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STRUCTURE OF THE ST. FRANCOIS MOUNTAINS
AND SURROUNDING LEAD BELT, S.E. MISSOURI:
INFERENCES FROM THERMAL IR
AND OTHER DATA SETS

Quarterly Report 1/1/82 - 1/31/82
Quarterly Report 2/1/82 - 4/30/82

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May 11, 1982
1. PROBLEMS: No problems were encountered during our analyses.

2. ACCOMPLISHMENTS:

1. Considerable effort was expended during the interval from 11/1/81 to 4/30/82 in revising the manuscript that we submitted to the Journal of Geophysical Research in November, 1981. Although the paper was accepted in its original form, we felt that revision was needed. The manuscript dealt with the discovery of a Precambrian rift running NW-SE through Missouri as seen in both free air and Bouguer gravity anomalies and HCMM data. The revised manuscript is attached. We have substantially changed the paper, including the addition of magnetic field anomalies, basement rock types, and seismic refraction profile data for the area. Of importance to this study, we substantially revised the section on linears seen in processed HCMM data covering the area. Included in the revised paper is a discussion of what HCMM data were utilized and a map that shows linear features seen from a merged daytime thermal image with a shaded relief map of topography. Also drawn on the Figure (Figure 11 of the paper) are mapped faults and folds, and the outline of the rift running through the state. HCMM linears were mapped separately by three geologists, with the linears drawn on the figure being ones seen by all three people. HCMM linears in some cases correspond to mapped features, in some cases they are extensions of mapped features, and in some cases they do not correspond to any mapped structure. The linears correlate nicely with the trend of the Precambrian rift as seen in the gravity data, suggesting that the
linears are indeed related to the underlying basement structure. The pattern of faulting is consistent with uplift, suggesting that the rift is isostatically readjusting. HCMM data proved to be particularly useful because the synoptic coverage and the broad pixel width in effect filtered out all but regional-scale structures.

The reason that JGR paper took so long to revise and the reason that these quarterly reports are delayed is that we were invited by the editor of EOS (Transactions, American Geophysical Union) to submit a paper on our Missouri rift, stressing digital image processing of potential field and topographic data. That paper is also attached - it appeared in the May 4, 1982 issue of EOS, with our color gravity maps on the cover.

2. Attached are HCMM daytime thermal IR, night time thermal IR, and apparent thermal inertia images that have been contrast-enhanced and transformed to Mercator projections. Also attached is a daytime IR overlain onto a shaded relief map and an apparent thermal inertia image overlain onto a shaded relief map. Frame numbers are A-A0045-19420-2, A-A0045-19420-1, and A-A0044-08310-3. These products were processed and used as part of a Masters Thesis finished in May 1, 1982 by John Strebeck. In the thesis Strebeck examined correlations between the HCMM data products, linears, and geologic units. The significant results are included in the attached J.G.R. paper. The thesis reference would be:

Strebeck, J.W., 1982, Structure of the Precambrian basement in the Ozark Plateau as inferred from gravity and remote sensing data,
Strebeck now works with Mobil Oil Corp., Dallas, Texas, where he should be joining their remote sensing/image processing group after preliminary "indoctrination" into the company.

3. We have begun to examine the difference in information content between day IR, night IR, albedo, and thermal inertia images. For the frames listed above, the day IR image was found to have the greatest discriminability for rock types and with regard to structural patterns. The reason seems to be primarily due to topography in that most geologic units in southern Missouri exhibit a distinctive topography and most structural features that we have mapped are controlled by the distribution of stream valleys. The day IR image best expresses these distributions because the brightness (relative temperature) is sensitive to differential solar heating due to slopes. For the three frames discussed above, the day IR contained 0.63 of the fractional variance of the three data sets, while the night IR contained 0.12 and the albedo data contained 0.25. Apparent thermal inertia images should provide an indication both of topographic roughness (since slope effects on differential solar heating have not been removed) and an indication of thermal anomalies that are controlled by variations in soil or rock exposure, vegetation type, and moisture content. We are presently concentrating on delineation of these latter features, i.e., identifying linears in southern Missouri that are not directly controlled by topography.
4. We have also coded the thermal IR and albedo data as hue, saturation, and brightness values to generate a color display, following the work of Haydn, University of Munich. However, we find that the transformation used by Haydn to go from hue, saturation, and brightness to red, green, and blue images is only correct for relatively narrow hue range. A universal derivation is attached, along with a color print where the day, night, and albedo images have been encoded as hue, brightness; and saturation. A color print is also included that has the apparent thermal inertia coded in a color spectrum and overlain onto a shaded relief map.

