curves in Fig. 3.3-1. The lack of agreement between the shape of these theoretical spectra and the estimated spectrum may be explained by the following possibilities:

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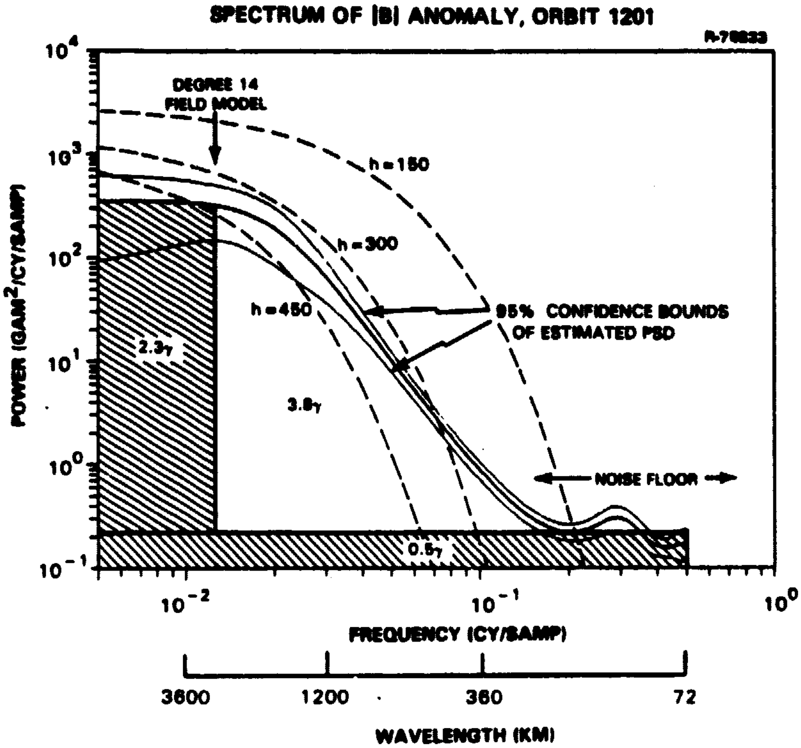

Figure 3.3-1 Observed Magsat spectrum for |B| of orbit 1201 compared with values given by the analytic model of Eq. 3.3-4. The effect of different heights h, is shown. (Orbit 1201 was at h=350 to 360 km during the pass over the investigation region.)

- The spectrum estimation technique may not be sensitive enough to resolve the properties of the anomaly field from the relatively short time series of observed data.
- Noise in the observations may distort the estimate of the spectrum of the crustal anomaly data.
- The AWN model may not describe the actual behavior of the crustal anomaly field.

In order to investigate these possibilities, computational tests of the autoregressive spectrum estimation algorithm were performed using synthetic data. These synthetic time series are realizations of a process which has the AWN (modified Bessel function) along-track power spectrum.

The synthetic time series were formed by computing a realization of the process in the frequency domain and then using the FFT to produce a time series. The PSD of the desired discrete-time zero-mean random process is $S_{xx}(F)$, where F is frequency in cycles/sample. The goal is to construct a time series $\{y_k, k=0,1,2,...n-1\}$ that is a realization of this process. The first step is to construct, the periodic complex sequence u_j, $j=0,1,2,...,N-1$, with period $N>>n$, given by:

$$u_j = (a_j + ib_j)\sqrt{N\, S_{xx}(F)} \qquad (3.3\text{-}1)$$

where the frequency $F = j/N$ and $\{a_j\}$ and $\{b_j\}$ are independent realizations of zero-mean white-noise processes, each with unit variance. Then the FFT of the sequence u_j is a complex periodic sequence, Z_k, with period $N>>n$ such that

$$y'_k = \mathrm{Re}[Z_k(N)], \quad k=0,1,2,3,...,n-1 \qquad (3.3\text{-}2)$$

and

$$y''_k = \mathrm{Im}[Z_k(N)], \quad k=0,1,2,3,...,n-1 \qquad (3.3\text{-}3)$$

are two independent realizations of a process that approaches the desired process y_k as $N/n \rightarrow \infty$.

