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FINAL TECHNICAL REPORT

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(E85-10103 NASA-CR-175614) IMPROVING THE GEOLOGICAL INTERPRETATION OF MAGNETIC AND GRAVITY SATELLITE ANOMALIES Final Report (Purdue Univ.) 67 p HC A04/MF A01 CSCL 08G
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This report describes research performed under NASA contract NAG5-304 entitled "IMPROVING THE GEOLOGICAL INTERPRETATION OF MAGNETIC AND GRAVITY SATELLITE ANOMALIES". The original proposal included a two-year research plan that was to be initiated by 1 Jan. 83. The objective of the proposal was to investigate current limitations in the quantitative interpretation of satellite-elevation geopotential field data and to develop techniques to overcome them or to determine the limitations that they impose on geological interpretation. Originally, the plan was to study orbital effects upon the quality of the data, including the utilization of downward continuation techniques, improved forward and inverse modeling procedures, and the utility and procedures for geological interpretation of gradient and vector geopotential satellite anomaly components. The investigation was to be performed analytically and empirically using geologically and geophysically constrained model studies, culminating in the application of the improved interpretational techniques to select anomaly features of the MAGSAT data. Funding constraints imposed by NASA delayed initiation of this program and severely reduced the overall level of funding. However, despite these modifications a significant portion of the original scope of research was maintained.

A major result has been the preparation of an improved scalar magnetic anomaly map for South America and adjacent marine areas directly from the original MAGSAT orbital data. This effort involved specially developed procedures for isolating crustal anomaly profiles which were subsequently reduced to a constant elevation and common radial pole by equivalent point source inversion. These procedures and resultant map were presented at the 1984 Spring meeting of the American Geophysical Union under the following citation:

1) Ridgway, J. R., W J. Hinze and L. W. Braile, 1984, MAGSAT scalar anomaly map of South America, EOS (Am. Geophys. Union Trans.), V. 65, p. 202.

These have also been documented under the following thesis citation:

2) Ridgway, J. R., 1984, Preparation and Interpretation of a Revised MAGSAT Magnetic Anomaly Map Over South America, Unpubl. MS-thesis, Purdue Univ., 121 pp.

The errors of numerically averaging satellite magnetic anomaly data for geologic analysis have been investigated using orbital anomaly simulations of crustal prisms by Gauss-Legendre quadrature integration. These simulations have shown that numerical averaging errors make small and relatively minor contributions to the total error-budget of higher orbital estimates (400 km), whereas for lower orbital estimates the error of averaging may substantially increase. As an alternative to numerical averaging, least-squares collocation was also investigated and found to produce substantially more accurate anomaly estimates as the elevation of prediction is decreased towards the crustal sources. These results were presented at the 1984 and 1985 Spring meetings of the American Geophysical Union under the following citations:

3) Goyal, H. K., R. R. B. von Frese, J. R. Ridgway, and W. J. Hinze, 1984, Geological analysis of averaged magnetic satellite anomalies, EOS (Am. Geophys. Union Trans.), V.65, p. 202.

4) Goyal, H. K., R. R. B. von Frese and W. J. Hinze, 1985, Statistical magnetic anomalies from satellite measurements for geologic analysis, EOS (Am. Geophys. Union Trans.), V. 66, p. 255.

These results have also been submitted for publication under the following citation:

5) Goyal, H. K., R. R. B. von Frese, and W. J. Hinze, 1985, Binning of satellite magnetic anomalies, Geophys. Res. Lett. (submitted).

Quantitative geologic modeling of MAGSAT data has mostly focused to date on the eastern portions of the prominent transcontinental magnetic anomaly of the U. S. This feature involves the crustal structure of the south-central U.S., the Mississippi Embayment and central Kentucky which is related to the mineralization and seismicity of a highly urbanized portion of the country. A crustal magnetic model of the south-central anomaly based on MAGSAT data was presented at the 1984 Spring meeting of the American Geophysical Union under the following citation:

6) Starich, P. J., W. J. Hinze, and L. W. Braile, 1984, The south-central United States magnetic anomaly, EOS (Am. Geophys. Union Trans.), V. 65, p. 202.

Fuller documentation of these results are contained in the following thesis:

7) Starich, P. J., 1984, The South-Central United States Magnetic Anomaly, Unpubl. MS-thesis, Purdue Univ., 76 pp.

To date our spherical-earth magnetic anomaly modeling procedure has proved complex and cumbersome in many geologic applications. Accordingly, simpler and faster flat-earth modeling was investigated and generally found to be a practical alternative to the spherical-earth modeling algorithm when dealing with gravity and differentially reduced to pole magnetic anomaly data at satellite elevations. These results have been presented at the 1984 Spring meeting of the American Geophysical Union under the following citation:

8) Parrot, M. H., W. J. Hinze, L. W. Braile, and R. R. B. von Frese, 1984, A comparative study of spherical and flat-earth geopotential modeling at satellite elevations, EOS (Am. Geophys. Union Trans.), V. 65, p. 181.

They have also been documented for publication under the citation:

9) Parrot, M. H., W. J. Hinze, L. W. Braile, and R. R. B. von Frese, 1984, A comparative study of spherical and flat-earth geopotential modeling at satellite elevations, Geophys. Res. Lett. (submitted).

Three papers involving the tectonic analysis of MAGSAT anomalies for the region (30°W, 60°E) (40°, 70°N) have been prepared by our group. These include:

10) Oliver, R., W. J. Hinze and R. R. B. von Frese, 1983, Reduced to pole long-wavelength magnetic anomalies of Africa and Europe, EOS, (Am. Geophys. Union Trans.), V. 65, p. 214.

11) Hinze, W. J., R. Olivier and R. R. B. von Frese, 1983, Euro-African MAGSAT anomaly-tectonic observations, IUGG XVIII General Assembly, Programme & Abstracts, V. II, p. 630; and

12) von Frese, R. R. B., R. Oliver and W. J. Hinze, 1983, Long-wavelength magnetic and gravity anomaly correlations of Africa and Europe, IAGA Bulletin, v. 47, p. 140.

The first paper illustrates the utility of differential magnetic pole reduction for geologic analysis of regional magnetic satellite anomalies, whereas the second paper considers in some detail the tectonic implications of reduced to pole Euro-African MAGSAT anomalies. The third paper illustrates the synergism of MAGSAT and regional free-air gravity anomalies for enhanced geologic interpretation.

Comparison of the reduced to pole MAGSAT anomalies for Euro-Africa with the South American data has shown the strong correlation of anomalies along the Atlantic rifted margins of the continents. This is a very interesting result, as to date it has been the mgnetic anomalies of the oceans which in addition to paleomagnetic studies have provided much of the critical evidence and details on continental drift and the evolution of the oceans. To investigate this further, we reduced the 2°-averaged MAGSAT anomalies to a common elevation and radial pole for the eastern Pacific Ocean, North and South America, the Atlantic Ocean, Europe, Africa, India, Ausralia and Antarctica. The results indicated that continental anomalies have prominent affiliations with ancient features and that they demonstrate remarkably detailed correlation of lithospheric magnetic sources across rifted margins when plotted on a reconstruction of Pangea. Accordingly, these anomalies, first observed as a result of NASA's magnetic satellite programs, describe geologic conditions of considerable age and provide new and fundamental constraints on the geologic evolution of the continents and their reconstructions.

These results were presented as an invited paper at the recent GRM conference and in a paper presented at the 1985 Spring meeting of the American Geophysical Union under the following citations:

13) von Frese, R. R. B., and W. J. Hinze, 1984, Continental and oceanic magnetic anomalies: Enhancement through GRM, Geopotential Research Mission Science Conference, Univ. of MD., Abstracts (Oct. 29-31, 1984), 4 pp.

14) von Frese, R. R. B., W. J. Hinze, R. Olivier, and C. R. Bentley, 1985, Continental magnetic anomaly constraints on continental reconstruction, EOS (Am. Geophys. Union Trans.), V. 66, p. 255.

These results have also been documented for publication as follows:

15) von Frese, R. R. B., W. J. Hinze, R. Olivier, and C. R. Bentley, 1985, Regional magnetic anomaly constraints on continental rifting, Geology (in-press).

In general, considerable and significant progress has been made under the auspices of this research program. This incudes thirteen papers that have been presented or submitted for publication and the completion of two master's theses that have been partially supported by this contract. Attached is an APPENDIX which includes the papers submitted for publication and the abstracts for presented papers and theses supported by the research program. The abstracts and papers are listed in the APPENDIX in the order that they are cited in this report.

Citation #1 (Presentation Abstract)

D1

MAGSAT SCALAR ANOMALY MAP OF SOUTH AMERICA

N85-31586

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A scalar magnetic anomaly map has been prepared for South America and adjacent marine areas directly from original MAGSAT orbits. The preparation of the map poses special problems, notably in the separation of external field and crustal anomalies, and in the reduction of data to a common altitude. External fields are manifested in a long-wavelength ring current effect, a medium-wavelength equatorial electrojet, and short-wavelength noise. The noise is reduced by selecting profiles from "quiet" periods ($k_p < 3$), and since the electrojet is confined primarily to dusk profiles, its effect is minimized by drawing the data set from dawn profiles only. The ring current is corrected through the use of the standard ring current equation, augmented by further filtering with a Butterworth bandpass filter. Under the assumption that the time-variant ring current is best removed when a replication of redundant profiles is achieved, a test set of 25 groups of 3 nearly coincident orbits per group is set up for filtering with a range of long-wavelength cutoffs, spanning 22 degrees to infinite wavelength, to determine which cutoff best replicates the residual profiles. Replication is determined by linear regression, which results in a correlation coefficient, a slope, and an intercept. By using these parameters in a triple test, the long-wavelength cutoff which best removes the ring current is found to be 50 degrees. Profiles thus filtered differ primarily in amplitude due solely to satellite altitude differences. These differences are then normalized by an inversion of the profile data onto a grid of equivalent point dipoles, and recalculated at an altitude of 350 km. The resulting map, when compared to the 2° averaged map, shows more coherent anomalies, with notable differences in the region affected by the electrojet, and promises much in regard to improved geologic interpretation.

D2

Citation #2 (Thesis Abstract) **N85-31587**

MAGSAT SATELLITE MAGNETIC ANOMALY MAP OVER SOUTH AMERICA

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A scalar magnetic anomaly map has been prepared for South America and adjacent marine areas directly from original MAGSAT orbits. The preparation of the map poses special problems, notably in the separation of external field and crustal anomalies, and in the reduction of data to a common altitude. External fields are manifested in a long-wavelength ring current effect, a medium-wavelength equatorial electrojet, and short-wavelength noise. The noise is reduced by selecting profiles from "quiet" periods (Kp ≤ 3), and the effect of the electrojet is minimized by drawing the data set from dawn profiles only.

The ring current is corrected through the use of a standard equation, augmented by further digital band-pass filtering. Under the assumption that the time-variant ring current is best removed when a replication of redundant profiles is achieved, a test set of 75 pairs of coincident orbits are filtered with a range of long-wavelength cutoffs to determine which cutoff best replicates the residual profiles. Replication is determined by linear regression, which results in a correlation coefficient, a slope, and an intercept. Using these parameters in a triple test, the long-wavelength cutoff which best removes the ring current is found to be 50 degrees.

Profiles thus filtered differ primarily in amplitude due solely to satellite altitude differences. These differences are normalized by an inversion of the profile data onto a grid of equivalent point dipoles, and recalculated at an altitude of 350 km. The low latitudes in the study area cause instability in the inversion, necessitating separate inversions of several sub-areas which are subsequently merged. The resulting map more accurately depicts crustal anomalies around the geomagnetic equator than previous maps of South America.

Crustal anomalies reduced-to-the-pole exhibit marked correlations to known tectonic features, and show promise for improved geologic intepretation.

N85-31588 D3

Citation #3 (Presentation Abstract)

GEOLOGIC ANALYSIS OF AVERAGED MAGNETIC SATELLITE ANOMALIES

H.K. Goyal(1), R.R.B. von Frese (1), J.R. Ridgway (2) and W.J. Hinze(2)

To investigate relative advantages and limitations for quantitative geologic analysis of magnetic satellite scalar anomalies derived from arithmetic averaging of orbital profiles within equal-angle or equal-area parallelograms, the anomaly averaging process was simulated by orbital profiles computed from spherical-earth crustal magnetic anomaly modeling experiments using Gauss-Legendre quadrature integration. The results indicate that averaging can provide reasonable values at satellite elevations, where contributing error factors within a given parallelogram include the elevation distribution of the data, and orbital noise and geomagnetic field attributes. Various inversion schemes including the use of equivalent point dipoles are also investigated as an alternative to arithmetic averaging. Although inversion can provide improved spherical grid anomaly estimates, these procedures are problematic in practice where computer scaling difficulties frequently arise due to a combination of factors including large source-to-observation distances (> 400 km), high geographic latitudes, and low geomagnetic field inclinations. Finally, a comparison of averaged scalar anomalies over South America taken from the global <2°> MAGSAT anomaly map with anomalies derived from a detailed analysis of orbital profiles by equivalent point source inversion indicates that external field and variable elevation effects contribute significantly to distortion in the <2°> anomalies.

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N85-31589

Citation #4 (Presentation Abstract)

STATISTICAL MAGNETIC ANOMALIES FROM SATELLITE MEASUREMENTS FOR GEOLOGIC ANALYSIS

H.R. Goyal(1), R.R.B. von Frese(1), W.J. Hinze(2)

The errors of numerically averaging satellite magnetic anomaly data for geologic analysis are investigated using orbital anomaly simulations of crustal magnetic sources by Gauss-Legendre quadrature integration. These simulations suggest that numerical averaging errors constitute small and relatively minor contributions to the total error-budget of higher orbital estimates ($\gtrsim$ 400 km), whereas for lower orbital estimates the error of averaging may increase substantially. Least-squares collocation is also investigated as an alternative to numerical averaging and found to produce substantially more accurate anomaly estimates as the elevation of prediction is decreased towards the crustal sources.

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D5

N85-31590

Citation #5 (Refereed Paper)

BINNING OF SATELLITE MAGNETIC ANOMALIES

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Abstract

The errors of numerically averaging satellite magnetic anomaly data for geologic analysis are investigated using orbital anomaly simulations of crustal magnetic sources by Gauss-Legendre quadrature integration. These simulations suggest that numerical averaging errors constitute small and relatively minor contributions to the total error-budget of higher orbital estimates ($\gtrsim$ 400 km), whereas for lower orbital estimates the error of averaging may increase substantially. Least-squares collocation is also investigated as an alternative to numerical averaging and found to produce substantially more accurate anomaly estimates as the elevation of prediction is decreased towards the crustal sources.

Introduction

Artificial, earth-orbiting satellites are making increasingly available consistent, regional-scale magnetic anomaly data for geologic analysis. These data are frequently presented as numerically averaged anomalies of orbital profile anomaly values within equal-angle or equal-area parallelepipeds or bins. (e.g., Regan et al., 1975; Langel et al., 1982; Ritzwoller and Bentley, 1983). The averaged anomaly is normally assigned to the center of the area at the arithmetically averaged elevation of the data within the bin. In general, it is felt without quantitative basis that the averaging process limits the utility of anomaly maps prepared from these data in geologic analysis, but the advantages to geologic interpretation of more sophisticated and costlier data processing are also not clear. The objective of this study is to investigate the errors of numerical averaging for satellite magnetic anomaly estimation using systematic spherical-earth magnetic anomaly simulations and to evaluate, as an alternative to arithmetic averaging, magnetic anomaly estimation by least-squares collocation.

Numerical Simulations and Procedures

The basic data of this study are orbital scalar magnetic anomaly values of two dimensional, 40 km thick crustal spherical prisms with widths of 50, 100, 200, 300, and 500 km (Fig. 1). The magnetic anomalies of these radially (normally) polarized prisms were calculated assuming 3 A/m magnetization by the Gauss-Legendre quadrature integration procedure (von Frese et al. (1981)). The anomaly values were computed at 0.25° intervals on 40°-length orbits that are at 25 km levels over elevations ranging from 100 to 700 km. The radial polarization and two dimensional assumptions were made to generalize the results while simplifying the computations.

Numerical averaging simulations were conducted using the procedure outlined by Langel et al. (1982) to obtain 2°-averaged scalar magnetic anomalies from MAGSAT. This procedure involves computing the mean and standard deviation of the anomaly values within a 2°-parallelepiped, eliminating anomaly values which are not within two standard deviations of the mean, and then recomputing the mean of the remaining values as the 2°-averaged anomaly estimate. To evaluate numerical averaging errors, the averaged anomaly values were computed from the simulated 2°-bins with elevations ranging from 100 to 300 km, 300 to 500 km, and 500 to 700 km, and compared to the modeled anomaly values at the center of each bin at elevations, respectively, of 200 km, 400 km, and 600 km.

Least-squares collocation, a statistical estimation technique which is widely applied to problems in physical geodesy (e.g., Moritz, 1972), was also used in this study. For satellite magnetic anomaly prediction, the observed anomaly values, ΔT, within a bin, may be modeled as

$$\Delta T = \Delta TC + N.$$

When the crustal anomaly, ΔTC, and random noise, N, are not correlated, a least-squares estimate of the crustal anomaly can be obtained from

$$\Delta TC_p = C(\Delta TC,\Delta T)^T C(\Delta T,\Delta T)^{-1}\Delta T,$$

where $C(\Delta TC,\Delta T)$ is the cross-covariance matrix between ΔTC and ΔT, and $C(\Delta T,\Delta T)$ is the covariance matrix of observations.

For optimal prediction, the statistical behavior of the anomalies can be assessed through an appropriate covariance function. In this study, covariances for all separation distances between observations within a 2°-bin were computed by forming the corresponding anomaly products which were, in turn, sorted into successive uniform intervals of the separation distance. For each interval of the separation distance, the average of the anomaly products, normalized to the covariance value at zero separation distance, was plotted against the mean separation distance to obtain the normalized covariance function shown in Fig. 2. For a spherical earth the separation distance, R_{12}, between points $P(r_1,\theta_1,\phi_1)$ and $Q(r_2,\theta_2,\phi_2)$ is given by

$$R_{12} = (r_1^2+r_2^2-2r_1r_2(\cos\theta_1\cos\theta_2+\sin\theta_1\sin\theta_2\cos(\phi_1-\phi_2)))^{1/2},$$

where (r_1,θ_1,ϕ_1) and (r_2,θ_2,ϕ_2) represent the radial, co-latitude and longitude coordinates for P and Q, respectively.