3. FUTURE WORK:

1. Presentation of results of analyses of HCMM data as part of a paper to be presented at COSPAR, Ottawa, Canada, on May 19, 1982, entitled:

Arvidson, R.E., E.A. Guinness, J.W. Strebeck, 1982, Structure of the Midcontinent basement - Topography, gravity, seismic, and remote sensing data.

and included in the session on Geophysical Measurements of Major Crustal Features From Space.

2. An oral presentation of our HCMM work at the spring meeting of the American Geophysical Union, Wash., DC. during the week of May 31, 1982. The abstract is attached and entitled:

Given 3 images and treating each as a separate component of color, it is possible to create a color image which contains information from all three original datasets. One possible application is to take HCMN albedo, day IR, and night IR and treat them as brightness (r), hue (α), and saturation (γ) respectively. Each point (r, α, γ) can be mapped into a point in "normal" color space; that is, a red, blue, and green intensity level.

Method: Solve for f in:

\[
\begin{bmatrix}
B \\
G \\
R
\end{bmatrix} = f(\begin{bmatrix}
G \\
R
\end{bmatrix})
\]

r = blue intensity
G = green intensity
R = red intensity

Geometry:

A data vector is defined by (r, α, γ) where

\[ r = \text{magnitude (length)} \]
\[ γ = \text{angle between the gray vector and data vector} \]

To understand α, we look at a plane cutting through the sphere of radius r. The plane is \perp to the gray vector and contains the data point plus a circular cross-section of the sphere.
\( \alpha \) is defined by a line drawn in our plane which intersects both the gray vector point shown and the point defined by the intersection of the plane and the \( R \)-axis. This is the line \( L \). Then \( \alpha \) is the negative angle (in the sense of the right-hand-rule using the gray vector) between \( L \) and the line connecting the data point and the gray vector.

Set up a coordinate system \( O \) with axes \( x, y \), and \( z \) such that the \( y \)-axis lies in the \( B-G \) plane and the \( x \)-axis lies along the gray vector.

Then in \( O \), we have

\[
D = r \sin \gamma
\]

where \( D \) is the perpendicular distance from data point to \( x \)-axis (gray vector) and the \( x \)-coordinate of the data point is

\[
x_1 = r \cos \gamma
\]
Now, to find \( y_1 \) and \( z_1 \), use \( \alpha \):

\[
y_1 = D \sin \alpha
\]

\[
z_1 = D \cos \alpha
\]

So from \((x, y) \Rightarrow (x_1, y_1)\)

To set \( B, G, R \) from \( x, y, z \) we simply rotate coordinate axes into alignment.

\( \text{YROT is the angle through which the } \mathcal{O} \text{ coord. system must be rotated about the } y\text{-axis to put the } x\text{-axis into the } B-G \text{ plane and the } z\text{-axis into alignment with the } R\text{-axis} \)

\[
\text{YROT} = \tan^{-1}\left(\frac{\sqrt{2}}{2}\right) \approx 35.26^\circ
\]

It is then a simple matter to rotate thru -45° about the \( z\)-axis and align the \( x \) and \( y \) axes to the \( B \) and \( G \) axes respectively.
Boundary condition: Normalizing $\gamma$

Since the input values of $\gamma$ range from 0 to 255 and the allowed angles $\alpha$ range from $0^\circ$ to $\tan^{-1}(\sqrt{2})$ ($\sim 55^\circ$), we must fit $\gamma$ into that range.