To construct the realizations appropriate for the Magsat problem illustrated in Fig. 3.3-1, N was 8192 and n was 180 samples. The spectrum $S_{xx}(F)$ was given by

$$S_{xx}(F) = C\, K_1(2\pi F(b+2h)) \qquad (3.3\text{-}4)$$

where F is frequency in cycles/sample, the paramter $C = 5.556\times10^6$ nT^2/cycle/sample, the parameter $b = 1.764\times10^{-2}$ samples, and h = 8.333 samples (h represents a height of 300 km and the typical distance between samples on the Investigator-B tapes is 36 km). The computed realizations were then comparable to the Magsat data provided on the Investigator B tapes.

A series of numerical experiments were conducted, using synthetic time series of varying length as inputs to the AR spectrum estimator. Figure 3.3-2 is the result of one of these computations. There is excellent agreement between the spectrum estimated by the autoregressive technique (using 360 samples) and the original theoretical (AWN) spectrum. These and other computations verify that the TASC autoregressive spectrum estimation technique is capable of resolving an exponential-type spectrum in the absence of noise, even when as few as 180 samples are used.

When white noise is added to the synthetic times series (to represent the measurement errors of the Magsat magnetometer), the AR spectrum estimation requires more samples to obtain an accurate estimate. As more and more white noise is added, the spectrum estimate using only 180 samples becomes biased in that it has a less-steep slope in the frequency range between 0.01 and 0.1 cycles/sample. However, when white noise with $\sigma = 0.5$ nT (see Fig. 3.3-1) is added, the spectrum estimate using only 180 samples is able to resolve the steepening roll-off of the PSD at frequencies lower than 0.1. This result is shown in Fig. 3.3-3.

The lack of agreement between spectra estimated from Magsat data (e.g., Fig. 3.3-1) and the spectrum estimate of Fig. 3.3-3, based on synthetic data, implies that the spectrum of Magsat data is not modeled well by an AWN contribution plus