The normalized covariance functions for all bins considered in this study were found to follow in a least-squares sense the functional form given by

$$C_n(R) = 1.00-(0.78*10^{-2})R-(0.2*10^{-4})R^2,$$

where $C_n(R)$ is the normalized covariance value at separation distance, R. Covariance values for the various separation distances are given by

$$C(R) = C_n(R)*C(0),$$

where C(0) is the value of the covariance function in nT^2 at zero separation, and R is the separation distance in km. This relationship was observed to hold for $R \lesssim 100$ km. For the covariance values in each bin, the correlation length was close to 56 km, where the correlation length, ξ, is the value of R for which $C(\xi) = C(0)/2$. Accordingly, observations within a radius of about 100 km of the prediction point were used to form the elements of the covariance matrix $C(\Delta T,\Delta T)$.

Results and Discussion

Typical examples of the radially polarized anomaly signals considered in this study are shown in Fig. 3. The upper panel (Fig. 3.A) illustrates how the anomalies broaden and increase in amplitude at 200 km elevation with increasing source widths, whereas the lower panel (Fig. 3.B) shows how the magnetic anomaly of a crustal prism of width 200 km increases in amplitude and wavenumber with decreasing orbital elevation. Similar observations hold at the other elevations for all the source widths considered in this study.

Fig. 4 provides characteristic results of how the averaging procedure described by Langel et al. (1982) performed in these simulations. The dotted line in each panel shows the small relative deviation (nT) of the estimates which are defined as the modeled (true) anomaly (solid line) minus the 2°-averaged anomaly value obtained from analysis of all the computed anomalies within each bin, which in this case has no values perpendicular to the profile. However, in the normal preparation of satellite magnetic anomaly maps, orbits with large external magnetic field activity indices are routinely rejected to enhance crustal anomaly components. This frequently results in severely decimated coverage with respect to the anomaly values available for averaging within a bin. To simulate this condition, the computed values within each bin were randomly decimated to 20% the original coverage.

Characteristic 2°-averaged anomaly deviations for the sparse data coverage are plotted as the dashed curves on the panels of Fig. 4.

In general, Fig. 4 shows that maximum deviations for both dense and sparse data coverage principally occupy the flank and peak regions of the anomalies, where the 2°-averages derived from sparse data coverage show the largest and most erratic deviations. Accordingly, to further evaluate errors of averaging, subsequent study focused on 2°-averaged predictions from the decimated data for the various crustal prisms at the locations of the peak amplitude, 50% peak amplitude, and 10% peak amplitude of the true (modeled) anomaly profiles over the principal elevations of 200 km, 400 km, and 600 km. An overview of these results is presented in TABLE I, where at each of the principal elevations the true amplitude at the point of prediction is listed along with A) the maximum averaging errors as defined by (deviation/true value)*100% and B) the maximum averaging deviations. Corresponding collocation errors and deviations in TABLE I are not trivial functions of elevation because the prediction is also affected by such factors as the variable number and distribution of data within the bins (Cruz, 1983).

These results suggest that the simple averaging procedure provides remarkably good anomaly estimates at elevations of 400 km and greater for the simulations considered here. In practice, the location of a satellite magnetometer measurement is typically known only to within plus or minus several tens of meters of the true position. This mislocation can produce errors in the calculation of the geomagnetic reference field as large as a few nanoteslas at 400 km and which increase with increasing orbital elevations. These errors are introduced when the reference field is subtracted from the observations to obtain the crustal anomaly residuals. External magnetic field effects, which are currently not well understood and difficult to account for, constitute an even greater error source in these residuals. Hence, inaccuracies due to numerical averaging represent only a minor contribution to the overall error-budget of satellite magnetic anomalies at these elevations. For lower elevations on the other hand, such as at 200 km where future satellite missions may be orbited, mislocation of the magnetometer sensor introduces errors of only 1 or 2 nT or less, yet numerical averaging can produce significantly large errors according to these simulations.

For comparison with the numerical averages, predictions based on least-squares collocation were also obtained for these sparsely populated bins. Differences between the anomaly estimates produced by the two methods smaller than or equal to 1.0 nT were attributed to numerical roundoff errors. For any differences above this cutoff, collocation yielded a significantly more accurate estimate than numerical averaging. Out of the 45 sparsely populated bins tested at the various elevations and source widths, collocation yielded significantly improved anomaly estimates for roughly 33% of them. The improvement of collocation predictions over averaging as defined by (1-(collocation deviation/averaging deviation))*100% was found to range from 51% to 99% over all the source widths (Fig. 5.A). However, improvement was more concentrated and significant at the lowest principal elevation (200 km) considered in this study (Fig. 5.B and TABLE I).

Conclusions

Crustal magnetic anomaly signals over satellite orbits were simulated to investigate numerical averaging as an anomaly estimator. Averaging is a convenient procedure for reducing satellite magnetometer data to manageable proportions for geologic analysis, although the precision of averaging as an anomaly estimator involves significant problems concerning spatial and amplitude smoothing of the satellite magnetic observations. The results of the simulations considered in this study suggest that the error of numerical averaging constitutes a small and relatively minor component of the total error-budget of higher orbital anomaly estimates ($\gtrsim$ 400 km), whereas for lower orbital estimates numerical averaging error increases substantially.

As an alternative to numerical averaging, least-squares collocation was investigated and observed to produce substantially more accurate anomaly estimates, particularly as the orbital elevation of prediction was decreased towards the crustal sources. In contrast to averaging, collocation is a significantly more resource-intensive procedure to apply because of the practical, but surmountable problems related to establishing and inverting the covariance matrix for accurate anomaly prediction. However, as demonstrated by these simulations, collocation may be much more effectively used to exploit the anomaly details contained in the lower orbital satellite magnetic data for geologic analysis.

Acknowledgements

The authors thank J. Y. Cruz of the Dept. of Geodetic Science at Ohio State for stimulating discussion and initial software for implementing least-squares collocation. Financial support for this investigation was provided by the Goddard Space Flight Center under NASA contract NAG5-304.

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von Frese, R. R. B., W. J. Hinze, L. W. Braile and A. J. Luca, 1981, Spherical earth gravity and magnetic anomaly modeling by Gauss-Legendre quadrature integration, J. Geophys., v. 49, p. 234-242.

TABLE I.A - Maximum Prediction Errors - Averaging vs. Collocation (Sparse Data Coverage Simulations)

Orbital Elevation [km]	True Anomaly Amplitude [nT]	Averaging Error [%]	Collocation error [%]
200	11.6	86.2	0.7
400	3.0	61.3	26.8
600	2.2	24.7	7.0

TABLE I.B - Maximum Prediction Deviations - Averaging vs. Collocation (Sparse Data Coverage Simulations)

Orbital Elevation [km]	True Anomaly Amplitude [nT]	Averaging Deviation [nT]	Collocation Deviation [nT]
200	99.3	25.0	0.4
400	49.0	2.7	1.0
600	2.2	0.5	0.2

Figure Captions

Fig. 1 Geometric and physical properties used for the satellite orbital magnetic anomaly simulations. This study focused on anomaly estimates for A = 2°.

Fig. 2 The least-squares polynomial curve in separation distance, R, fitting the normalized covariance functions of this study is given by $C_n(R) = 1.00-(0.78*10^{-2})R-(0.20*10^{-4})R^2$.

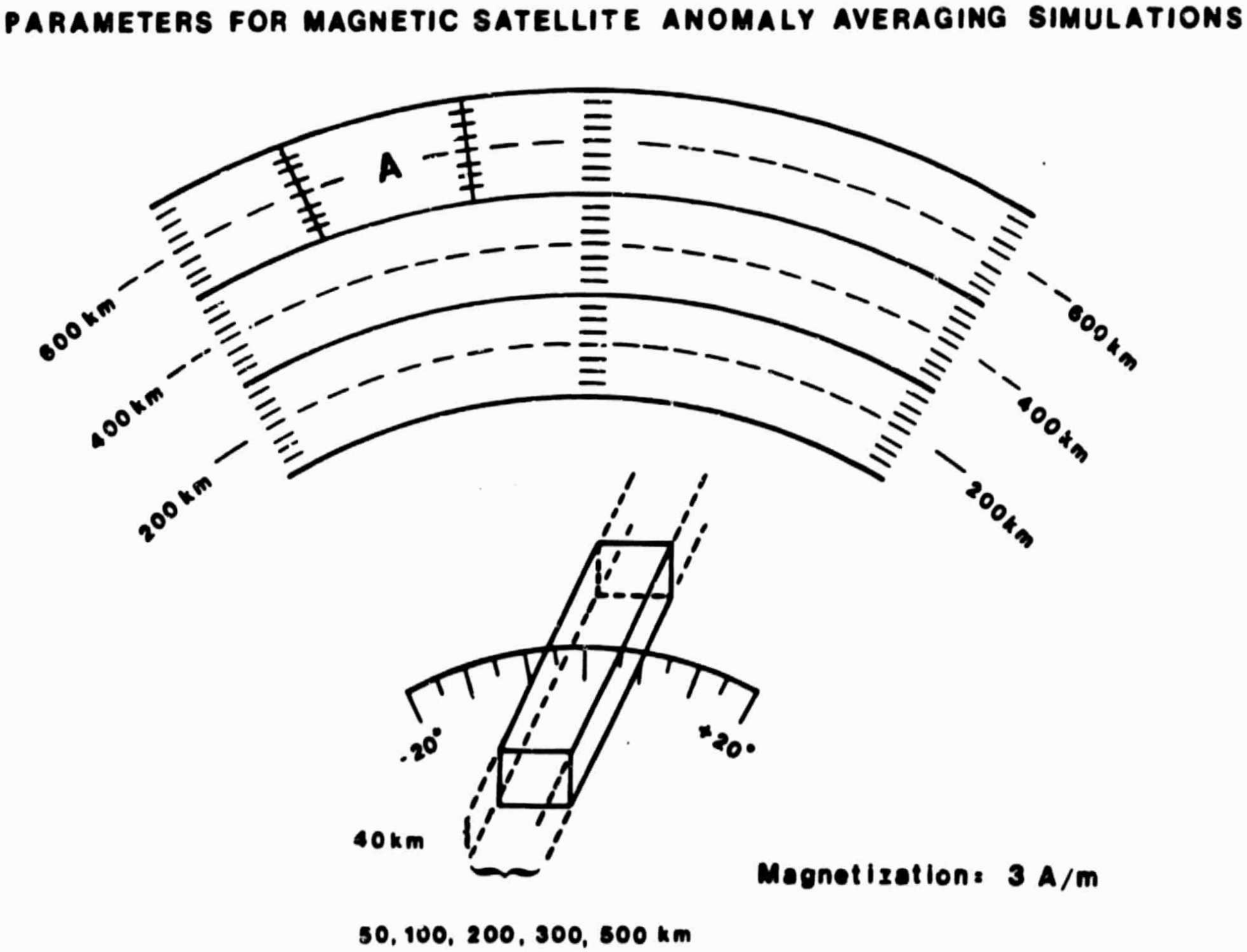
Fig. 3 Characteristics of radially polarized magnetic anomalies for different crustal prism widths at 200 km elevation (A), and at different satellite elevations for a crustal prism 200 km wide (B).

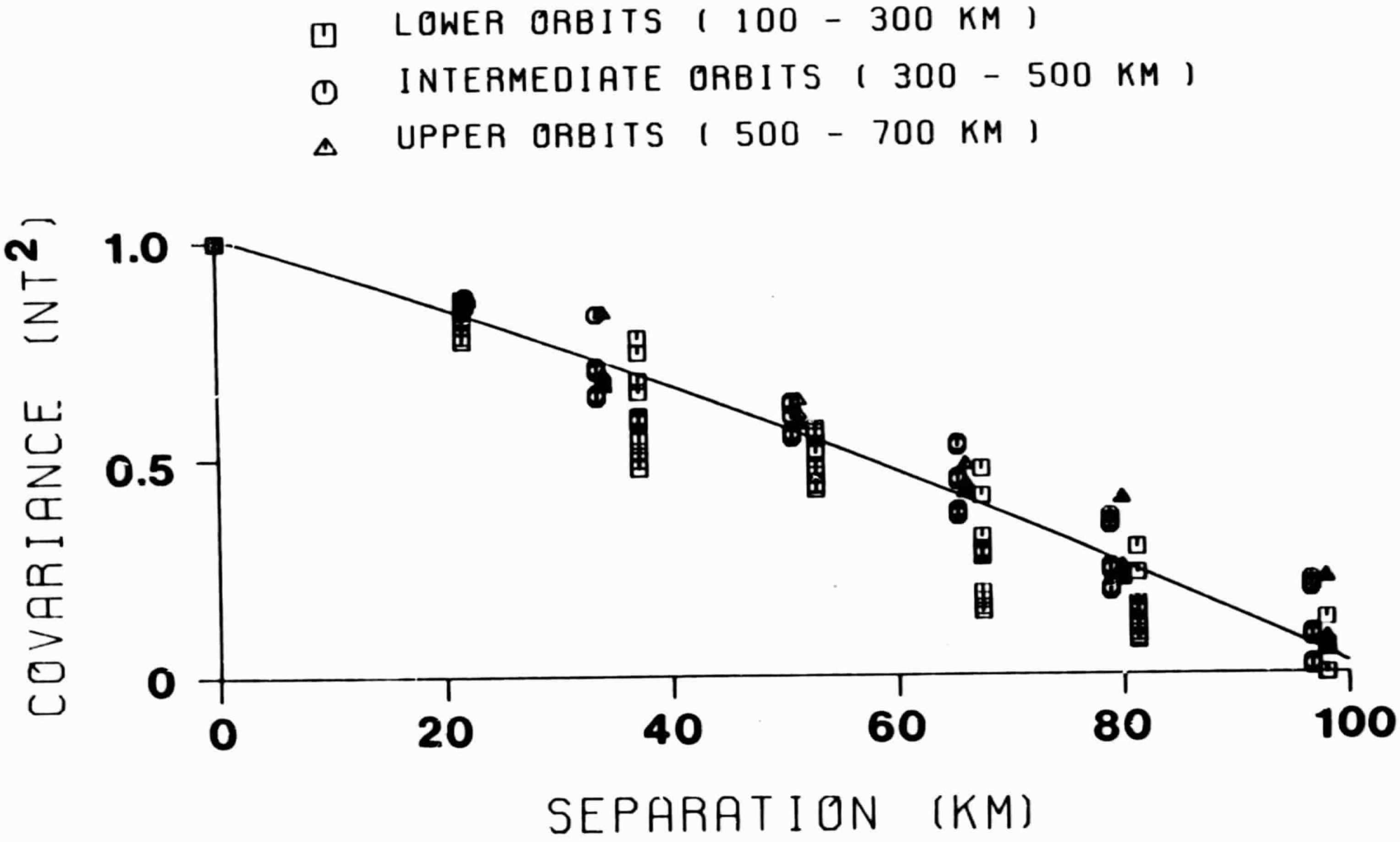
Figure Captions (Cont.)

Fig. 4 Comparison of true anomalies due to a 200 km wide crustal prism with corresponding deviations of 2°-averaged estimtes derived from dense (dotted) and sparse (dashed) data coverge at (A) 200 km elevation, (B) 400 km elevation, and (C) 600 km elevation.

Fig. 5 Percent improvement of collocation estimates over those obtained by averaging plotted as a function of (A) the source widths and (B) the principle satellite elevations considered in this study. Numbers beside superimposed data points give the number of data points in the cluster.