There is an additional problem. Taking $\gamma = \gamma_{\text{max}}$ and using all possible values of $\alpha$ ($0^\circ$ to $360^\circ$), a cone is swept out. The cone is shown below in relation to the R-G, G-B, and B-R planes. The plane of the paper is the same plane used before to illustrate $\alpha$; it is normal to the gray vector.

The point $V$ is the intersection of our plane and the gray vector. Taking $V = (255, 0, 0)$ ($x = 255, y = 0, z = 0$), it is quite obvious that $\gamma_{\text{max}}(\alpha = 0^\circ) \neq \gamma_{\text{max}}(\alpha = 55^\circ)$.

That is, if $\gamma = 55^\circ$ were used for all $\alpha$'s, then dark points would be created that would fall to the outside of the triangle created by the RGB coordinate system. In effect, the results would be negative color intensities.

We are helped along by several facts:

1) $\gamma_{\text{max}}$, the angular distance between the gray vector and any color axis (R, G, or B) is given by $\tan^{-1}(\sqrt{2})$

2) $\gamma_{\text{min}}$, the angle between the gray vector and any color plane along the normal to that plane is given by $\tan^{-1}(\sqrt{2})$
3) \( Y \) is at a distance of 255 units from the origin of both the color coordinates and \( O \).

To find \( Y' \), the normalizing factor, we must then find a distance \( \text{DIST} \) where

\[
\text{DIST} \text{ is a function of } \alpha \text{ such that}
\]

\[
\text{DIST} (0^\circ) = \text{DIST} (120^\circ) = \text{DIST} (240^\circ) = \text{DIST} (360^\circ)
\]

and

\[
y' = \tan^{-1} \left( \frac{\text{DIST}}{255} \right)
\]

\( y' \) varies from \( \tan^{-1}(1/2) \) to \( \tan^{-1}(\sqrt{3}) \).

There are three cases for \( y' (\alpha) \).

**Case I**) \( 0^\circ \leq \alpha \leq 120^\circ \)

By the Law of Sines,

\[
\frac{\sin 30^\circ}{\sin (150^\circ - \alpha)} = \frac{\text{DIST}}{D'}
\]

\( \text{DIST} = \frac{.5D'}{\sin (150^\circ - \alpha)} \)

**Case II**) \( 120^\circ \leq \alpha \leq 240^\circ \)

\( c = (270^\circ - 30^\circ) - \alpha = 240^\circ - \alpha \)

and

\[
\frac{\sin 30^\circ}{\sin (150^\circ - c)} = \frac{\text{DIST}_2}{D'}
\]

\( \text{DIST}_2 = \frac{.5D}{\sin (90^\circ - \alpha)} = \frac{.5D}{\cos \alpha} \)
Case III) \( \alpha > 240^\circ \)

\[
\begin{align*}
\gamma &= \tan^{-1} \left( \frac{\text{DIST}_3}{255} \right) \\
\gamma &= \gamma_0 \cdot \text{DN} \times \left( \frac{\gamma}{255 \cdot \text{DN}} \right)
\end{align*}
\]

Next we find \( D' \)

From the figure to the left, since \( \gamma_{\text{max}} = \tan^{-1} (\sqrt{2}) \)
and \( \gamma_{\text{max}} = \tan^{-1} \left( \frac{D'}{255} \right) \)

\( D' = \sqrt{2} \cdot 255 \)

So finally we can take

\[
\gamma = \frac{255}{255} \times \tan^{-1} \left( \frac{D_n}{\sqrt{2}} \right) \quad n = 1, 2, 3
\]

\[
D_n = \begin{cases} 
\sqrt{\sin (150^\circ - \alpha)} & 0^\circ \leq \alpha \leq 120^\circ \quad n = 1 \\
-\frac{\cos \alpha}{\sin (30^\circ - \alpha)} & 120^\circ < \alpha < 240^\circ \quad n = 2 \\
\frac{1}{\sin (30^\circ - \alpha)} & 240^\circ \leq \alpha \leq 360^\circ \quad n = 3
\end{cases}
\]
IDENTIFICATION OF A PRECAMBRIAN RIFT THROUGH MISSOURI BY DIGITAL IMAGE PROCESSING OF GEOPHYSICAL AND GEOLOGICAL DATA