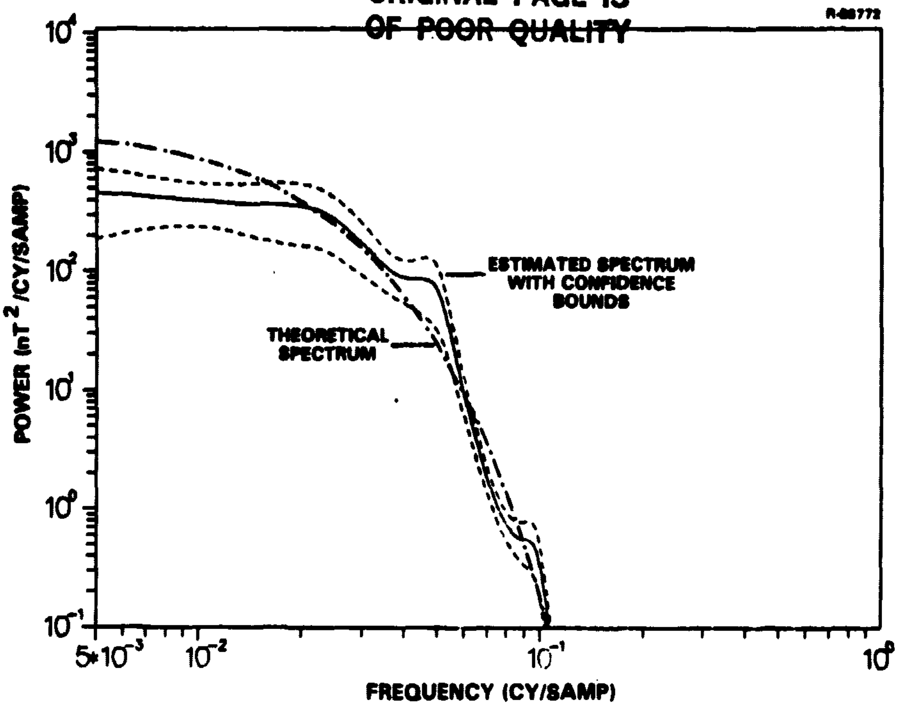

Figure 3.3-2 Comparison of Theoretical PSD (dash-dot curve) and PSD Estimate from Synthetic Time Series (360 Samples).

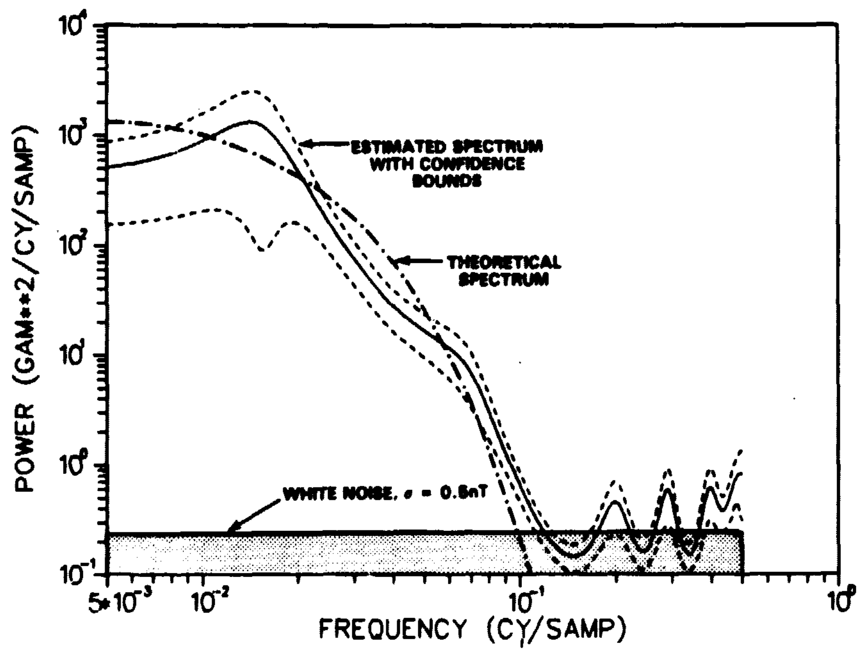

Figure 3.3-3 Results of Spectrum Estimation Test Using Synthetic Data Plus White Noise with $\sigma=0.5$ nT.

white noise. While the AWN model for the crustal anomaly field cannot be ruled out, Magsat along-track data may contain some colored noise which reduces the rate of roll-off of the estimated spectrum. The colored noise may be due to variations in the external field, and thus would be uncorrelated between adjacent Magsat tracks. The presence of this colored noise might account for the fact that spectral coherence between nearly coincident Magsat tracks is not significant for wavelengths less than 700 km, even though the noise floor of individual Magsat spectra is not reached until wavelengths as short as about 300 km (Ref. 3).

The following points summarize the results of the tests that verified the technique of spectrum analysis of along-track Magsat data:

- The TASC AR spectrum estimation technique is capable of giving correct spectrum estimates from relatively short time series of observations such as the Magsat data.
- The spectrum estimates obtained from Magsat crustal anomaly profiles are not consistent with a model in which the data spectrum consists only of an AWN component (from crustal anomalies) plus white noise (from the sensor).
- The spectrum estimates and spectral coherence computations from Magsat data indicate that these data may contain a noise contribution from the external field and that this contribution may have more power than the crustal anomaly field for wavelengths less than about 700 km.

These conclusions have important implications relative to the production and interpretation of crustal magnetic anomaly maps from Magsat data. More work is necessary to ensure that the time-varying effects of the external field do not contaminate these maps.