FIGURE 1


PARAMETERS FOR MAGNETIC SATELLITE ANOMALY AVERAGING SIMULATIONS


□ LOWER ORBITS (100 - 300 KM)
○ INTERMEDIATE ORBITS (300 - 500 KM)
△ UPPER ORBITS (500 - 700 KM)
COVARIANCE (NT^2)
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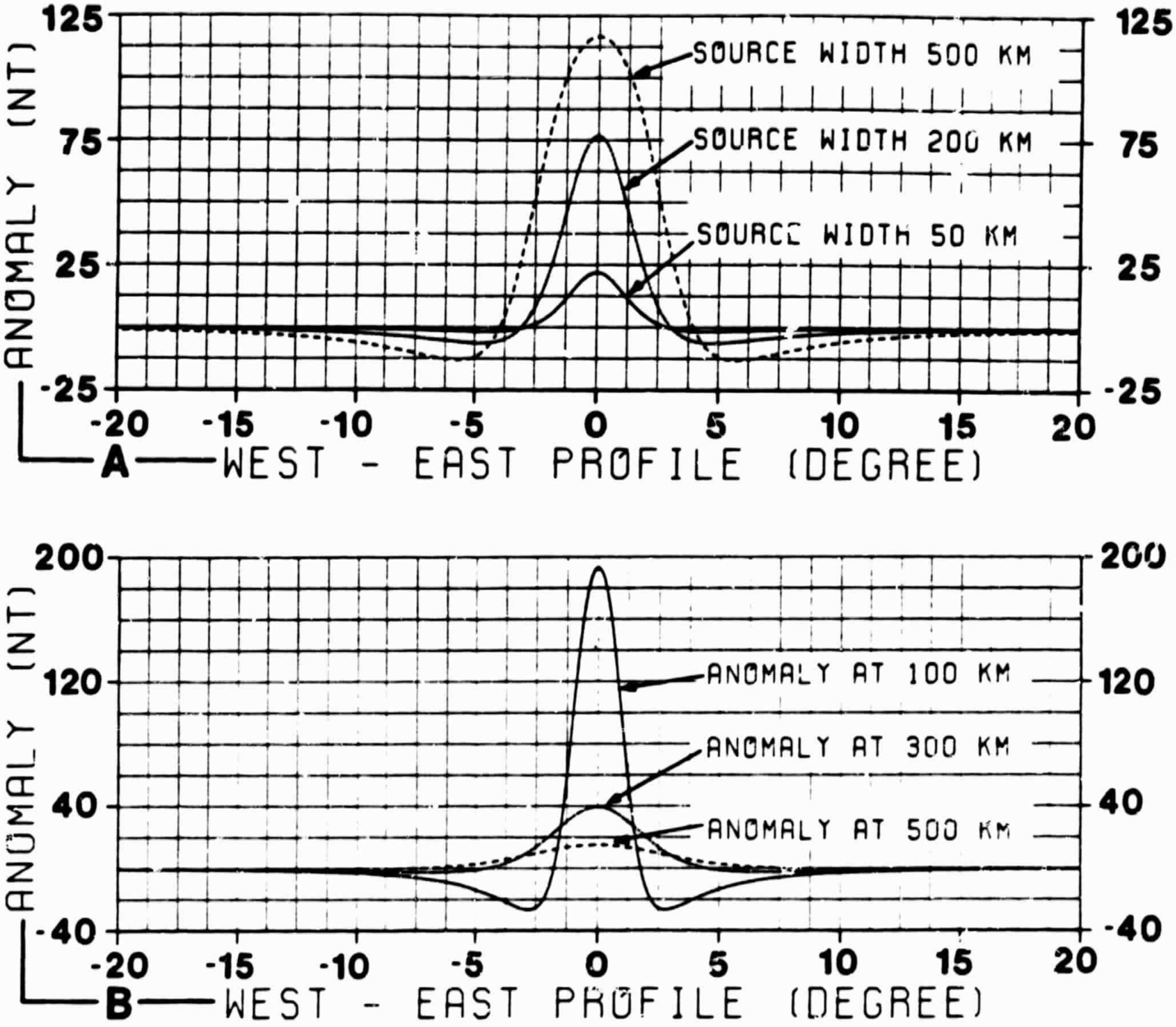
0.5
0
0
20
40
60
80
100
SEPARATION (KM)

FIGURE 2

FIGURE 3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75
25
-25
ANOMALY (NT)
SOURCE WIDTH 500 KM
SOURCE WIDTH 200 KM
SOURCE WIDTH 50 KM
-20
-15
-10
-5
0
5
10
15
20
A
WEST - EAST PROFILE (DEGREE)
200
120
40
-40
ANOMALY (NT)
ANOMALY AT 100 KM
ANOMALY AT 300 KM
ANOMALY AT 500 KM
B
WEST - EAST PROFILE (DEGREE)

FIGURE 4

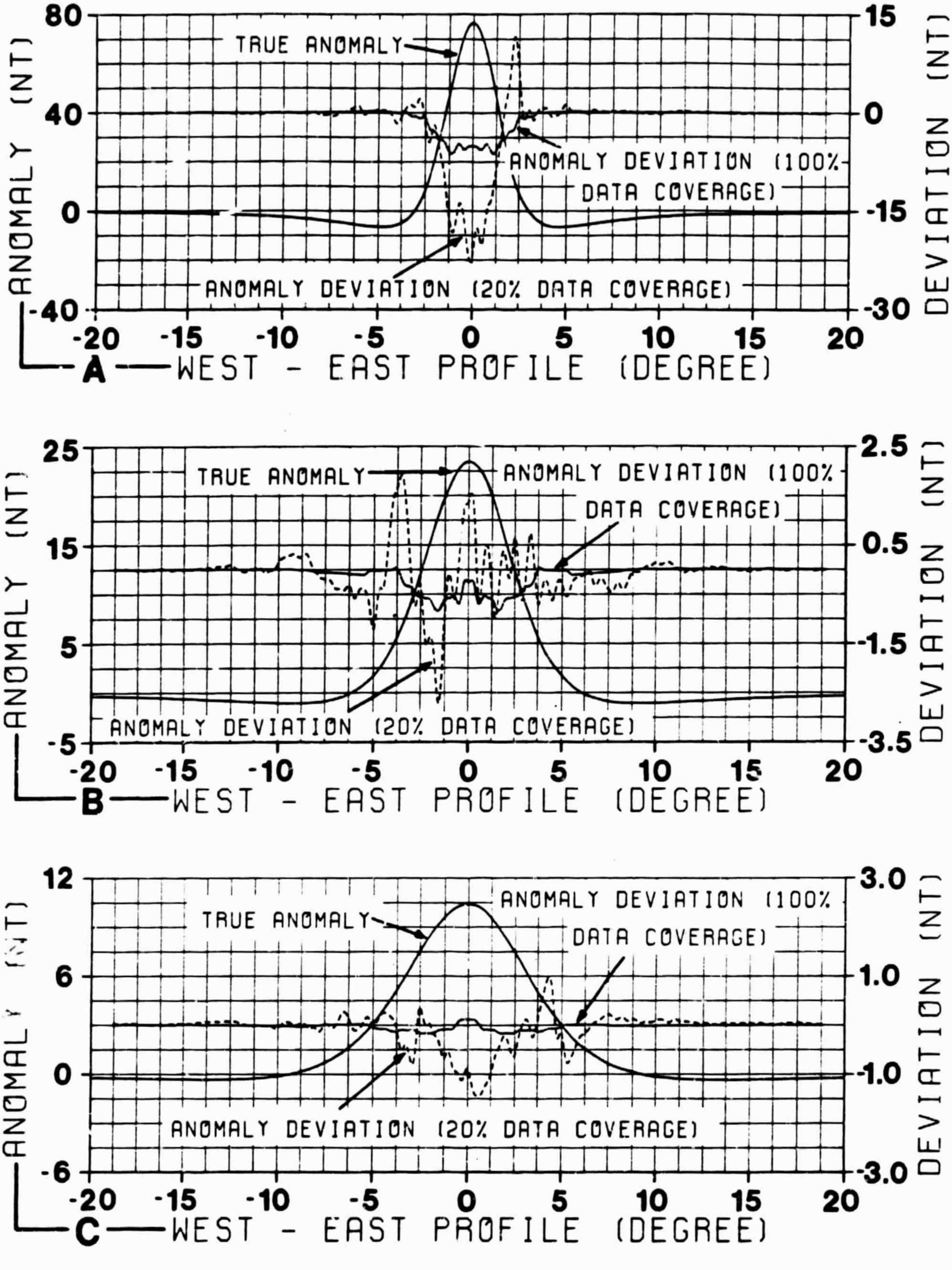
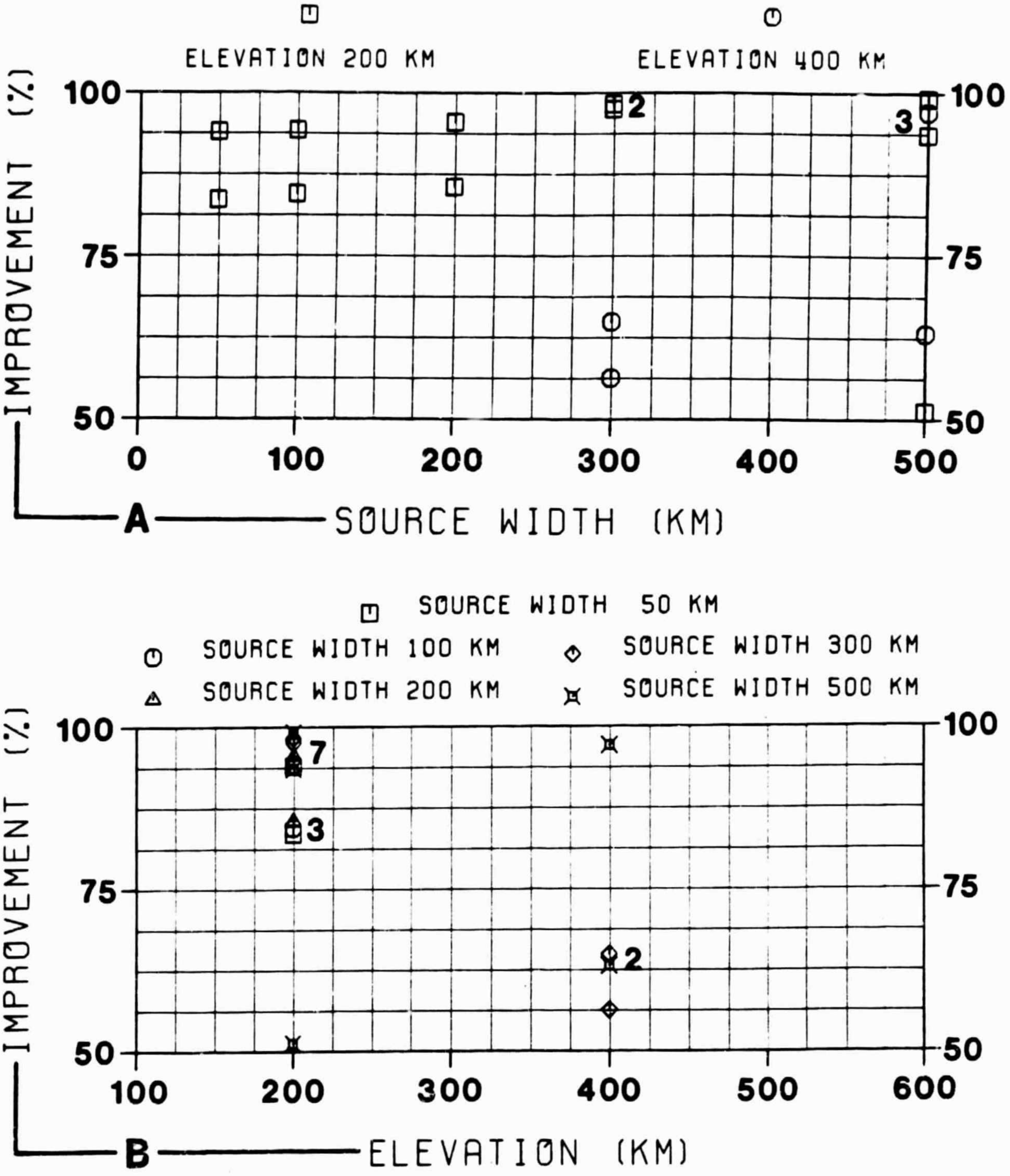

TRUE ANOMALY
ANOMALY DEVIATION (100% DATA COVERAGE)
ANOMALY DEVIATION (20% DATA COVERAGE)
ANOMALY (NT)
DEVIATION (NT)
80
40
0
-40
15
0
-15
-30
-20
-15
-10
-5
0
5
10
15
20
A
WEST - EAST PROFILE (DEGREE)
TRUE ANOMALY
ANOMALY DEVIATION (100% DATA COVERAGE)
ANOMALY DEVIATION (20% DATA COVERAGE)
ANOMALY (NT)
DEVIATION (NT)
25
15
5
-5
2.5
0.5
-1.5
-3.5
-20
-15
-10
-5
0
5
10
15
20
B
WEST - EAST PROFILE (DEGREE)
TRUE ANOMALY
ANOMALY DEVIATION (100% DATA COVERAGE)
ANOMALY DEVIATION (20% DATA COVERAGE)
ANOMALY (NT)
DEVIATION (NT)
12
6
0
-6
3.0
1.0
-1.0
-3.0
-20
-15
-10
-5
0
5
10
15
20
C
WEST - EAST PROFILE (DEGREE)

FIGURE 5


ELEVATION 200 KM
ELEVATION 400 KM
IMPROVEMENT (%)
100
75
50
2
3
0
100
200
300
400
500
A
SOURCE WIDTH (KM)
SOURCE WIDTH 50 KM
SOURCE WIDTH 100 KM
SOURCE WIDTH 200 KM
SOURCE WIDTH 300 KM
SOURCE WIDTH 500 KM
IMPROVEMENT (%)
100
75
50
7
3
2
100
200
300
400
500
600
B
ELEVATION (KM)

Citation #6 (Presentation Abstract)

D6

N85-31591

THE SOUTH-CENTRAL UNITED STATES MAGNETIC ANOMALY

P.J. Starich, W.J. Hinze and L.W. Braile
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A positive magnetic anomaly, which dominates the MAGSAT scalar field over the south-central United States, results from the superposition of magnetic effects from several geologic sources and tectonic structures in the crust. The highly magnetic basement rocks of this region show good correlation with increased crustal thickness, above average crustal velocity and predominantly negative free-air gravity anomalies, all of which are useful constraints for modeling the magnetic sources.

The positive anomaly is composed of two primary elements. The westernmost segment is related to middle Proterozoic granite intrusions, rhyolite flows and interspersed metamorphic basement rocks in the Texas panhandle and eastern New Mexico. The anomaly and the magnetic crust are bounded to the west by the north-south striking Rio Grande Rift, a zone of lithospheric thinning and elevated heat flow, in central New Mexico. The anomaly extends eastward over the Grenville age basement rocks of central Texas, and is terminated to the south and east by the buried extension of the Ouachita System.

The northern segment of the anomaly extends eastward across Oklahoma and Arkansas to the Mississippi Embayment. It corresponds to a general positive magnetic region associated with the Wichita Mountains igneous complex in south-central Oklahoma and 1.2 to 1.5 Ga. felsic terrane to the north. The magnetic terrane terminates along a roughly east-west line in southern Kansas.

A subdued northeasterly extension of the anomaly, from southwest Missouri into the Great Lakes region, appears to be related to the felsic terrane which extends northeast across the Midcontinent.

D7

Citation #7 (Thesis Abstract) **N85-31592**

THE SOUTH-CENTRAL UNITED STATES MAGNETIC ANOMALY

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Dept. of Geosciences
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The South-Central United States Magnetic Anomaly is the most prominent positive feature in the MAGSAT scalar magnetic field over North America. The anomaly correlates with increased crustal thickness, above average crustal velocity, negative free-air gravity anomalies and an extensive zone of Middle Proterozoic anorogenic felsic basement rocks.

The anomaly and the magnetic crust are bounded on the west by the north-striking Rio Grande Rift, a zone of lithospheric thinning and high heat flow in central New Mexico. The anomaly extends eastward over the Grenville age basement rocks of central Texas and is terminated to the south and east at the burial extension of the Ouachita Orogenic System which is the southern edge of the North American craton. The anomaly also extends eastward across Oklahoma and Arkansas to the Mississippi Embayment. A subdued northeasterly extension of the anomaly continues into the Great Lakes region. The feature terminates along the east-west boundary of the felsic terrain in southern Kansas.

Spherical dipole source inversion of the MAGSAT scalar data and subsequent calculation of reduced-to-pole and derivative maps provide additional constraints for a crustal magnetic model which corresponds geographically to the extensive Middle Proterozoic felsic rocks trending northeasterly across the United States. These felsic rocks contain insufficient magnetization or volume to produce the anomaly, but are rather indicative of a crustal zone which was disturbed during a Middle Proterozoic thermal event which enriched magnetic material deep in the crust.

D8

Citation #8 (Presentation Abstract)

N85-31593

A COMPARATIVE STUDY OF SPHERICAL AND FLAT-EARTH GEOPOTENTIAL MODELING AT SATELLITE ELEVATIONS

M.H. Parrott(1), W.J. Hinze(1), L.W. Braile(1), and R.R.B. von Frese(2)

Flat-earth modeling is a desirable alternative to the complex spherical-earth modeling process, but do errors invalidate the use of flat-earth assumptions at satellite elevations? These methods were compared using $2\frac{1}{2}$-D flat-earth and spherical modeling to compute gravity and scalar magnetic anomalies along profiles perpendicular to the strike of variably dimensioned rectangular prisms at altitudes of 150, 300, and 450 km. Comparison was achieved with percent error computations (spherical-flat/spherical) at critical anomaly points. At the peak gravity anomaly value, errors are less than ±5% for all prisms. At $\frac{1}{2}$ and $\frac{1}{10}$ of the peak, errors are generally less than 10% and 40% respectively, increasing to these values with longer and wider prisms at higher altitudes. For magnetics, the errors at critical anomaly points are less than -10% for all prisms, attaining these magnitudes with longer and wider prisms at higher altitudes. In general, in both gravity and magnetic modeling, errors increase greatly for prisms wider than 500 km, although gravity modeling is more sensitive than magnetic modeling to spherical-earth effects. Preliminary modeling of both satellite gravity and magnetic anomalies using flat-earth assumptions is justified considering the errors caused by uncertainties in isolating anomalies.

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D9

N85-31594

Citation #9 (Refereed Paper)

A COMPARATIVE STUDY OF SPHERICAL AND FLAT-EARTH GEOPOTENTIAL MODELING AT SATELLITE ELEVATIONS

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Purdue University
West Lafayette, In 47907

and

R.R.B. von Frese
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July, 1984

ABSTRACT

Flat-earth and spherical-earth geopotential modeling of crustal anomaly sources at satellite elevations are compared by computing gravity and scalar magnetic anomalies perpendicular to the strike of variably dimensioned rectangular prisms at altitudes of 150, 300, and 450 km. Results indicate that the error caused by the flat-earth approximation is less than 10% in most geometric conditions. Generally, errors increase with larger and wider anomaly sources at higher altitudes. For most crustal source modeling applications at conventional satellite altitudes, flat-earth modeling can be justified and is numerically efficient.

INTRODUCTION

It is well known that geopotential modeling at satellite elevations using flat-earth assumptions disregards the sphericity of the earth. To eliminate resulting errors, spherical-earth modeling has been developed and implemented in recent years (von Frese et al., 1981). However, currently available spherical modeling algorithms are far more complex than flat-earth algorithms, resulting in a considerable increase in computational effort. Because of the great computational efficiency which causes flat-earth modeling to be a desirable alternative, it is therefore important to understand the errors involved with the use of flat-earth assumptions at satellite elevations. A comparative study of the two modeling procedures was performed to determine the errors resulting from the use of the flat-earth assumptions for both gravity and scalar magnetic anomalies due to various source geometries.