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ABSTRACT

Digital free air and Bouguer gravity anomaly images have been constructed for the region bordered by 25° to 49° N. lat. and 80° to 110° W. long. from approximately 287,000 station readings. The technique used to interpolate between station locations was based on a two dimensional spatial filter, where the average of the anomaly values located within the filter area was computed. The images contain as many as 256 contours (values in byte variable), so that subtle anomaly patterns can be identified and traced with much greater certainty than on most contour maps. A newly discovered feature in the midcontinent is a gravity low that begins at a break in the midcontinent gravity high in S.E. Nebraska, extends across Missouri in a NW-SE direction, and intersects the Mississippi Valley granite to form the Pascola arch. The anomaly varies from 120 to 160 km in width, extends about 700 km, and has a medial gravity high for part of its length. The maximum Bouguer amplitude of the anomaly is approximately 34 milligals below values for the surrounding region and cannot be explained on the basis of a thickened section of Paleozoic sedimentary rock. The gravity data and the sparse seismic refraction data for the region are consistent with an increased crustal thickness beneath the gravity low. Discrete positive magnetic anomalies, some of which correspond to mafic intrusives, are concentrated along the borders of the gravity low. Digitally enhanced thermal infrared images from the Heat Capacity Mapping Mission show a distinct alignment of linear structures with the gravity feature. The linears in some cases correspond to mapped
high angle normal faults, to drape folds over relief within the Precambrian basement, and in some cases to extensions of mapped structures. The gravity anomaly also cuts across the major Precambrian boundary in S.E. Missouri marking the change from older, sheared granites and metasedimentary rocks, to younger granites and rhyolites. Given the cumulative evidence, the gravity anomaly is probably the present expression of a failed arm of a rifting event, perhaps one associated with the spreading that led to or preceded formation of the granite and rhyolite terrain of southern Missouri.

INTRODUCTION

We have been pursuing relationships between the pattern, age, and origin of structural features within the Precambrian basement rocks of southern Missouri and the locations and genesis of ore deposits. The area is a well known lead mining district, where Mississippi Valley type Pb-Zn-Cu ores have accumulated in Cambrian carbonate rocks associated with stromatolitic reef and backreef facies (Gerdemann and Meyers, 1972). The location of these facies was controlled by the location of the shore line, which was in turn controlled by the pattern of faulting of the Precambrian basement (Grundmann, 1977; Sweeny et al., 1977; Evans, 1977; Paarlberg and Evans, 1977; Mouat and Clendenin, 1977). In addition, iron ores of magmatic origin can be found in the Precambrian basement rocks along fracture zones (Kisvarsanyi, 1976).

Structural studies of basement rocks in southern Missouri have been pursued for a considerable amount of time (see: Kisvarsanyi
and Kisvarsanyi, 1976), and a significant amount of information has been gained on the distribution of Precambrian rock types and ages (Kisvarsanyi, 1974; Bickford et al., 1981; VanSchmus and Bickford, 1981). However, little has been done in terms of understanding how the structure of the region is related to the overall structural configuration of the midcontinent or how such features are related to the structural history of the area. In this paper we utilize digital image processing techniques to reduce and display a variety of potential field, topography, geologic, and remote sensing data for the midcontinent. The intent is to delineate how structural patterns in southern Missouri are related to the broader features of the midcontinent.

DISCRIPITION OF DATA AND PROCESSING METHODS

Digital image processing techniques have a potentially wide range of utility for display and analysis of geographically (i.e., array) oriented data sets. In our case, data covering the midcontinent were processed on a PDP-11/34 minicomputer with interactive image display peripherals, using standard digital image enhancement, filtering, and geometric operations. The reader is referred to standard texts such as Moik (1980) for further information on image processing techniques, and to Arvidson et al. (1982) for examples of the utility of image processing in processing, display, and interpretation of topographic and gravity data for the continental United States.