4. PLANS FOR THE NEXT REPORTING PERIOD

Figure 4-1 (b) is a map of gravity anomaly in the investigation region, upward continued to the altitude of the Magsat magnetic anomaly map (350 km). The upward continuation operation greatly attenuates the short spatial wavelengths, and the result looks similar to the gecid undulation (see Fig. 4-1). (Geoid undulation also emphasizes the longer wavelength features relative to gravity anomaly at the surface.)

An important question is whether or not there is any correlation between the gravity anomalies and the Magsat anomaly map. Long-wavelength gravity anomalies may be an expression of density contrasts in the upper mantle, while the magnetic anomalies are presumably crustal features. A study of the correlations between these two data will provide information about the origins of both anomaly fields. Accordingly, the plans for the final reporting period are:

- Compute correlations between Magsat anomaly map and gravity maps
- Interpret results
- Prepare draft final report.

The final interpretations will relate the geologic and tectonic setting of the investigation region to the magnetic anomaly, gravity, and bathymetric observations.

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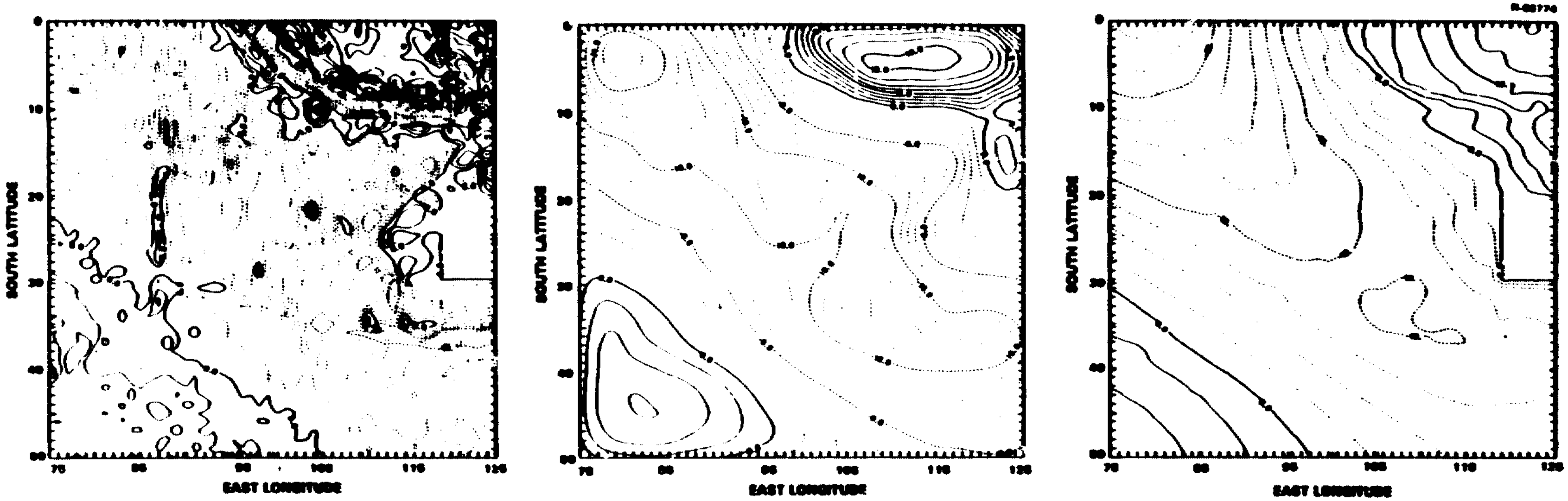

(a) (b) (c)

Figure 4-1 (a) Gravity Anomaly at Surface, (b) Gravity Anomaly Upward Continued to 350 km, (c) Geoid Undulation

5. COST DATA

Total expenditures through 30 June have been $38,659. Expenditures during the quarter 1 April through 30 June were $1,219.00.

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