ANALYSIS PROCEDURE

A computational approach was selected for the error analysis. Flat-earth modeling used 21/2 dimensional gravity and magnetic modeling programs, which assume homogeneous potential field characteristics throughout the anomalous body. Spherical modeling was performed by an algorithm which computes gravity or magnetic anomalies by concentrating the potential field characteristics in a specified number of point sources distributed throughout the anomalous body. The comparative study involved computation of gravity and scalar magnetic anomalies, using both modeling techniques, along common profiles perpendicular to the strike of variably dimensioned rectangular prisms. These computations were made at observation elevations of 150, 300, and 450 km for bodies with widths varying from 50 to 2000 km, and strike lengths of both 2 and 10 times the elevation. The radial (vertical) dimension of the bodies was held constant, extending from the surface to a depth of 40 km. Figure 1 shows the specifications of the prisms and observation profiles. The density contrast (0.25 g/cc) and susceptibility contrast (0.005 emu/cm^3) were arbitrarily chosen, and are simply scaling factors for the purposes of this study. Magnetic anomalies were calculated assuming vertical polarization across the entire source body to facilitate the comparisons, but testing of selected profiles was performed using inclinations of 75°, 60°, and 45°. The profiles were compared by calculating the percent error (spherical-flat/spherical) at critical anomaly points along the profiles. This method of analysis eliminates subjective scaling factors. Gravity anomalies were compared at the maximum anomaly value, and at 1/2 and 1/10 of the maximum. Magnetic anomalies were compared at the maximum, 1/2 of the maximum, and at the minimum value. Also, the offset of the minimum magnetic anomaly values was calculated.

RESULTS

Errors for the various source geometries and observation elevation for gravity and magnetic modeling are shown on Figures 2-8, with each figure showing the percentage error for variable prism width and observation elevation, at strike lengths of 2 and 10 times the elevation. Figures 2-4 show the error at critical gravity anomaly points. Figure 2 indicates the errors at the maximum value as being less than 5% in all cases. At 1/2 and 1/10 of the maximum, Figures 3 and 4 show a trend of increasing error with increasing distance from the anomaly midpoint. Maximum errors are 12% at 1/2 of the peak value, and 40% at 1/10 of the peak, increasing to those values with increasing prism width, strike length, and observation elevation. Figures 5-8 show the errors resulting from magnetic modeling using flat-earth assumptions. Figures 5 and 6 show the errors at the maximum and 1/2 of the maximum as being less than 12% and 11% respectively, increasing to those values with increasing prism width, strike length, and observation elevation. At the minimum value, Figure 7 shows the errors to be less than 2% for all cases. Use of the two modeling techniques also creates an offset in the minimum anomaly value, which is indicated by Figure 8, with the offset increasing with increasing observation elevation and strike length and decreasing prism width. Several of the comparisons were repeated using inclinations of 75°, 60°, and 45° with similar results. At these inclinations, each test showed the error at the maximum value to vary not more than 1.1% from the vertical polarization case.

Figures 9 and 10 show the extreme examples for the comparison of both gravity and magnetic modeling using flat-earth (dashed line) and spherical-earth (solid line) modeling. These figures demonstrate the range in error anticipated using flat-earth modeling for data acquired at satellite elevations.

CONCLUSIONS

Generally, preliminary modeling of both magnetic and gravity satellite anomalies using flat-earth assumptions is justified. However, a modeler should use flat-earth assumptions only with full awareness of the errors involved, and with added discretion when modeling bodies wider than 500 km. For these bodies, gravity modeling comparisons show errors increasing greatly as compared to those associated with smaller bodies, at all observation elevations. Magnetic modeling shows similar large increases in error, but only at observation elevations of greater than 300 km. At an elevation of 150 km, errors are relatively constant for all body dimensions, as magnetic modeling is less sensitive to spherical-earth effects than gravity modeling. Increasing errors along the flanks should not be of great concern to the modeler, because those large percentage errors reflect limited differences in magnitude due to the small amplitudes along the flanks, and also because of errors associated with uncertainties in precisely isolating anomalies.

REFERENCE

1. von Frese, R.R.B., W.J. Hinze, L.W. Braile and A.J. Luca, Spherical-earth gravity and magnetic modeling by Gauss-Legendre quadrature integration, J. Geophysics, 49, 234-242, 1981.

FIGURE CAPTIONS

Figure 1. Specifications of anomalous prisms and observation profile.

Figure 2. Percentage error (spherical-flat/spherical) at maximum gravity anomaly values with strike length = a) 2*elevation and b) 10*elevation.

Figure 3. Percentage error (spherical-flat/spherical) at one-half maximum gravity anomaly value with strike length = a) 2*elevation and b) 10*elevation.

Figure 4. Percentage error (spherical-flat/spherical) at one-tenth maximum gravity anomaly value with strike length = a) 2*elevation and b) 10*elevation.

Figure 5. Percentage error (spherical-flat/spherical) at maximum magnetic anomaly value with strike length = a) 2*elevation and b) 10*elevation.

Figure 6. Percentage error (spherical-flat/spherical) at one-half maximum magnetic anomaly value with strike length = a) 2*elevation and b) 10*elevation.

Figure 7. Percentage error (spherical-flat/spherical) at minimum magnetic anomaly value with strike length = a) 2*elevation and b) 10*elevation.

Figure 8. Offset of minimum magnetic anomaly values with strike length = a) 2*elevation and b) 10*elevation.

Figure 9. Comparison of gravity anomalies computed by flat-earth (dashed line) and spherical-earth (solid line) methods, with dimensions of: a) z=150 km, w=50 km, strike=2z and b) z=450 km, w=2000 km, strike=10z.

Figure 10. Comparison of magnetic anomalies computed by flat-earth (dashed line) and spherical-earth (solid-line) methods, with dimensions of: a) z=150 km, w=50 km, strike=2z and b) z=450 km, w=2000 km, strike=10z.

Figure 11. Linear regression analysis of extreme examples of the gravity anomaly comparisons.

Figure 12. Linear regression analysis of extreme examples of the magnetic anomaly comparisons.

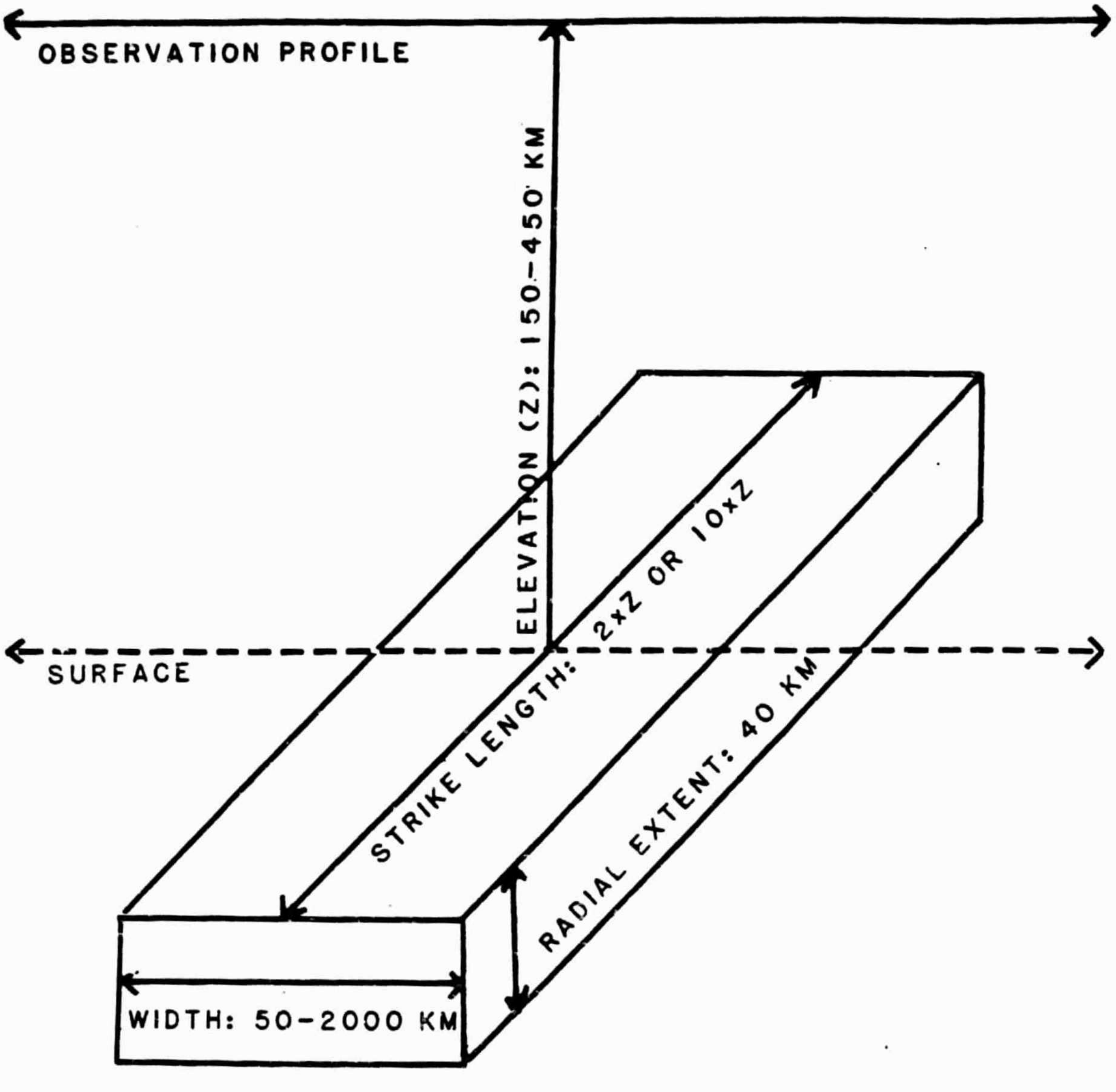
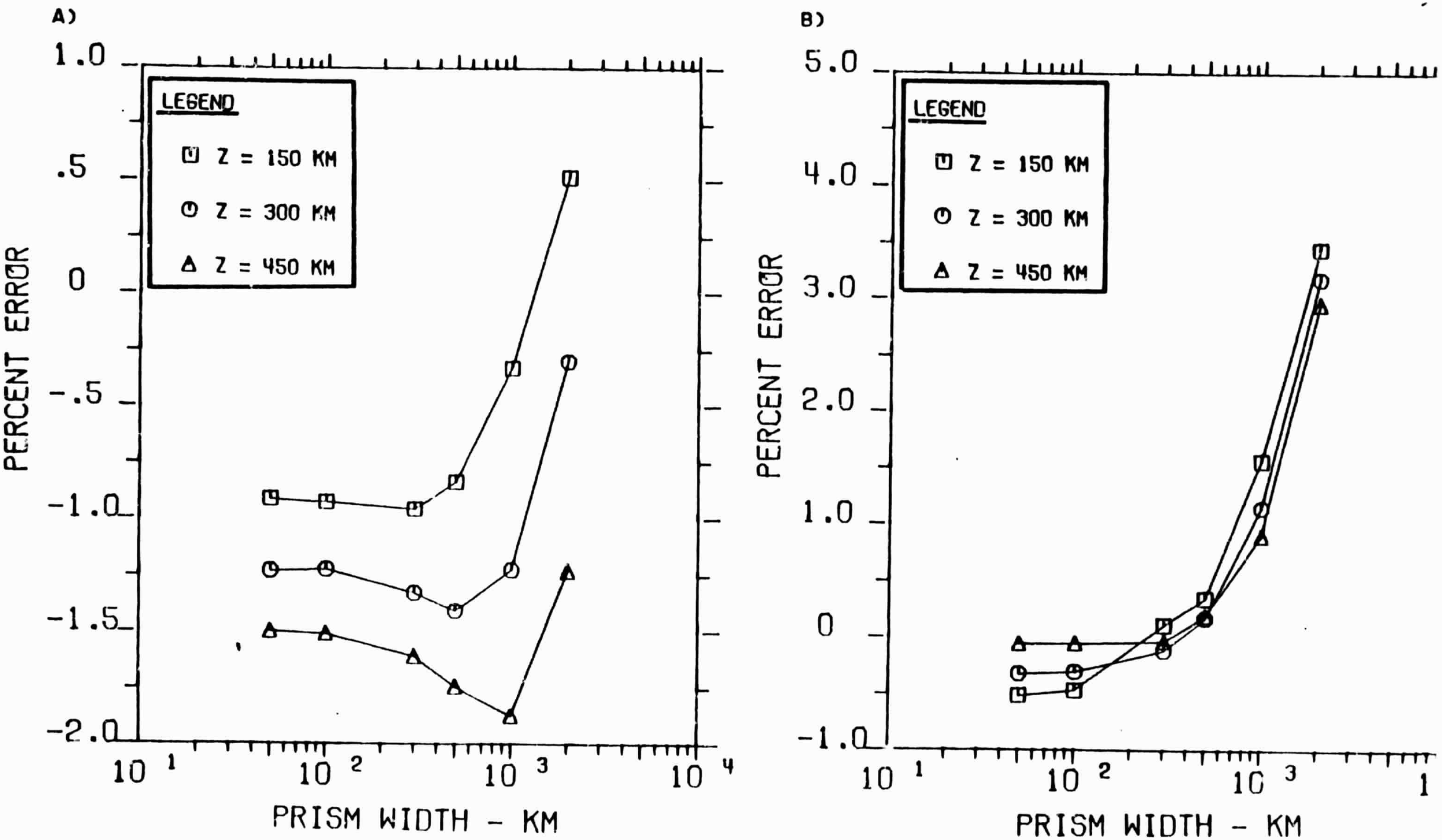

OBSERVATION PROFILE
ELEVATION (Z): 150-450 KM
2xZ OR 10xZ
SURFACE
STRIKE LENGTH:
RADIAL EXTENT: 40 KM
WIDTH: 50-2000 KM

FIGURE 1


A)
1.0
.5
0
-.5
-1.0
-1.5
-2.0
PERCENT ERROR
LEGEND
Z = 150 KM
Z = 300 KM
Z = 450 KM
10 1
10 2
10 3
10 4
PRISM WIDTH - KM
B)
5.0
4.0
3.0
2.0
1.0
0
-1.0
PERCENT ERROR
LEGEND
Z = 150 KM
Z = 300 KM
Z = 450 KM
10 1
10 2
10 3
1
PRISM WIDTH - KM

Figure

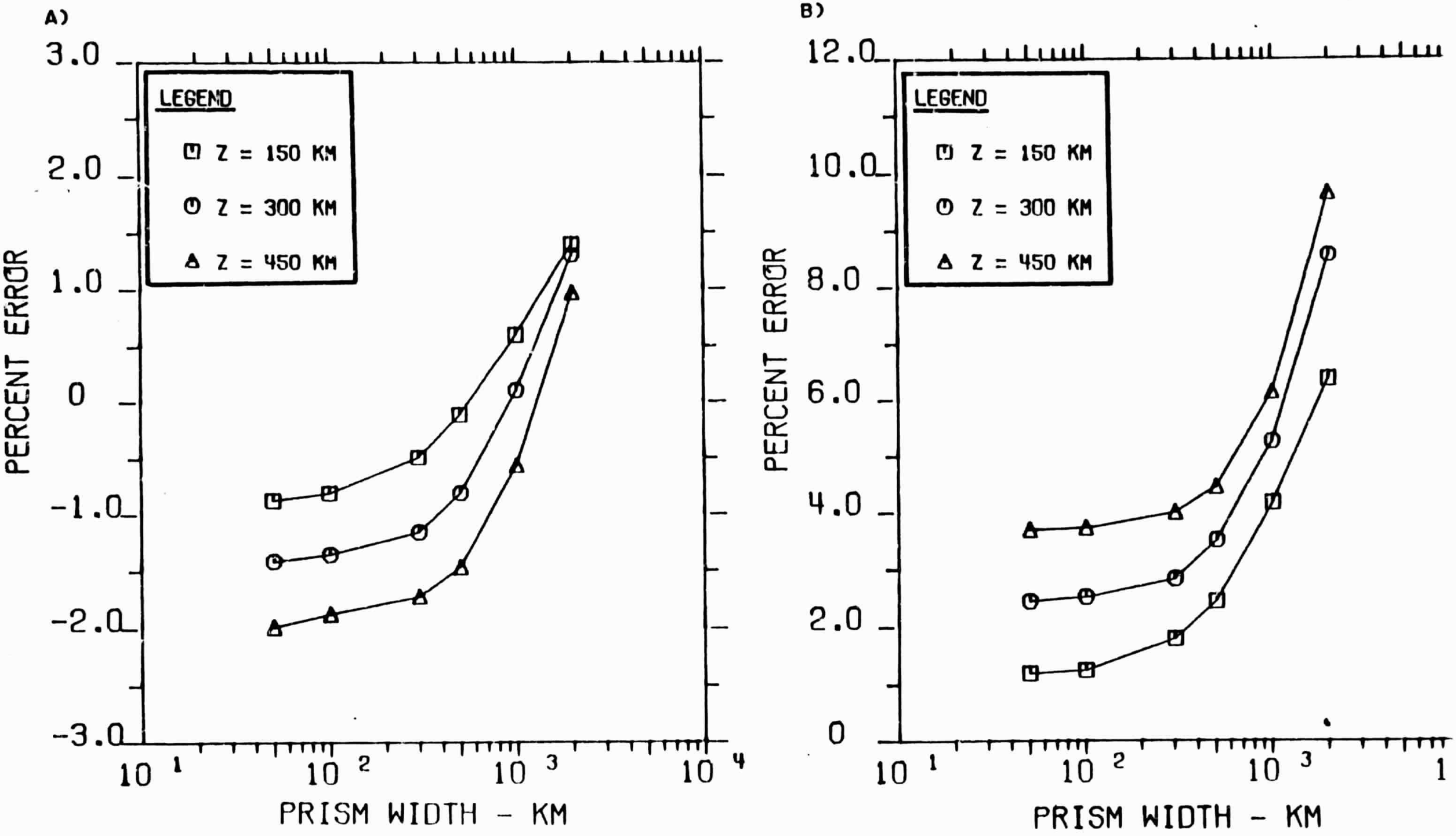

A)
B)
LEGEND
Z = 150 KM
Z = 300 KM
Z = 450 KM
PERCENT ERROR
PRISM WIDTH - KM
3.0
2.0
1.0
0
-1.0
-2.0
-3.0
12.0
10.0
8.0
6.0
4.0
2.0
0
10^1
10^2
10^3
10^4
1