National Oceanic and Atmospheric Administration (NOAA) digital
topography, together with land station measurements of gravitational acceleration, comprise two important data sets that we employed in the study. The area chosen for analysis of the topography and gravity ranges from 25° to 49° N. lat. and 80° to 110° W. long., thereby covering regions from the eastern edge of the Rockies on the west to the Appalachians on the east, and from the Superior Province on the north, to the Gulf of Mexico on the south. The topography consists of average elevations for areas covering 30 seconds in both latitude and in longitude. Gravity stations are typically spaced three km apart, but vary between hundreds of meters to ten kilometers over the study area. The gravity data were reduced to free air and to Bouguer anomalies courtesy of the Defense Mapping Aerospace Agency Center, St. Louis, Missouri. The reference field at sea level used was based on the 1967 International Gravity Formula, with all the data referenced to the 1971 International Gravity Standardization Net. Bouguer anomalies were computed based on a slab model with a density of 2.67 gm/cm³. No local terrain corrections were included.

Magnetic anomalies were also included in the analysis. Unfortunately, digital data for the region were not available at a reasonable cost. Consequently we restricted inclusion of magnetic coverage to the state of Missouri, based on the 1943 statewide contour map of vertical field intensity anomalies. The state map was photographed onto film and then the film was digitized, resulting in a digital image of magnetic anomaly contours for Missouri. Similarly, the basement rock type map for the midcontinent compiled by Bickford et al. (1981) and VanSchmus and
Bickford (1981) was transformed to a digital format for use in comparison with other data sets.

Other digital data sets that were utilized in this work included Heat Capacity Mapping Mission (HCMM) images. HCMM consisted of a satellite with sensors capable of imaging the surface in the visible to the reflected infrared (0.5 to 1.1 micrometers) and in the thermal infrared (10.5 to 12.5 micrometers) (Price, 1977). Each image element in the HCMM data covers about 500m across and one scene covers about 700 km in width and in height. The visible-reflected infrared sensor was used to measure the broad band albedo of the surface, while thermal infrared data acquired during the day and night provided information on the magnitude of diurnal temperature changes. These parameters can be used to solve for the thermal inertia of the surface, a thermophysical property that depends on the density, thermal conductivity, and specific heat (Kahle et al., 1976). Thermal infrared data, including estimates of thermal inertia, have been shown to be useful in delineating structural features in a variety of geological contexts (Sabins, 1969; Offield et al., 1975; Watson, 1981). HCMM data were included in this study both because of the applicability of thermal data in structural studies and because the synoptic view is appropriate for examining the surface expression of regional-scale structures. HCMM images for southern Missouri were contrast enhanced, digitally registered to one another, and displayed in a variety of formats designed to emphasize structural trends. Details of HCMM processing techniques will be discussed in a later section.

The first step in the analysis of topographic and gravity data
was to scale the dynamic range of the data to fit within the range of a byte variable (i.e., 8 bits or 256 discrete values). The byte data were then stored in image arrays, registered to a common base if needed, and processed. Final displays were transformed to Mercator projections and overlayed with latitude-longitude grids. The byte-encoded topographic data were first stored in an array with 30 second spacing in both latitude and longitude. The data could be displayed as an image if the byte-encoded values were converted to brightness or to color values. Alternatively, a shaded relief image could be constructed if a photometric function for the surface is assumed. Figure 1 shows a shaded relief image transformed to a Mercator projection and depicting topography under the assumption that the surface obeys Lommel-Seeliger scattering law (Batson et al., 1975). The simulated sum is from the northeast at 20° above the horizon.

Generation of images from the gravity anomaly values is more complicated than generating displays from the topographic data. The reason is that the gravity stations are not located along regular grid intersections. We chose a simple, but powerful spatial filtering technique for interpolating between station locations. The byte-encoded anomaly values were first assigned to array locations closest to the station locations. This procedure produced an array in part occupied by valid data and in part occupied by blank zones. The filtering algorithm that we then applied was developed by Eliason and Soderblom (1977), used to produce topographic maps from the Pioneer-Venus altimetry data (Pettengill et al., 1980), and applied to generating gravity images for the
continental United States by Arvidson et al. (1982). The technique involves use of a spatial filter of \(N \times N\) elements. The average of the valid data points within any given filter location is computed and used to replace the midpoint value, but only if a valid datum does not already exist at that array location. In practice, the gravity data were processed using several filter passes, beginning with a \(3 \times 3\) element filter and ending with a \(21 \times 21\) element filter. The choice of filter sizes was governed by station spacings, which varied from hundreds of meters to ten kilometers. The result is an interpolated data set, except for regions that had so few valid data points that a user-defined threshold was not met. In our case, we set the threshold so that at least 20\% of the elements for any filter position would have to have been occupied by valid data for an interpolation calculation to proceed.

The interpolated gravity data can be displayed as a gray tone image, as is done in Figure 2 for free air anomalies. Black areas in the image correspond to zones with too few stations to allow valid interpolations. The gravity data can also be displayed as a shaded relief image, where gravity highs and lows are illuminated as if they were hills and valleys. Figure 3 is a shaded relief image of the free air anomalies with the simulated sun placed at 15° above the northeastern horizon.

The gravity anomaly images displayed in Figures 2 and 3 and equivalent Bouguer anomaly presentations have been checked against published maps (e.g. Woolard and Joesting, 1964; McGinnis et al., 1979; Simpson and Goodson, 1981). Generally the images and published maps correspond. However, the images have intrinsically
more information displayed, for at least three reasons. First, the grid spacing used to interpolate between station readings is more closely spaced than the spacing used to generate most published continental-wide contour maps. Second, there can be as many contour intervals in our displays as there are values in a byte (256). Third, because of the particular filtering algorithm used, areas with closely spaced stations retain local details of anomaly patterns. For instance, Figures 2 and 3 show a major gravity feature (free air low) that begins at a break in the midcontinent gravity high and extends about 700 km to the southeast. One of the distinguishing aspects of this feature is not the amplitude of the low but rather the sharp gravity gradient associated with the edges of the anomaly. Although sections of the feature have been noted in the past (see: Phelan, 1969; Cordell, 1979; Russ, 1981), the images shown in Figures 2 and 3 provide new information and a broader perspective that show the trend and location much more accurately than can be seen in published maps.

Finally, an important aspect of comparing data sets is the ability to merge or overlay one data set onto another to produce a visual display that maximizes the eye's ability to see correlations between the data sets. A useful technique is to allow one data set (gravity anomalies, for instance) to control the hue (dominant wavelength) and saturation (degree of purity) of a color image, while another data set (topography, for instance) controls the color brightness (Arvidson et al., 1982). Also, it is possible to combine values of a given parameter with a shaded relief presentation of that parameter by allowing the value to control the color hue and
saturation, while the local gradient, expressed in shaded relief form, controls the brightness (Pettengill et al., 1980; Kobrik, 1982). For example, Figure 4 is a version of the free air image where the anomaly values have been color-coded and overlain onto a shaded relief version of the anomalies. The effect is to produce an enhancement showing information related both to the value of the anomaly and to the local gravity gradient.

BASEMENT STRUCTURE IN MISSOURI AS DEFINED BY GRAVITY ANOMALIES AND SEISMIC PROFILES

Figure 5 is a sketch map showing the major structural features seen in the free air anomaly images shown in Figures 2, 3, and 4 and in Bouguer images covering the same region. The free air data facilitated mapping of major topographic features associated with the Cordillera, Ouachitas, and the Appalachians. The Bouguer data provided new information that allowed us, for instance, to map the strong positive anomalies associated with the Mississippi embayment.