FIGURE 3

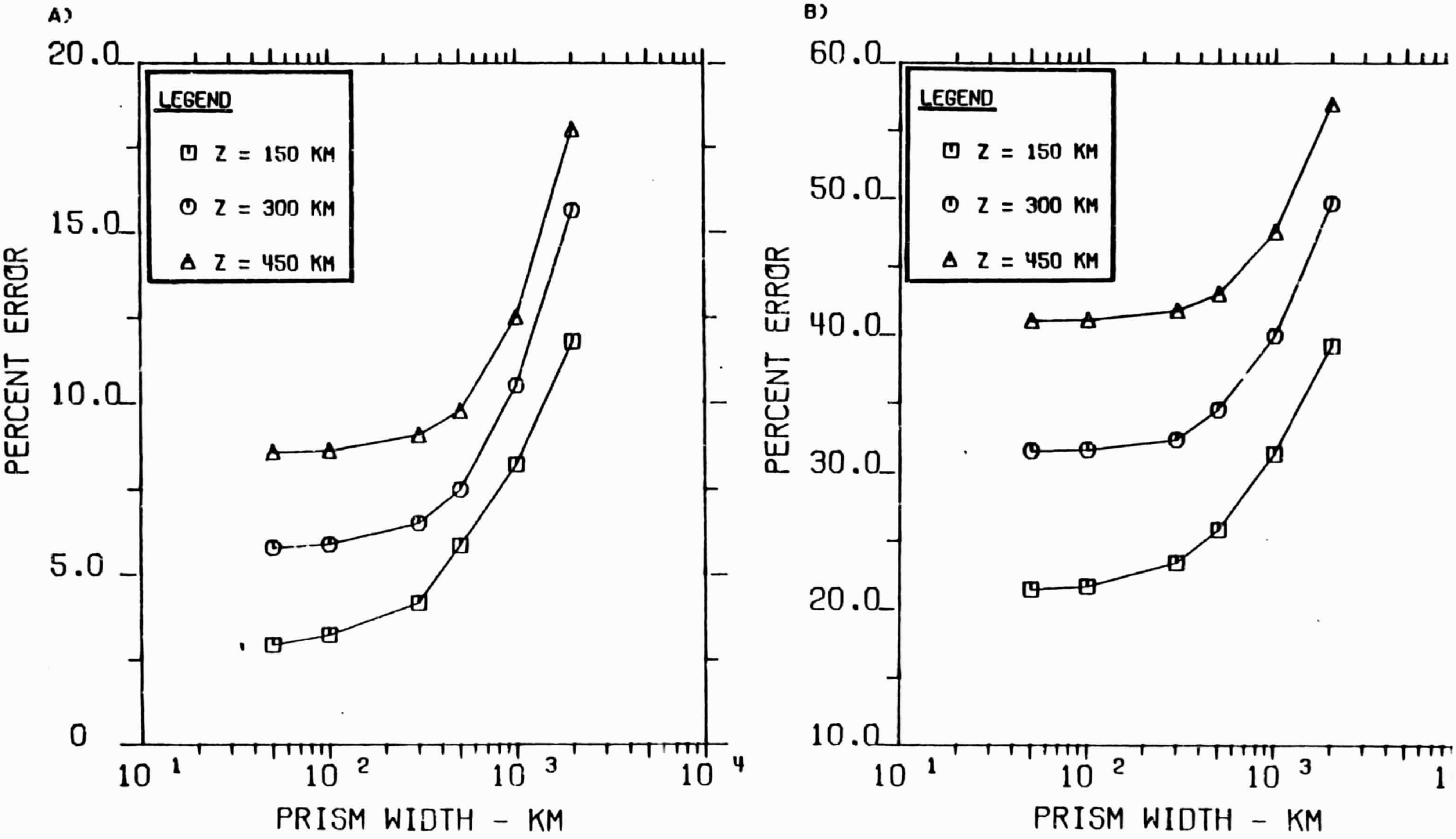

A)
LEGEND
Z = 150 KM
Z = 300 KM
Z = 450 KM
20.0
15.0
10.0
5.0
0
PERCENT ERROR
10^1
10^2
10^3
10^4
PRISM WIDTH - KM
B)
LEGEND
Z = 150 KM
Z = 300 KM
Z = 450 KM
60.0
50.0
40.0
30.0
20.0
10.0
PERCENT ERROR
10^1
10^2
10^3
1
PRISM WIDTH - KM

FIGURE 4

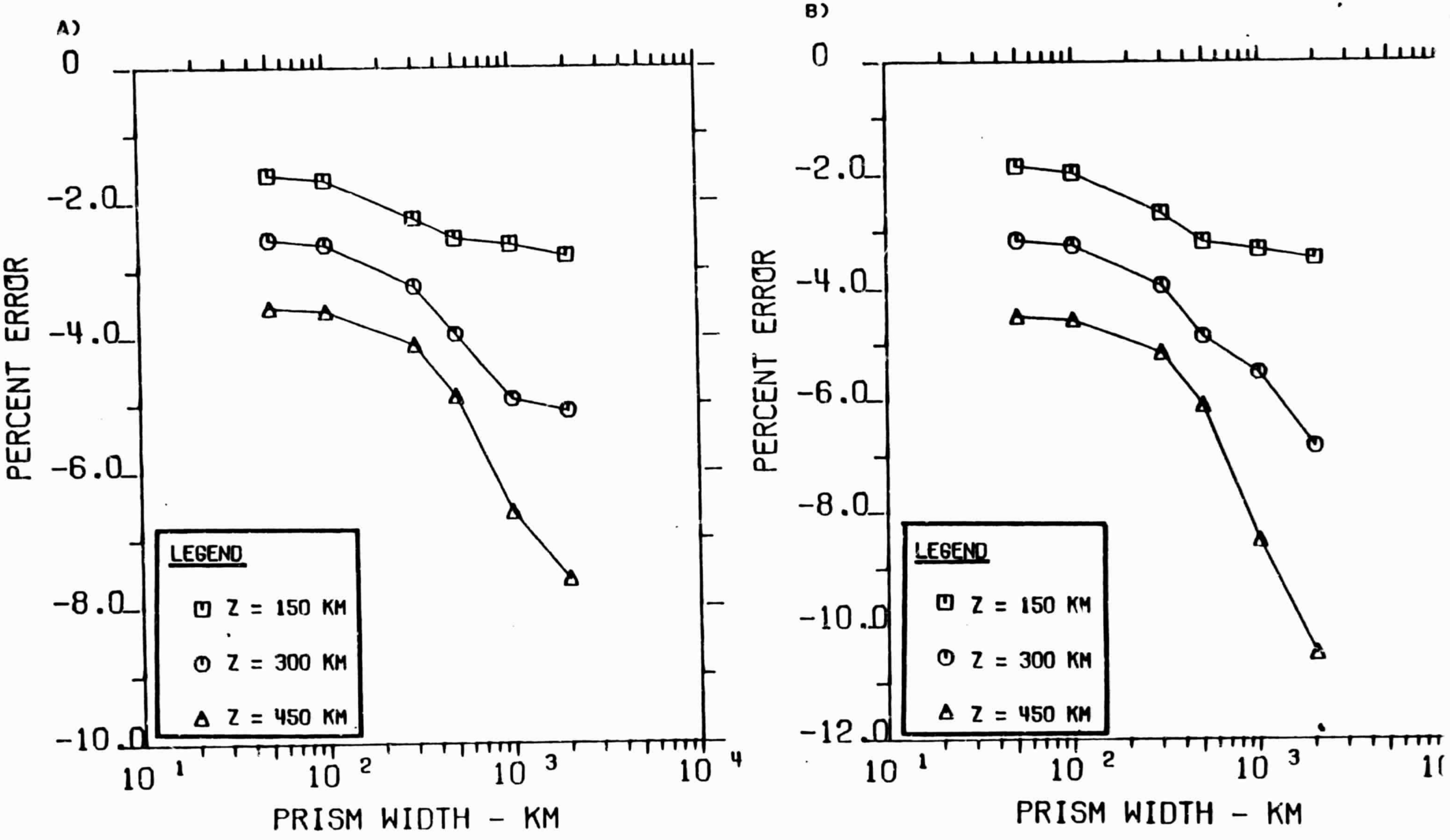

A)
B)
PERCENT ERROR
0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
PRISM WIDTH - KM
10^1
10^2
10^3
10^4
LEGEND
Z = 150 KM
Z = 300 KM
Z = 450 KM

FIGURE 1

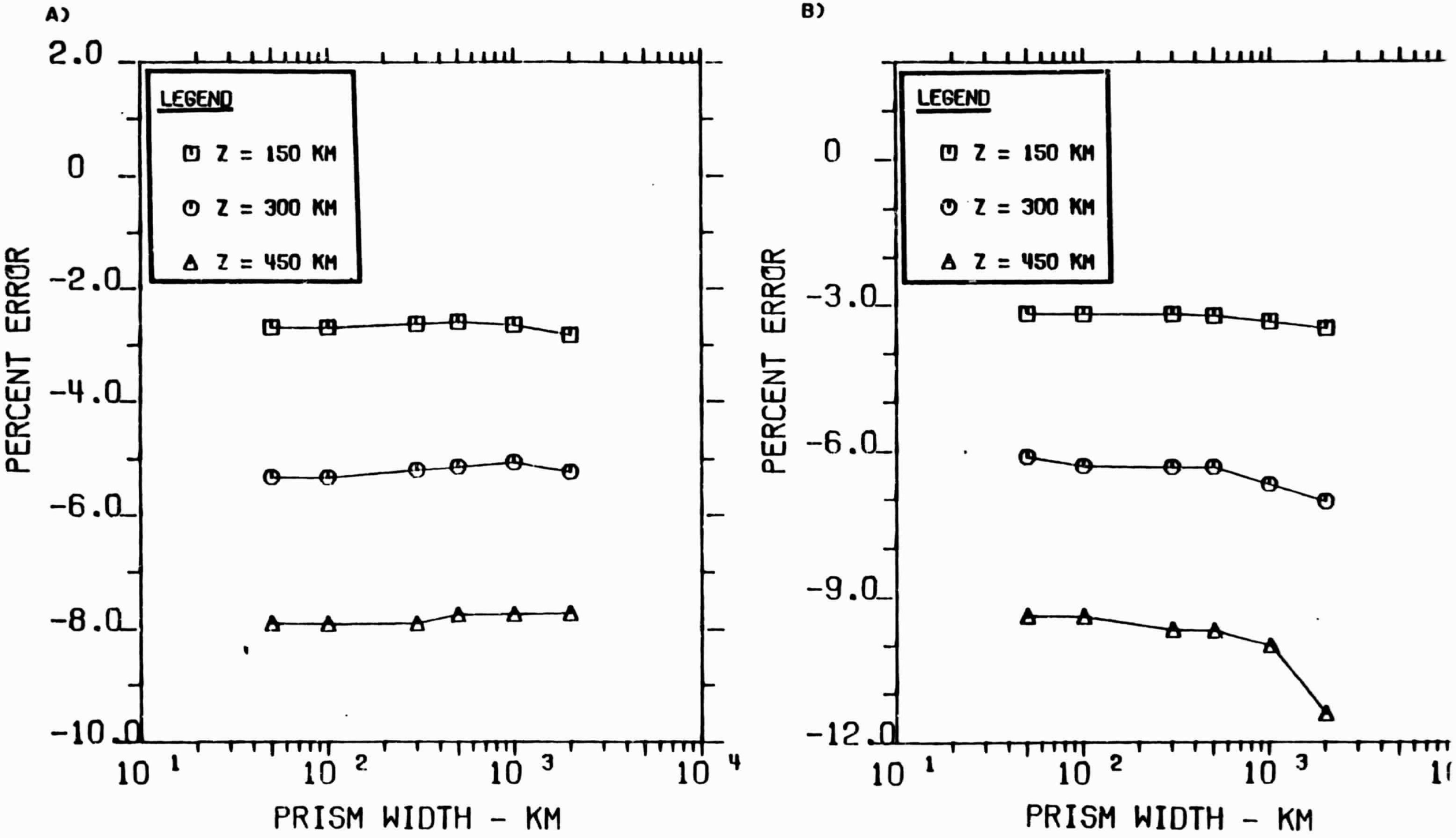
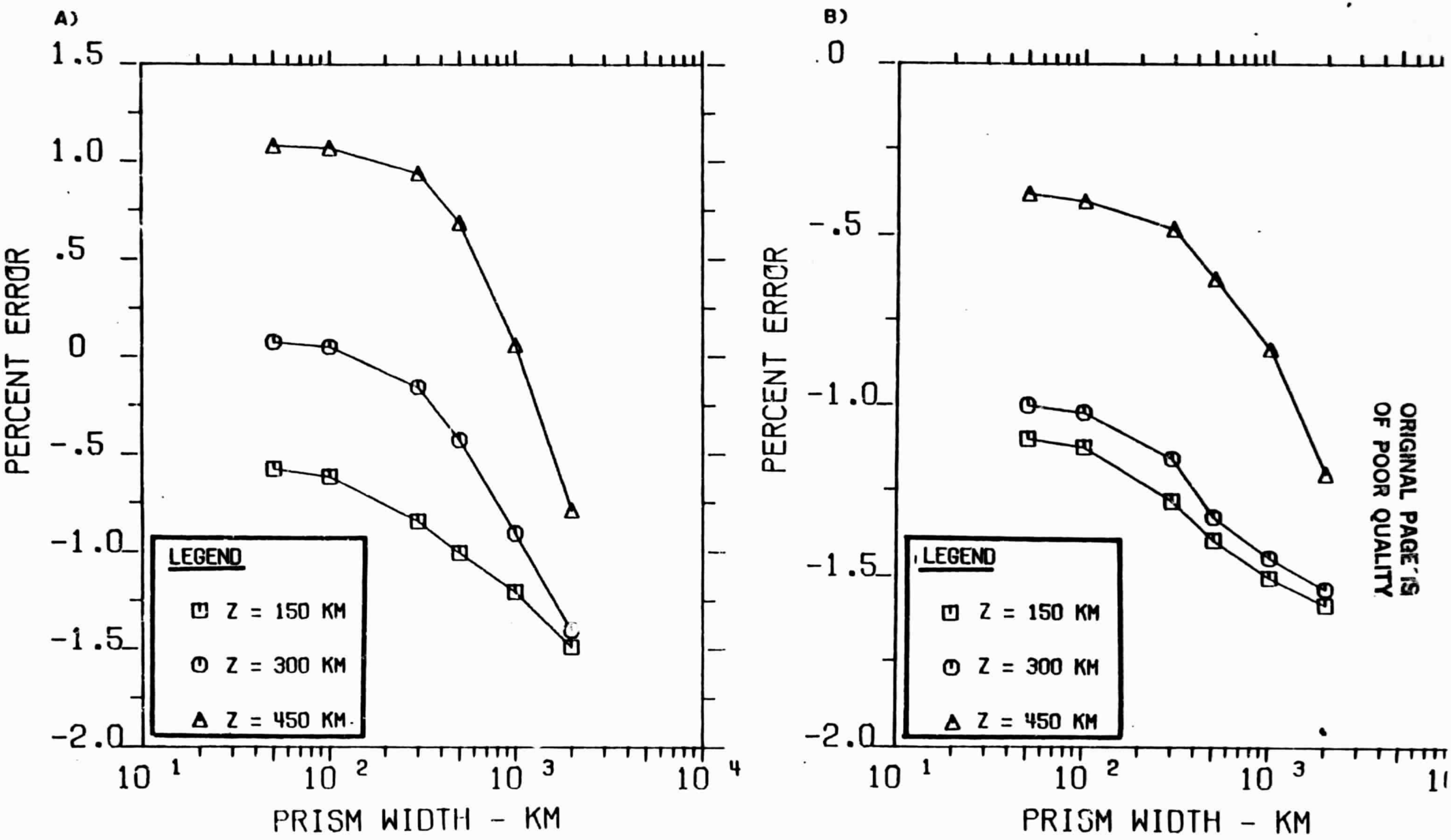

A)
2.0
0
-2.0
-4.0
-6.0
-8.0
-10.0
PERCENT ERROR
LEGEND
Z = 150 KM
Z = 300 KM
Z = 450 KM
10 1
10 2
10 3
10 4
PRISM WIDTH - KM
B)
0
-3.0
-6.0
-9.0
-12.0
PERCENT ERROR
LEGEND
Z = 150 KM
Z = 300 KM
Z = 450 KM
10 1
10 2
10 3
PRISM WIDTH - KM