The midcontinent gravity high is a major gravity anomaly in the midcontinent. In our data this feature has a maximum free air anomaly of 85 milligals and a maximum Bouguer anomaly of 50 milligals. The midcontinent gravity high is about 70 km wide, contains Keewanawan basalts that date at 1.1 Ga, and has been interpreted as a failed continental rift (Chase and Gilmer, 1973). Flanking lows on either side of the high have been modeled as thick (several kilometers) arkosic sediments deposited as the load associated with the basalts caused regional subsidence.
Considerable structure also be seen in the greenstone-granitic terrain of the Superior Province located to the northwest of the midcontinent gravity high. The Wisconsin Arch, the Ouachitas, and the Wichita-Arбuckle system are just a few of the other features that have a recognizable gravity signatures. For reference, the Quachitas have a maximum free air and Bouguer anomaly magnitudes of 76 and 54 milligals below the surrounding regions.

A subtle, but pervasive gravity feature seen in both the free air and Bouguer images is a linear low that begins at a break near the southeastern end of the midcontinent gravity high (40.6° N. lat., 96° W. long.), strikes in a southeasterly direction, and extends to the Mississippi Embayment (36° N. lat., 90° W. long.). The low varies between 120 to about 160 km in width, extends about 700 km in length, and for part of its length exhibits a medial gravity high. The maximum Bouguer anomaly associated with the low is about 34 milligals below values for surrounding regions. The feature begins just to the northwest of Missouri and ends just beyond the southeastern boundary of the state. We therefore informally refer to the feature as the Missouri gravity low. As discussed in Arvidson et al. (1982), the intersection of the Missouri gravity low with the Mississippi Valley graben as defined by Kane et al. (1981), is the site of the majority of the microseismic epicenters recorded in the 1970's by the St. Louis University seismic network (Stauder et al., 1977). In addition, the northern boundary of the intersection is the site of the circular Bloomfield anomaly, while the southern boundary is the site of the Covington anomaly. Both features can be seen in the free air and
Bouguer data as distinct, circular positive anomalies. Kane et al. (1981) suggest that these two anomalies, which are also positive magnetic anomalies, are due to intrusions of magmas during the Mesozoic Era. The intersection of the Missouri gravity low and the Mississippi Valley graben is also the site of the Pascola arch as defined by Phelan (1969) and Ervin and McGinnis (1975).

Several gravity profiles were generated across the Missouri gravity low to illustrate its form and to model subsurface density configurations. The location of the southern-most profile is shown in the sketch map in Figure 5. Values for the topography, free air, and Bouguer anomalies for this profile are shown in Figure 6. A simple model for the anomaly would be a thickened section of relatively low density sedimentary rock overlying a downwarped region of the Precambrian basement. However, drill holes covering the general area of the profile A-A' indicate a typical cover of Paleozoic sediments of only a few hundred meters over the low, with no discernable thinning on either side (Kisvarsanyi, 1974). Thus, the gravity signature must be related to an inhomogeneity within the Precambrian basement rocks. Cordell (1979) reached a similar conclusion for that part of the low located in the southwestern part of the Rolla quadrangle (37° to 38° N. lat.; 90° to 92° W. long.), where there is a slight local thickening of sedimentary cover over the gravity low.

Some seismic data exist for Missouri that provide information on the possible subsurface configurations of the crust that would give rise to the observed gravity anomaly patterns. Stewart (1968) conducted a reversed seismic refraction survey of about 300 km in
length along an east-west line in northern Missouri crossing the gravity low at about 39.8° N. lat. Results indicate that the crust consists of three major layers, with average depths of about 5, 20, and 40 km and a 3/4 degree of dip toward the west. Stewart (1968) also conducted a reversed profile in southern Missouri that extends across the gravity low at about 50 km to the northwest of the gravity profile A-A' (Figure 5). The refraction data for Stewart's (1968) southern profile exhibit very low signal/noise ratios, perhaps because of significant lateral inhomogeneities within the crust. Results are compromised by the low quality of the data, although an argument can be made for a thickened crustal section in the southwestern half of the profile and somewhat higher crustal velocities beneath the northeastern half of the traverse (Nuttli, 1976). Finally, McCamy and Meyer (1966) conducted a seismic refraction survey from Little Rock, Arkansas to Cape Girardeau, Missouri, reversing a survey done several years earlier. The refraction profile cut across the Bloomfield gravity anomaly and ran in a NE-SW direction within the Mississippi embayment (i.e., to the southeast of profile A-A' of Figure 5). As discussed by Ervin and McGinnis (1975), this region is unusual in that the crust is slightly thicker and underlain by an anomalously high velocity layer as compared to Stewart's (1968) profile in northern Missouri. The anomalous layer probably corresponds to high density material at the base of the crust, material that may have been emplaced in association with the Precambrian rifting that produced the Reelfoot rift.