FIGURE 6



ORIGINAL PAGE IS OF POOR QUALITY

FIGURE 7

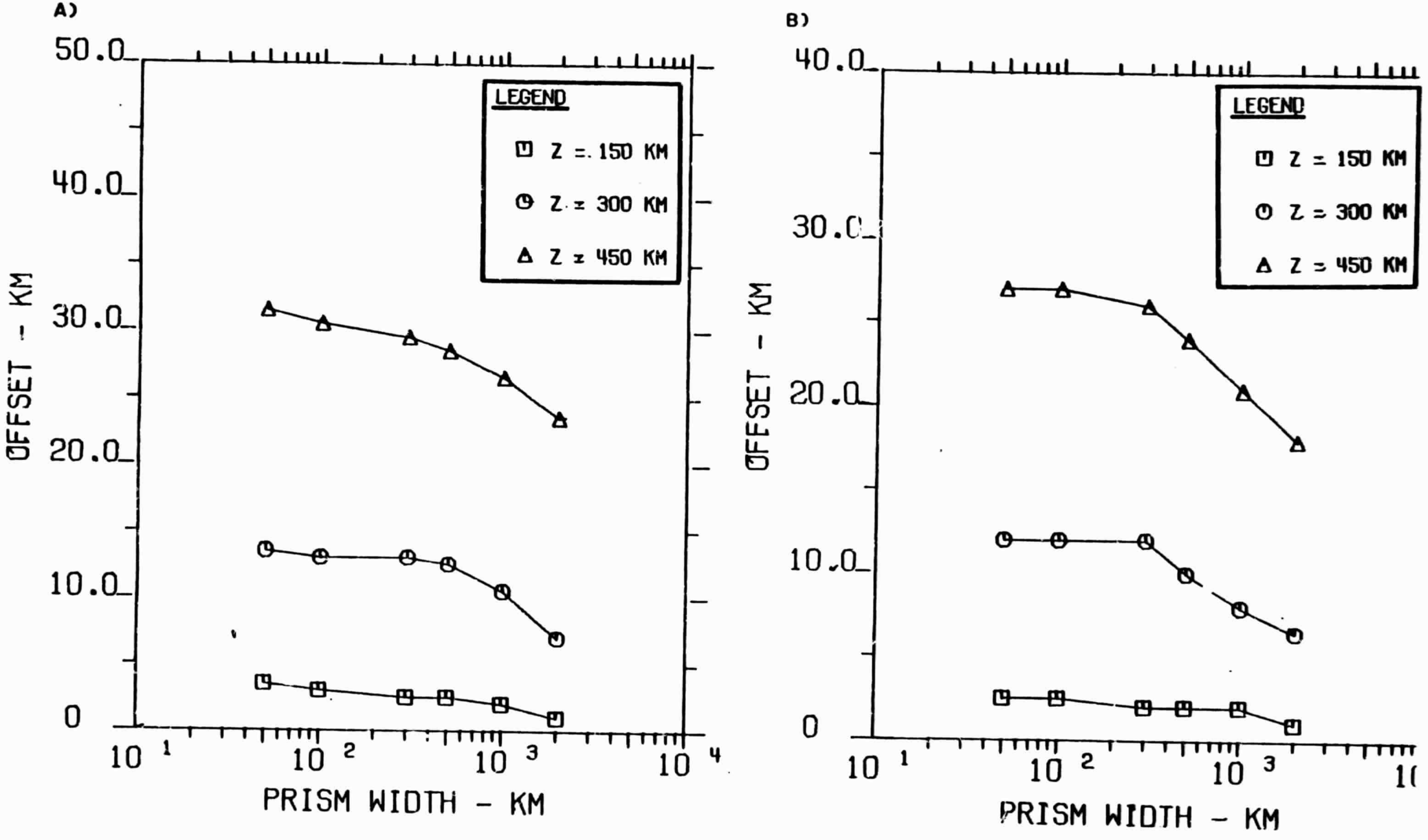

A)
50.0
40.0
30.0
20.0
10.0
0
OFFSET - KM
LEGEND
Z = 150 KM
Z = 300 KM
Z = 450 KM
10^1
10^2
10^3
10^4
PRISM WIDTH - KM
B)
40.0
30.0
20.0
10.0
0
OFFSET - KM
LEGEND
Z = 150 KM
Z = 300 KM
Z = 450 KM
10^1
10^2
10^3
PRISM WIDTH - KM

FIGURE 8

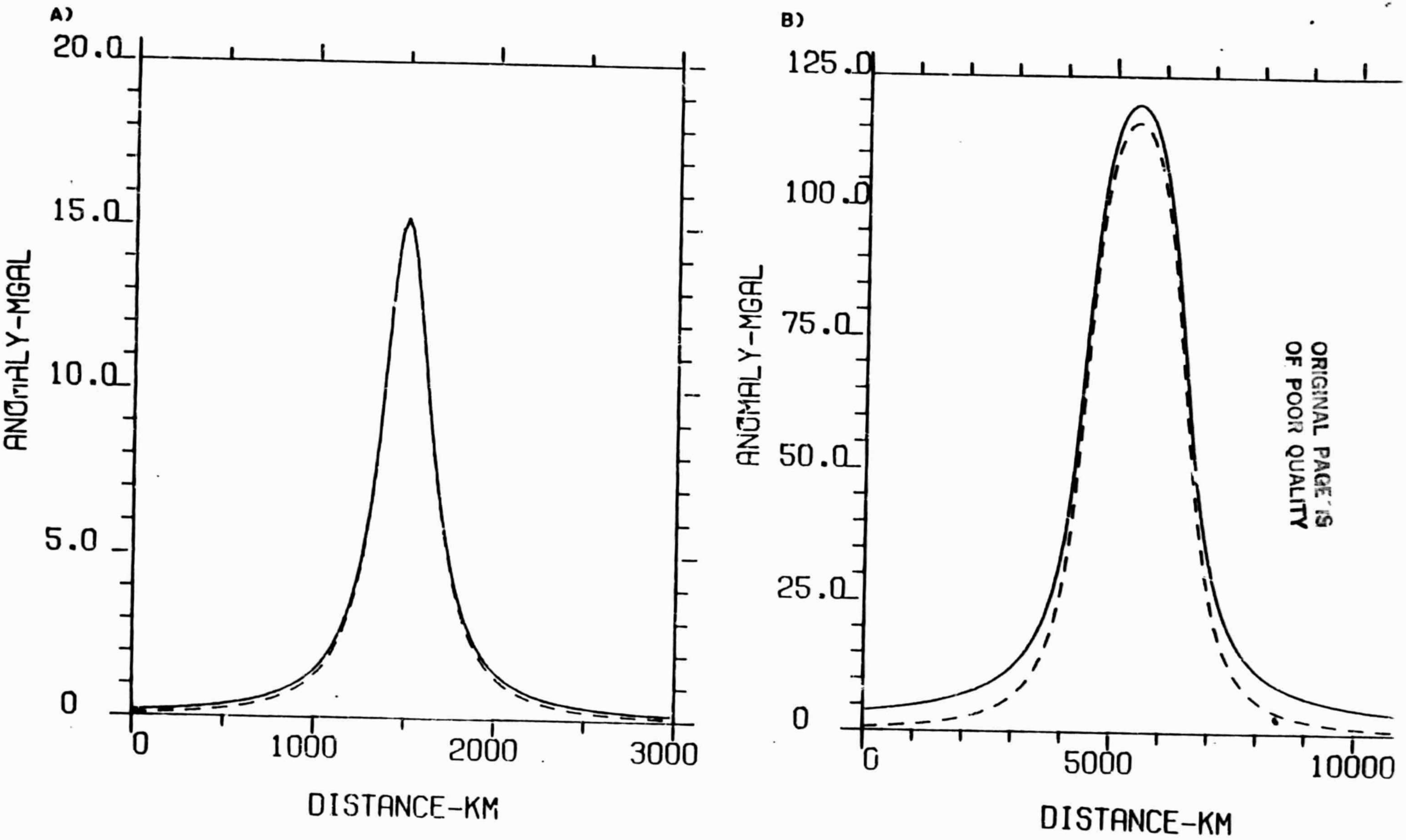

A)
20.0
15.0
10.0
5.0
0
ANOMALY-MGAL
0
1000
2000
3000
DISTANCE-KM
B)
125.0
100.0
75.0
50.0
25.0
0
ANOMALY-MGAL
0
5000
10000
DISTANCE-KM

FIGURE 9

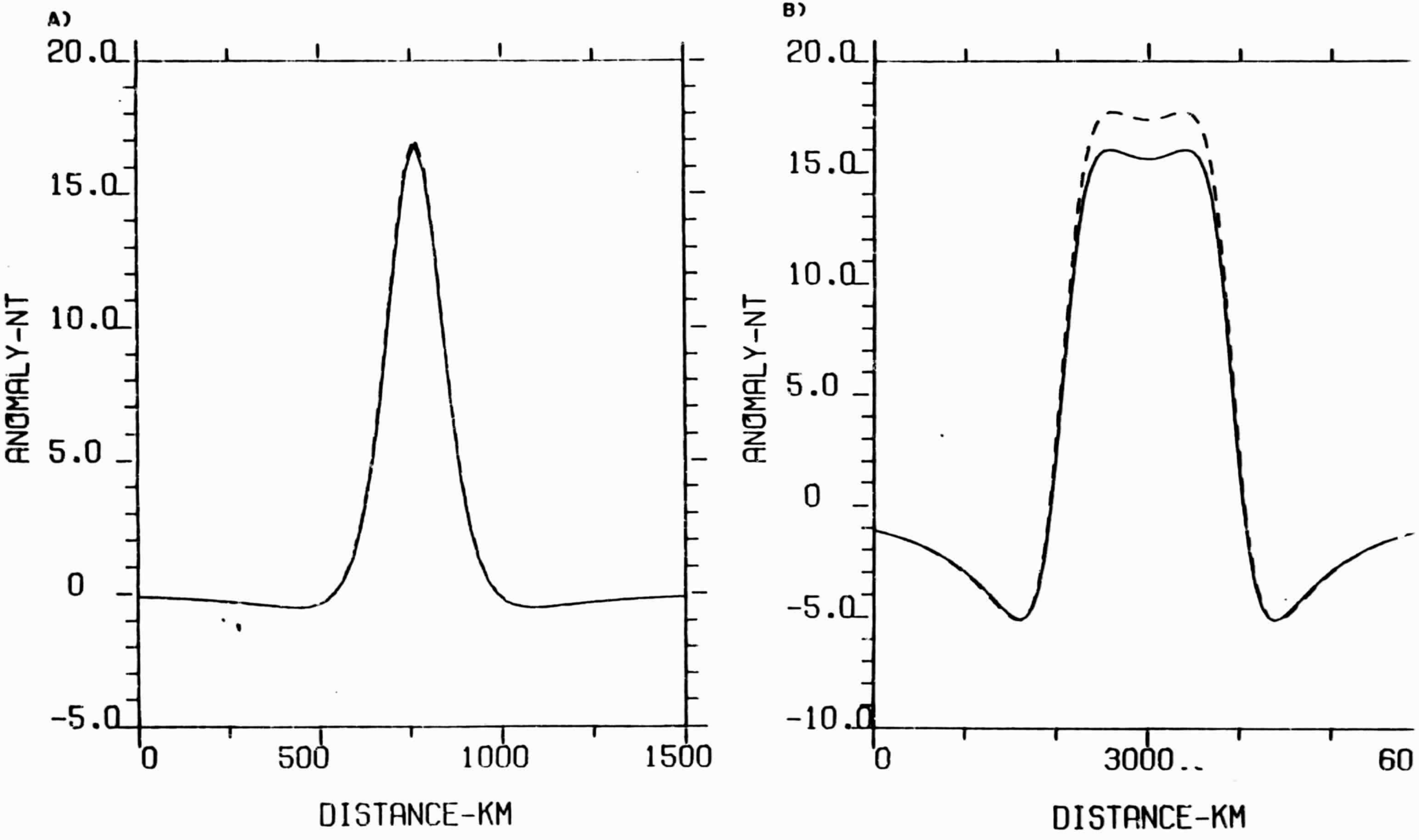

A)
20.0
15.0
10.0
5.0
0
-5.0
ANOMALY-NT
0
500
1000
1500
DISTANCE-KM
B)
20.0
15.0
10.0
5.0
0
-5.0
-10.0
ANOMALY-NT
0
3000..
60
DISTANCE-KM

FIGURE 1(

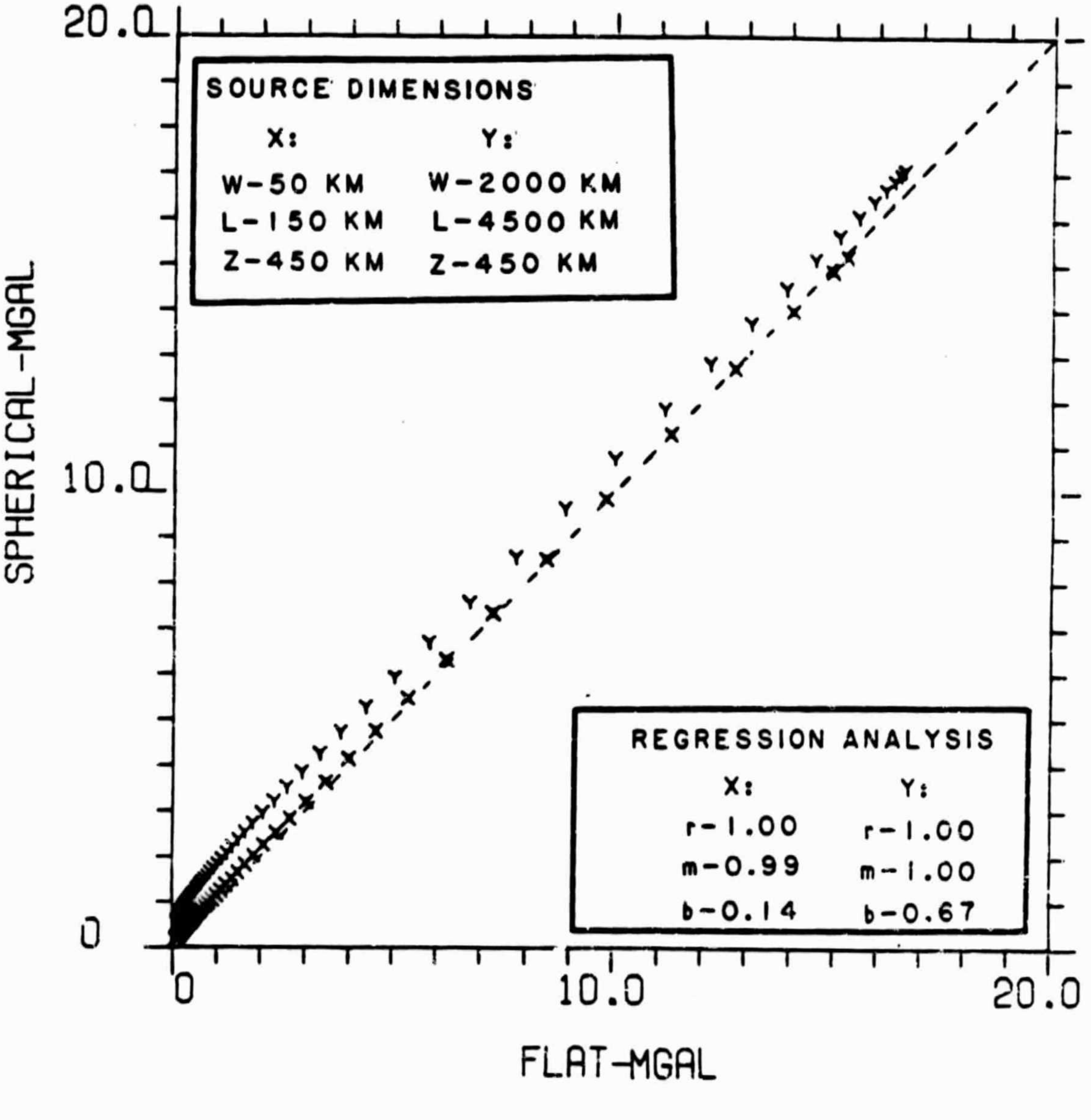

SOURCE DIMENSIONS
X:
Y:
W-50 KM
L-150 KM
Z-450 KM
W-2000 KM
L-4500 KM
Z-450 KM
REGRESSION ANALYSIS
X:
Y:
r-1.00
m-0.99
b-0.14
r-1.00
m-1.00
b-0.67
20.0
10.0
0
10.0
20.0
SPHERICAL-MGAL
FLAT-MGAL

FIGURE 1

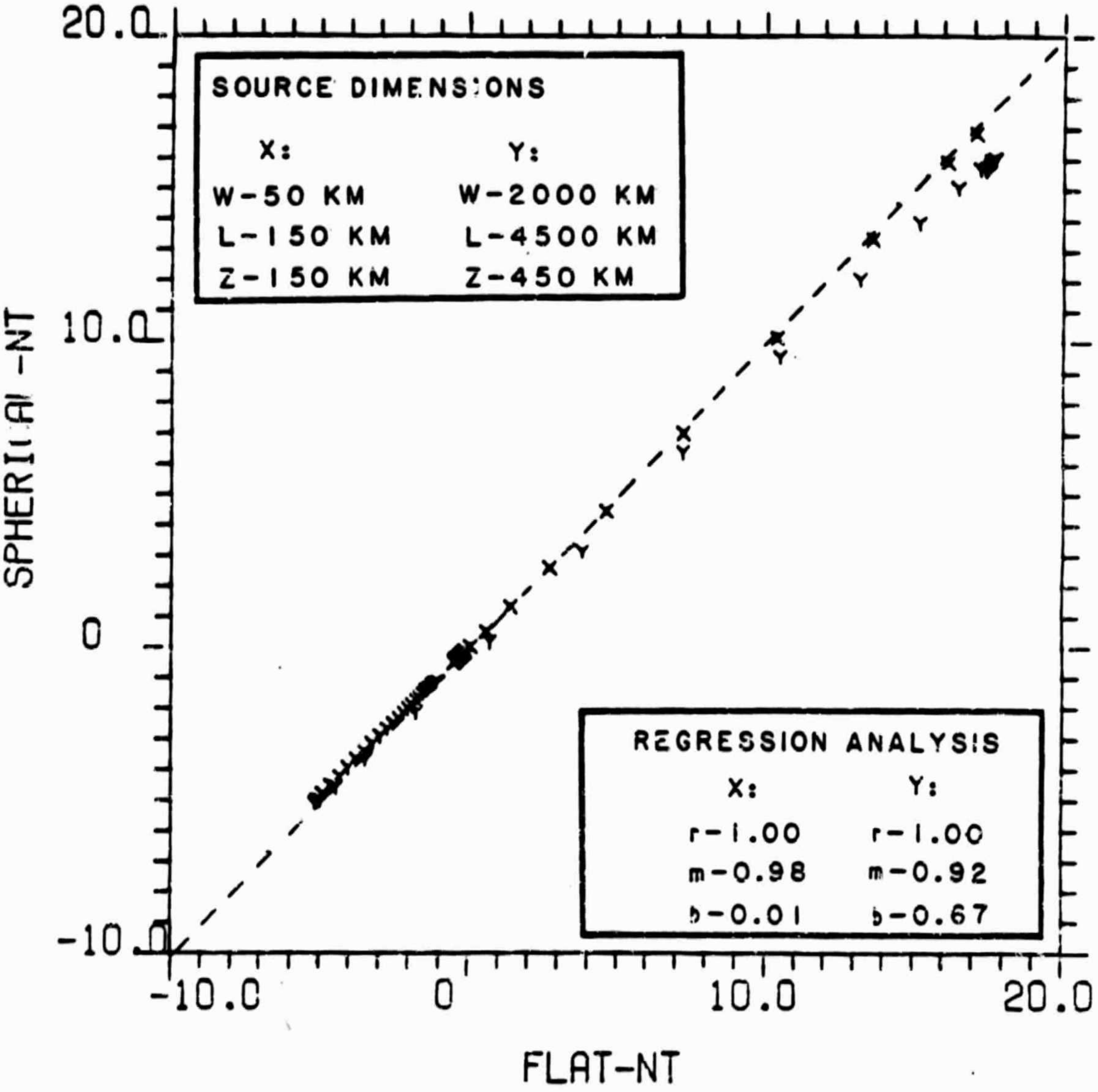

SOURCE DIMENSIONS
X:
Y:
W-50 KM
W-2000 KM
L-150 KM
L-4500 KM
Z-150 KM
Z-450 KM
REGRESSION ANALYSIS
X:
Y:
r-1.00
r-1.00
m-0.98
m-0.92
b-0.01
b-0.67
20.0
10.0
0
-10.0
SPHERICAL-NT
-10.0
0
10.0
20.0
FLAT-NT

FIGURE 12

D10

Citation #10 (Presentation Abstract) **N85-31595**

REDUCED TO POLE LONG-WAVELENGTH MAGNETIC ANOMALIES OF AFRICA AND EUROPE

R. Olivier(1), W.J. Hinze(2), R.R.B. von Frese(3)

To facilitate analysis of the tectonic framework for Africa, Europe and adjacent marine areas, magnetic satellite (MAGSAT) scalar anomaly data are differentially reduced to pole and compared to regional geologic information and geophysical data including surface free-air gravity anomaly data upward continued to satellite elevation (350 km) on a spherical earth. Comparative analysis shows magnetic anomalies correspond with both ancient as well as more recent Cenozoic structural features. Anomalies associated with ancient structures are primarily caused by intra-crustal lithologic variations such as the crustal disturbance associated with the Bangui anomaly in west-central Africa. In contrast, anomalies correlative with Cenozoic tectonic elements appear to be related to Curie isotherm perturbations. A possible example of the latter is the well-defined trend of magnetic minima that characterize the Alpine orogenic belt from the Atlas mountains to Eurasia. In contrast, a well-defined magnetic satellite minimum extends across the stable craton from Finland to the Ural mountains. Prominent magnetic maxima characterize the Arabian plate, Iceland, the Kursk region of the central Russian uplift, and generally the Precambrian shields of Africa.

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D11

Citation #11 (Presentation Abstract) **N85-31596**

EURO-AFRICAN MAGSAT ANOMALY-TECTONIC OBSERVATIONS

W.J. Hinze(1), R. Olivier(2), and R.R.B. von Frese(3)

Preliminary satellite (MAGSAT) scalar magnetic anomaly data are compiled and differentially reduced to radial polarization by equivalent point source inversion for comparison with tectonic data of Africa, Europe and adjacent marine areas. A number of associations are evident to constrain analyses of the tectonic features and history of the region. Rift zones and aulacogens, for example, tend to be magnetically negative. The most intense positive anomaly of the region is the Bangui anomaly which has been interpreted as due to a deep crustal positive magnetization source. There are no near-surface sources which will explain this anomaly. By contrast, the next most intense positive anomaly is over the Kursk region in the Russian Ukraine. This anomaly extends 450 km in a northeasterly direction and is roughly 150 km wide, and is caused according to aeromagnetic anomaly interpretations by near-surface, intensely magnetic ferruginous quartzites. Apparently there is sufficient long-wavelength energy in these near-surface anomalies for them to be observed at satellite elevations. The Precambrian shields of Africa and Europe exhibit varied magnetic signatures. All shields are not magnetic highs and, in fact, the Baltic shield is a marked minimum. The reduced to the pole magnetic map shows a marked tendency for northeasterly striking anomalies in the eastern Atlantic and adjacent Africa, which is coincident to the track of several hot spots for the past 100 million years. However, there is little consistency in the sign of the magnetic anomalies and the track of the hot spots. Comparison of the radially polarized anomalies of Africa and Europe with other reduced to the pole magnetic satellite anomaly maps of the Western Hemisphere support the reconstruction of the continents prior to the origin of the present-day Atlantic Ocean in the Mesozoic Era.

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Citation #12 (Presentation Abstract)

D12

N85-31597

LONG-WAVELENGTH MAGNETIC AND GRAVITY ANOMALY CORRELATIONS ON AFRICA AND EUROPE

R.R.B. von Frese(1), R. Olivier(2), and W.J. Hinze(3)

Regional geopotential anomalies and their correlations provide important constraints for investigating the megatectonic framework of Africa and Europe. Accordingly, preliminary satellite (MAGSAT) scalar magnetic anomaly data are compiled for comparison with long-wavelength-pass filtered free-air gravity anomalies and regional heat-flow and tectonic data. To facilitate the correlation analysis at satellite elevations over a spherical-earth, equivalent point source inversion is used to differentially reduce the magnetic satellite anomalies to the radial pole at 350 km elevation, and to upward continue the first radial derivative of the free-air gravity anomalies. Correlation patterns between these regional geopotential anomaly fields are quantitatively established by moving-window linear regression based on Poisson's theorem. Prominent correlations include direct correspondences for the Baltic Shield, where both anomalies are negative, and the central Mediterranean and Zaire Basin where both anomalies are positive. Inverse relationships are generally common over the Precambrian Shield in northwest Africa, the Basins and Shield in southern Africa, and the Alpine Orogenic Belt. Inverse corelations also persist over the North Sea Rifts, the Benue Rift, and more generally over the East African Rifts. The results of this quantitative correlation analysis support the general inverse relationships of gravity and magnetic anomalies observed for North American continental terrane which may be broadly related to magnetic crustal thickness variations.

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(3) Dept. of Geosciences, Purdue University, West Lafayette, IN 47907

N85-31598 D13

Citation #13 (Presentation Abstract)

CONTINENTAL AND OCEANIC MAGNETIC ANOMALIES: ENHANCEMENT THROUGH GRM

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William J. Hinze
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Earth-orbiting satellites over the past two decades have provided consistent global magnetic anomaly data sets which have given us unique insight on regional petrologic variations of the crust and upper mantle, and crustal thickness and thermal perturbations. Verification of the satellite magnetic data has been demonstrated by quantitative comparisons with aeromagnetic anomalies of the conterminous U.S. and western Canada. In contrast to the POGO and MAGSAT satellites, the GRM satellite system will orbit at a minimum elevation to provide significantly better resolved lithospheric magnetic anomalies for more detailed and improved geologic analysis. In addition, GRM will measure corresponding gravity anomalies to enhance our understanding of the gravity field for vast regions of the earth which are largely inaccessible to more conventional surface mapping. Crustal studies will greatly benefit from the dual data sets as modeling has shown that lithospheric sources of long-wavelength magnetic anomalies frequently involve density variations which may produce detectable gravity anomalies at satellite elevations. Furthermore, GRM will provide an important replication of lithospheric magnetic anomalies as an aid to identifying and extracting these anomalies from satellite magnetic measurements.

After the question of the formation of the earth itself, the most fundamental problem of the geosciences concerns the origin and characterization of the continents and oceans. An essential difference in the earth is between the continents and the oceans which is reflected in gravity via the Bouguer anomaly. However, as in the case of free-air and isostatic gravity anomalies, satellite magnetic measurements indicate no overwhelming difference between these regions. This is illustrated in Figure 1 which shows scalar 2°-averaged MAGSAT anomalies differentially reduced to the radial pole of intensity 60,000 nT at 400 km elevation for the eastern Pacific Ocean, North and South America, the Atlantic Ocean, and Euro-Africa. These radially polarized anomalies have been adjusted for differential inclination, declination and intensity effects of the geomagnetic field, so that in principle these anomalies directly reflect the geometric and magnetic polarization attributes of crustal magnetic sources. Characteristics of the data given in Figure 1 include the amplitude ra[illegible] (AR), amplitude mean (AM), contour interval (CI), and the normalizatio[illegible]plitude (AMP) for the radially polarizing field.

A subtle indication of the difference between oceans and continents is obtained by computing mean magnetic anomalies for the region shown in Figure 1. The analysis indicates that the mean magnetic anomaly of the continents (0.3 nT) is greater than the average for the oceans (-1.8 nT). This observation is compatible with the shallow crust of the ocean basins and evidence that suggests that the Moho is a magnetic boundary between crustal magnetic and upper mantle non-magnetic rocks. However, this result may be muted by remanence effects which for regional crustal magnetic sources are generally not well known and at MAGSAT elevations are not well resolved.

Low-level observations of the oceans indicate that most of the magnetic anomalies reflect the age of the crust and are caused by the acquisition of remanent magnetization in the reversing magnetic field as the rocks pass through their Curie Point. However, as shown in Figure 1, only the broader scale Mesozoic and Cretaceous quiet zones seem to be clearly affiliated, respectively, with pronounced negative and positive radially polarized anomalies at MAGSAT elevations. In contrast, the satellite elevation magnetic anomalies of the continents seem to have a predominance of induction effects. There are remanent effects, but these are characteristically high wavenumber anomalies and are attenuated at higher elevations in the continental areas. The increased anomaly resolution derived from GRM's 160 km elevation orbits will significantly contribute to an understanding of the role which remanence has in causing regional anomalies of the oceans and continents.

Continental satellite magnetic data show an apparent sharp truncation and even parallelism of the anomalies along the leading edges of the North and South American plates, whereas across trailing plate continental margins prominent anomalies tend to continue into the ocean. Detailed analysis of the MAGSAT orbital data for South America indicates that the trailing edge anomalies have no apparent relationship to external fields, so these anomalies appear to be internally derived. Many of these anomalies show a striking parallelism with the tracks of hotspots particularly in the south Atlantic, although there is little consistency in the sign of the radially polarized anomalies and the hotspot tracks. Gravity and bathymetric correlations also suggest possible affiliation of some of these anomalies with subsided continental fragments. Clearly, information on these features is very limited and their origin is an important area of inquiry. High resolution magnetic data and correlative gravity anomalies provided by GRM will significantly facilitate understanding their origin and possible role in the evolution and dynamics of the continents and oceans.

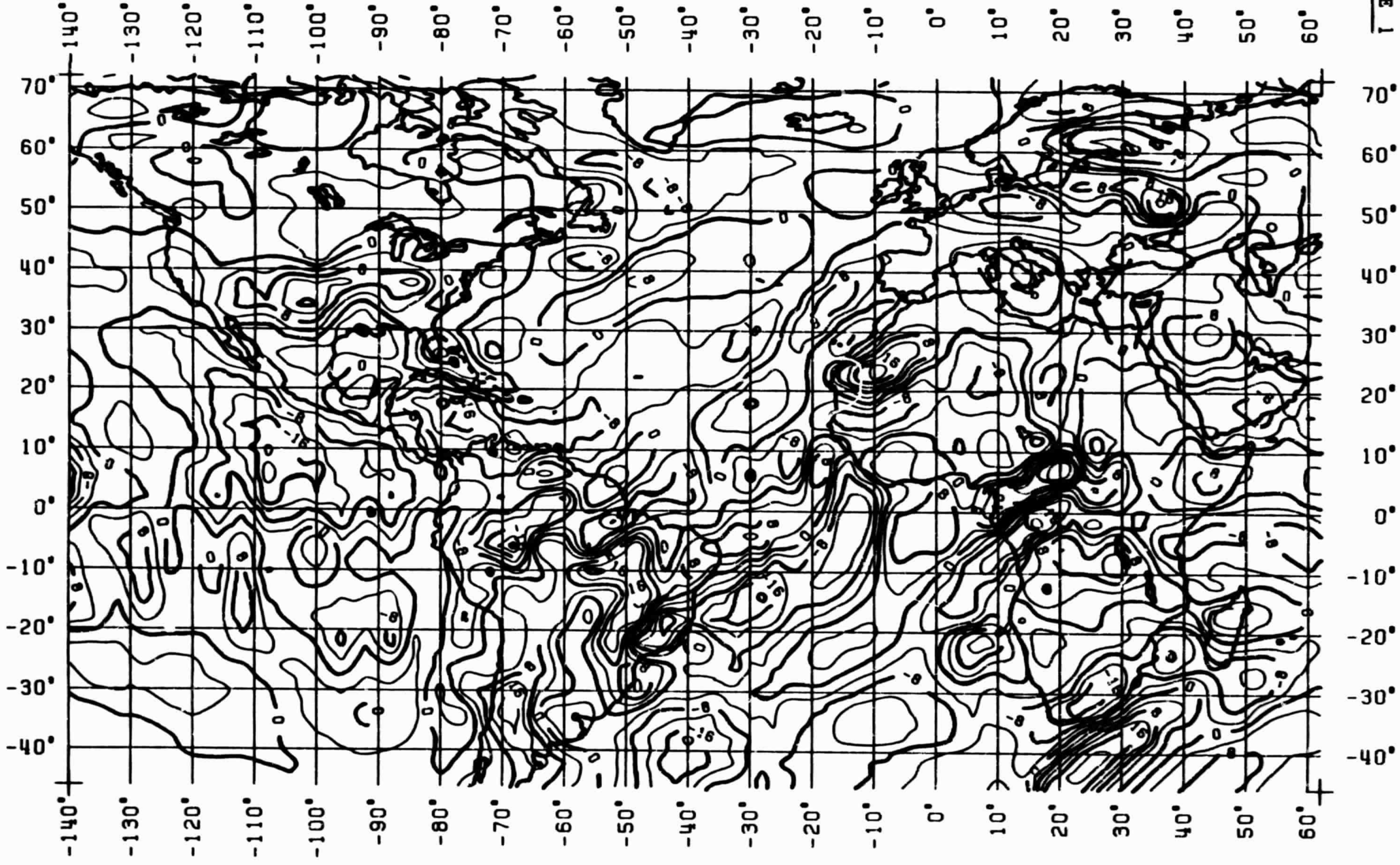
The radially polarized anomalies of Figure 1 permit testing the reconstruction of the continents prior to the origin of the present day Atlantic Ocean in the Mesozoic Era. Indeed, as demonstrated in Figure 2, the radially polarized MAGSAT anomalies of North and South America, Euro-Africa, India, Australia and Antarctica exhibit remarkably detailed correlation of regional magnetic crustal sources across rifted margins when plotted on a reconstruction of Pangea. Obviously, these results suggest great ages for the geologic conditions which these anomalies desribe and provide new and fundamental constraints on the geologic evolution of the continents. The high resolution regional magnetic and correlative gravity anomaly data potentially available from the GRM offer the clear promise to improve quantitative geologic modeling of these features and to detail their development through geologic time.

RADIALLY POLARIZED <2°> MAGSAT MAGNETIC ANOMALIES

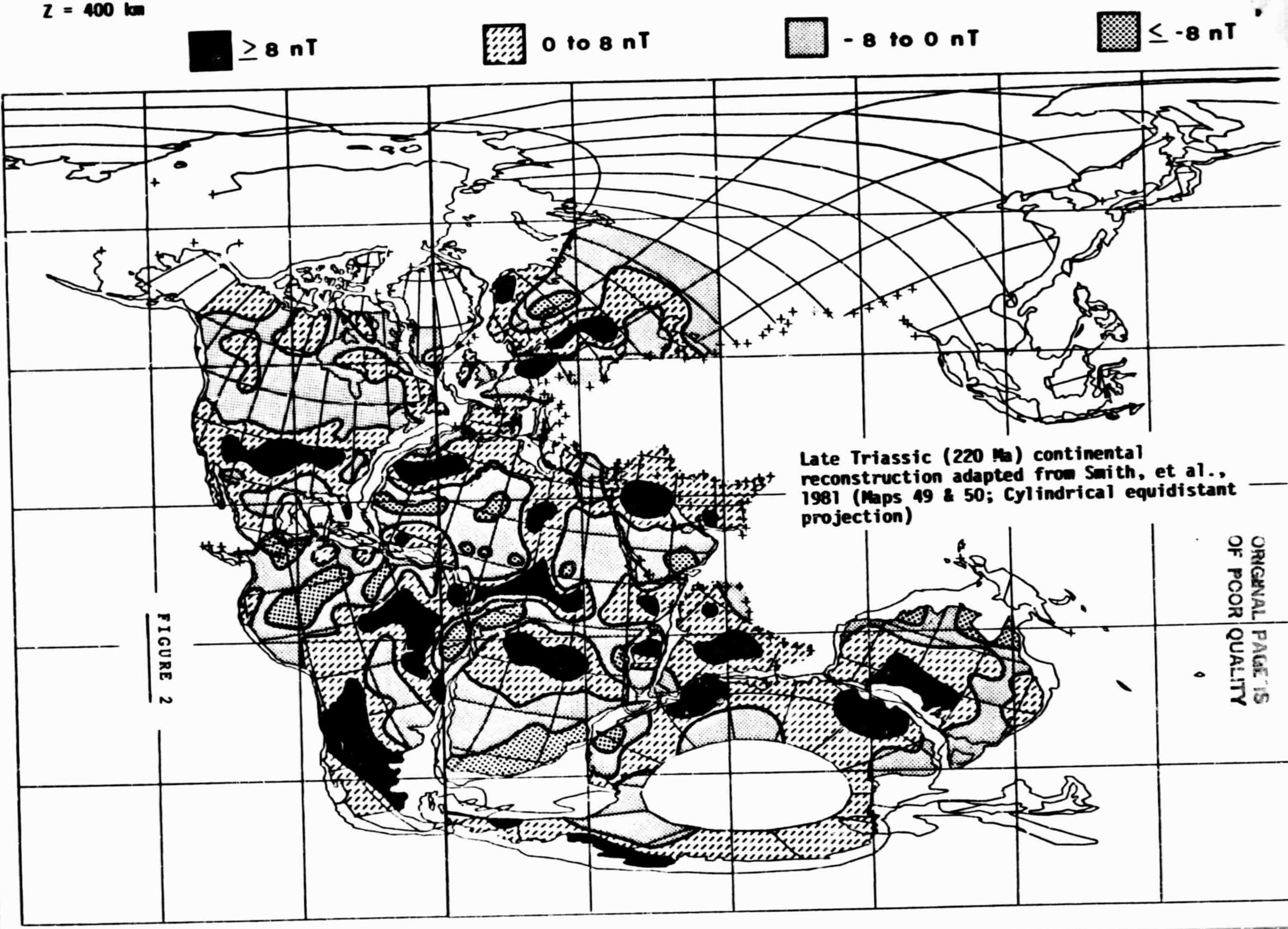
Z = 400 km AMP = 60,000 nT

AR = [32.8, −25.1] nT CI = 4 nT AM = −0.8 nT

FIGURE 1



PANGEA AND RADIALLY POLARIZED <2°> MAGSAT MAGNETIC ANOMALIES



Late Triassic (220 Ma) continental reconstruction adapted from Smith, et al., 1981 (Maps 49 & 50; Cylindrical equidistant projection)

FIGURE 2

D14

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CONTINENTAL MAGNETIC ANOMALY CONSTRAINTS ON CONTINENTAL RECONSTRUCTION

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Crustal magnetic anomalies mapped by the MAGSAT satellite for North and South America, Europe, Africa, India, Australia and Antarctica and adjacent marine areas have been adjusted to a common elevation of 400 km and differentially reduced to the radial pole of intensity 60,000 nT. These radially polarized anomalies are normalized for differential inclination, declination and intensity effects of the geomagnetic field, so that in principle they directly reflected the geometric and magnetic polarization attributes of sources which include regional petrologic variations of the crust and upper mantle, and crustal thickness and thermal perturbations. Continental anomalies demonstrate remarkably detailed correlation of regional magnetic sources across rifted margins when plotted on a reconstruction of Pangea. Accordingly, they suggest further fundamental constraints on the geologic evolution of the continents and their reconstructions.

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D15

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REGIONAL MAGNETIC ANOMALY CONSTRAINTS ON CONTINENTAL RIFTING

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Abstract

Lithospheric magnetic anomalies mapped by the MAGSAT satellite for North and South America, Europe, Africa, India, Australia, Antarctica, and adjacent marine areas have been adjusted to a common elevation of 400 km and differentially reduced to the radial pole of intensity 60,000 nT. In principle, these radially polarized anomalies are normalized for differential inclination, declination and intensity effects of the geomagnetic field. Hence, they directly reflect the geometric and magnetic polarization attributes of lithospheric magnetic sources which include regional petrologic variations of the crust and upper mantle and crustal thickness and thermal perturbations. Continental anomalies demonstrate remarkably detailed correlation of regional lithospheric magnetic sources across rifted margins when plotted on a reconstruction of Pangea. Accordingly, these anomalies provide new and fundamental constraints on the geologic evolution and dynamics of the continents and oceans.

Introduction

Satellite magnetic observations are providing new insight into the structure and petrophysics of the earth's crust. Initial compilations of satellite magnetic anomalies for lithospheric applications involved scalar magnetometer observations for the conterminous U.S. collected by the Russian COSMOS 49 satellite at 375 km mean altitude (Zietz _et al_., 1970), as well as quasiglobal 1°-averages of scalar anomaly data derived from NASA's three Polar Orbiting Geophysical Observatory (POGO) satellites over orbital elevations ranging between 400 and 700 km (Regan _et al_., 1975). For geologic analysis, however, the best resolved anomaly data set to date has been obtained by NASA's most recent magnetic satellite mission, MAGSAT, which was orbited at altitudes ranging from 200 to 550 km (Langel, 1980 & 1982).

Satellite magnetic anomalies have a limited history of geological interpretation. However, as reviewed by Mayhew _et al_. (1985), the origins of these anomalies appear to include regional petrologic variations of the crust and upper mantle, and crustal thickness and thermal perturbations. Frey _et al_. (1983) have noted the geographic coincidence of many satellite magnetic anomalies with ancient shields and cratons, suggesting that these anomalies may be of great age and predate the breakup of Pangea. Indeed, they plotted predominantly total field POGO satellite magnetic anomalies directly on a Pangea reconstruction to show that prominent anomalies appear to abut each other along the rifted continental margins.

Previous studies, however, have been limited by the use of variable elevation magnetic anomalies which are also distorted to various degrees of severity by the attitude and intensity variations of the main geomagnetic field over the continents in their present configuration. The regional correlations of lithospheric magnetic sources for South America, Africa and India are particularly problematic when total field magnetic anomalies are used because these magnetic anomalies exhibit continuously variable relationships to their sources from the geomagnetic poles to the equator where inversion of the anomaly signs occurs.

To facilitate regional scale correlation analysis, however, total field magnetic anomalies can be adjusted for variable elevation and differential inclination, declination and intensity variations of the geomagnetic field by equivalent point source inversion (von Frese et al., 1981). This procedure involves least squares matrix inversion of magnetic anomaly data using an appropriate geomagnetic reference field model to determine magnetic susceptibilities for a spherically orthogonal array of point dipoles. An estimate of the magnetic anomalies at a common elevation and reduced to a radial (normal) pole of constant field strength is obtained by simply recomputing the equivalent point dipole anomalies at constant elevation assuming radial inclination at source and observation points and polarizing the dipoles by a uniform field strength. Geologic applications which demonstrate this procedure are given by von Frese et al. (1982a) for North America, Hinze et al. (1982) for South America and Olivier et al. (1982) for Europe and Africa.

If remanence can be ignored, then radially polarized anomalies are in principle centered over their sources and anomaly variations directly reflect the geometric and magnetic polarization variations of the lithospheric sources. This has profound implications for continental or global scale tectonic analyses as geologic source regions may be compared directly in terms of their radially polarized magnetic anomaly signatures. The degree to which continental remanent magnetization may affect regional magnetic anomalies remains uncertain, as the magnetic properties of the crust are not well known. However, thermal remanent effects which commonly complicate the magnetic analysis of upper crustal rocks are characteristically high wavenumber anomalies that are attenuated at satellite elevations. Within the lower crust, magnetic susceptibility will be increased over certain temperature ranges and thermal remanent magnetization will be decreased by the higher ambient temperatures and increased age of the rocks (Wasilewski _et al_., 1979). Furthermore, viscous magnetization directed along the earth's magnetic field will increase as temperature increases, thus enhancing total magnetization. In general, limited evidence to date tentatively suggests that remanent magnetization on a large scale in the crust is relatively unimportant (Mayhew, _et al_., 1985).

To investigate the reconstruction of the continents prior to the origin of the present day Atlantic Ocean in the Mesozoic Era, 2°-averaged MAGSAT anomalies produced by Langel _et al_. (1982) for North and South America, Euro-Africa, India and Australia, and 3°-averaged anomalies for Antarctica from Ritzwoller & Bentley (1983) were differentially reduced to the pole at constant elevation by equivalent point source inversion. Stable point dipole models were produced which fit the averaged anomalies with negligible error using the IGS'75 geomagnetic reference field model updated to 1980. The corresponding MAGSAT anomalies at 400 km elevation differentially reduced to the pole with a normalization intensity of 60,000 nT are plotted in Figure 1 on a late Triassic reconstruction of the continents after Smith _et al._ (1981).

Pangea and Radially Polarized 2°-Averaged MAGSAT Anomalies

When normalized by differential reduction to the pole, the MAGSAT data indicate remarkably detailed continuity of regional magnetic crustal anomaly sources across the rifted continental margins. The sources of the magnetic anomalies on the Pangea reconstruction are many and complex, and only a relative few have been quantitatively investigated using constraining geologic and ancillary geophysical data. These include aspects of the prominent positive U.S. transcontinental magnetic anomaly which consists of three peaks centered over the Colorado Plateau, the Anadarko Basin and the southern Cincinnati Arch in central Kentucky. The anomaly from the central peak eastwards corresponds to a well-defined regional trend of free-air gravity minima. This together with limited seismic evidence suggests that the transcontinental magnetic feature may characterize a region of thicker crust (von Frese et al., 1982a).

Isotopic evidence indicates that the central and eastern peaks delineate a middle Proterozoic terrane of basement rocks (Van Schmus & Bickford, 1981). To the west the central peak is separated from the Colorado Plateau by magnetic minima over the Rio Grande Rift which reflect thinned magnetic crust due to increased heat flow. To the east the transcontinental feature is also breached by minima which have been related by spherical earth modeling to the paleo-rift structure of the Mississippi Embayment (von Frese, 1982). Here however, crustal seismic P_n-velocities are anomalously high (Braile et al., 1984), so the decrease in crustal magnetization is probably related to a lithologic variation.

The Takatu and Amazon River rift systems of northeastern South America are also characterized by positive gravity and negative magnetic anomalies analogous to the regional inverse correlations observed for the Mississippi Embayment and Rio Grande Rift (Longacre et al., 1982). Synthesis of the radially polarized MAGSAT data with deep crustal magnetization constraints indicates tectonic models which relate the negative magnetic anomalies to a failed-rift component defining nonmagnetic blocks within the lower crust.

The prominent positive Bangui Anomaly of westcentral Africa correlates with regional heat flow and gravity minima (Olivier et al., 1982) and has been modeled by Regan & Marsh (1982) as originating from a major intracrustal lithologic feature. The Bangui Anomaly is bordered to the north by the Benue Rift and associated magnetic minima. The anomaly has a northward projection to the central Mediterranean Sea and an eastward extension onto Somalia which is breached by magnetic minima over the East African rift system. To the west across the Atlantic rift margin, the Bangui Anomaly projects magnetically as positive anomalies associated with the Sao Luiz Craton of northeastern Brazil and the Central Brazilian Shield. The magnetic signature of the Sao Luiz Craton also correlates well with the positive anomalies of the Precambrian Shield of southern northwest Africa. The Bangui Anomaly is bordered to the south by a pronounced magnetic minimum which troughs at its eastward extension over the Zaire Basin. This feature projects across the Atlantic rift margin as a comparable magnetic minimum over the Sao Francisco Craton.

The prominent magnetic minimum over the Cape Orogen in South Africa roughly corresponds with the East Antarctic minimum over Queen Maud Land and the minima of southern India and Madagascar. The Antarctic positive anomaly farther east over Enderby Land is generally consistent with the Indian positive over the northern shield and Himalayan rocks. The Antarctic high over Wilkes Land is reflected by a strikingly comparable positive anomaly overlying Archean-Proterozoic cratonic blocks of southcentral and western Australia. The prominent positive Australian anomaly is flanked on the west by a magnetic minimum which follows the western boundary of the Tasman Orogenic Zone and also includes the Eromanga Basin. This minimum may be related to an elevated Curie Point isotherm as Sass & Lachenbruch (1978) identify a high heat flow province here attributable to young magmatic heat sources within the crust. The magnetic low over the Alelaide and Tasman Orogens corresponds to an Antarctic minimum over the Ross Sea Embayment and

Transantarctic Mountains. This Antarctic minimum compliments an underlying anomalously thin crust with high heat flow (Ritzwoller & Bentley, 1983) which may be related to an ancient rift zone (Hayes & Davey, 1975) that probably was active 65 Ma ago during separation of Antarctica from Australia.

For the most part, the radially polarized anomalies are sufficiently consistent in amplitude and shape that they may be readily contoured across or along the rifted continental margins. However, exceptions occur because the trailing margins have been subjected to intense rifting and related thermal activity which potentially can lead to anomalies of the magnitude and scale that could be observed at MAGSAT elevations. Examples may include the lack of positive anomaly in Africa across the Gulf of Guinea in western Africa and in northwestern Africa in the vicinity of the Alpine age Atlas Mountains. However, the general lack of a significant long-wavelength anomaly focused on the continental joins testifies to the lack of broadscale igneous activity on the continental side of the rift which led to the present oceans.

The close correspondence of most of the radially polarized MAGSAT anomalies across the continental joins verifies the pre-Cretaceous origin of their magnetic lithospheric sources. However, there are places indicated by the magnetic data which may involve problems with respect to the continental reconstruction adopted in Figure 1. For example, the magnetically positive source region of Florida could be brought down to the vicinity of the join between northwestern Africa and northeastern South America to better accommodate the radially polarized anomalies. The worst correspondence of magnetic anomalies in Figure 1 involves the juxtaposition of the large positive of Madagascar with the pronounced minimum at the join to the eastcentral African coast. Geologic and bathymethric constraints permit attaching Madagascar at other points along the east African coast up to about 15° south of its position in Figure 1 (Powell et al., 1980). Magnetically, the preferred position is roughly 10° south of its location in Figure 1 (i.e., close to its present-day position), where the Madagascar high would correlate with a broad African positive magnetic anomaly overlying the Cubango Basin and an extensive region of Precambrian Shield rocks.

Conclusions

Radially polarized MAGSAT anomalies of North and South America, Euro-Africa, India, Australia and Antarctica demonstrate remarkably detailed correlation of regional magnetic lithospheric sources across rifted margins when plotted on a reconstruction of Pangea. These major magnetic features apparently preserve their integrity until a superimposed metamorphic event alters the magnitude and pattern of the anomalies. The longevity of continental scale magnetic anomalies contrasts markedly with that of regional gravity anomalies which tend to reflect predominantly isostatic adjustments associated with neo-tectonism. First observed as a result of NASA's magnetic satellite programs, these anomalies provide new and fundamental constraints on the geologic evolution and dynamics of the continents and oceans. Accordingly, satellite magnetic observations provide a further tool for investigating continental drift to compliment other lines of evidence in paleoclimatology, paleontology, paleomagnetism, and studies of the radiometric ages and geometric fit of the continents.

Acknowledgements

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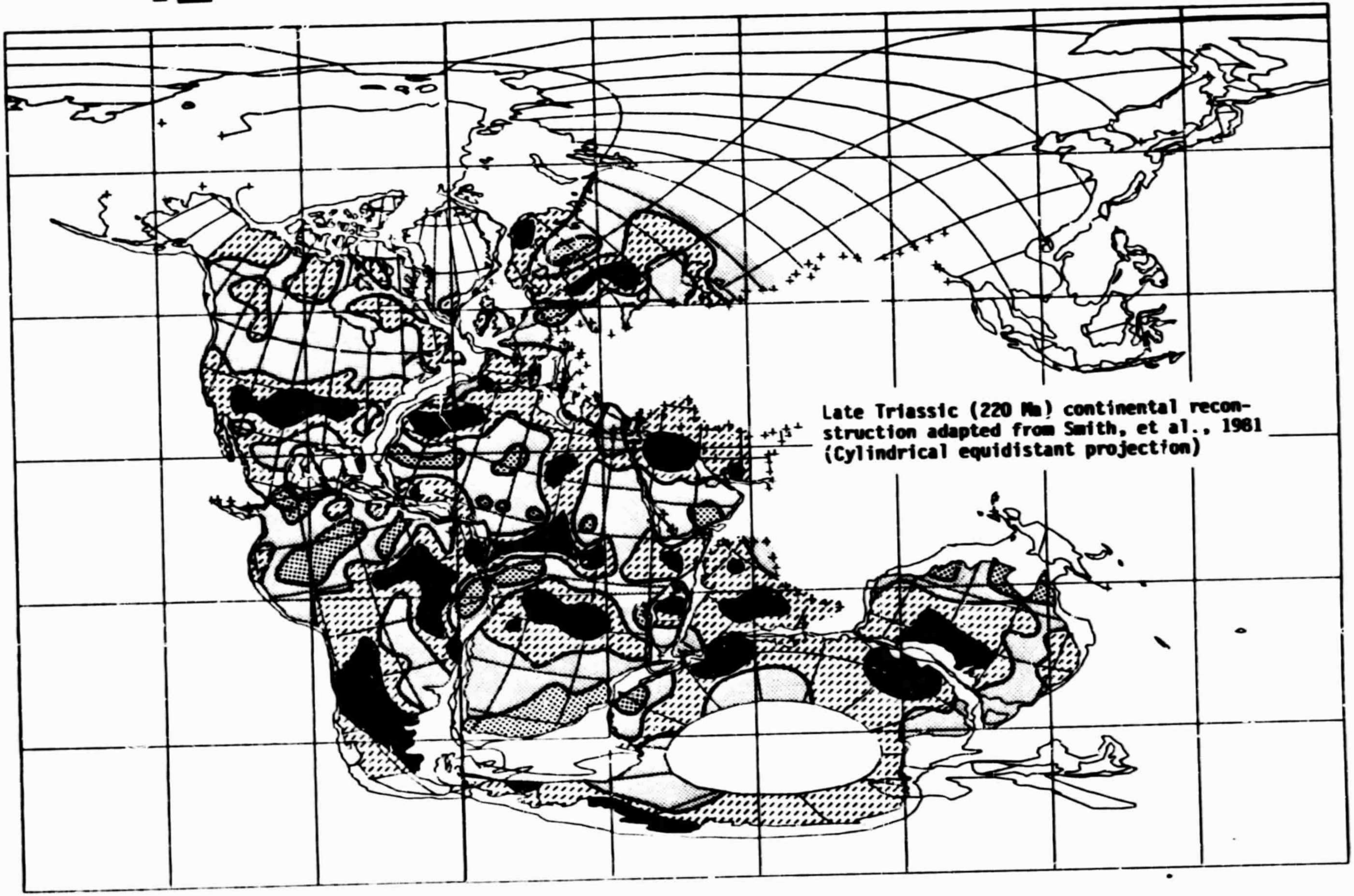
Figure Caption

Figure 1 Pangea and averaged MAGSAT scalar magnetic anomalies reduced to an elevation (Z) of 400 km and to a radial pole strength (AMP) of 60,000 nT.

PANGEA AND RADIALLY POLARIZED <2°> MAGSAT MAGNETIC ANOMALIES

8 nT ≥ ■ 0 to 8 nT ▨ Z = 400 km AMP = 60,000 nT ☐ - 8 to 0 nT ▩ ≤ -8nT



Late Triassic (220 Ma) continental reconstruction adapted from Smith, et al., 1981 (Cylindrical equidistant projection)

FIGURE 1