In summary, the seismic data suggest a slightly thicker crustal
section under the Missouri gravity low. although this interpretation is compromised by poor data and the complicating influence of rocks associated with processes that probably lead to formation of the Mississippi embayment. If it is assumed that the Missouri gravity low is due to a thickened crust, then a 34 milligal anomaly, and a density contrast of 0.3 gm/cm$^3$ between crust and mantle, is consistent with a crustal excess of about 3.3 km under the anomaly (Strebeck, 1982). Alternatively, if it is assumed that lateral density variations cause the gravity anomaly, than the anomaly would be consistent with rocks that were 0.1 gm/cm$^3$ less dense than surrounding materials for the first 4 to 8 km below the surface (Strebeck, 1982). Of course, other models of crustal inhomogeneities can be generated. However, in the absence of other constraints, they are not worth pursuing at this point.

RELATIONSHIP OF MISSOURI GRAVITY LOW TO PRECAMBRIAN ROCK PROVINCES AND TO MAGNETIC ANOMALIES

Information on the distribution of Precambrian rock types in Missouri is limited because of the relatively few drill holes that have penetrated into the basement and because of the complexity of the Precambrian geology in the area (Kisvarsanyi, 1974; Bickford et al., 1981; VanSchmus and Bickford, 1981). There is, however, a major boundary between 1.6 Ga old rocks composed largely of sheared granites and metasediments, and younger 1.4 Ga old granites and rhyolites. The boundary runs in a NE-SW direction, as is shown in
Figure 7, where the basement rock map of Bickford et al. (1981) has been overlain onto a shaded relief map depicting Bouguer anomalies. The Missouri gravity low cuts across the boundary at nearly right angles. There is also clearly an extension of what are thought to be older metasedimentary rocks into the younger terrain along the gravity low. Kisvarsanyi (1974) notes that the area containing the reentrant of older rocks is also a structural high on contour maps depicting the paleotopography of the Precambrian surface and on structured contour maps of Paleozoic sedimentary formations. Presumably, older Precambrian rocks are exposed along the low because of isostatic readjustment and erosion of the younger granites and rhyolites preferentially along the feature.

The observation that the gravity low cuts across the major Precambrian age and rock type boundary in Missouri suggests that the low is related to a structural feature. Further support for this suggestion can be found in the locations of areas with discrete, positive magnetic anomalies. Figure 8 shows regions with vertical intensity magnetic anomalies higher than 600 gammas as black splotches superimposed on the gray tone and shaded relief versions of Bouguer anomalies for Missouri. The 600 gamma contour interval was chosen on the basis of delineating discrete magnetic highs. The magnetic highs are in part clustered along the flanks of the gravity low, i.e., where the gravity gradient is high. Other magnetic highs coincide with discrete gravity highs, such as in the area underlain by the Bloomfield intrusion in southeastern Missouri or the Salem intrusion in the middle of the gravity low (Figure 8). Clearly, more work needs to be done to establish the pattern of magnetic
anomalies in more detail, along with establishing the relationship of the anomaly patterns and the gravity low. Examination of unpublished maps constructed by I. Zietz supports the observation that the magnetic highs are along the flanks of the gravity low.

Previous work shows that some magnetic highs in Missouri can be correlated with relatively iron rich igneous rock bodies (Phelan, 1969; Cordell, 1979). The location of the discrete magnetic highs along the flanks of the gravity low suggests that the flanks correspond to zones of weakness where magmas have been intruded. Kane et al. (1981) note a similar correlation of magnetic highs along the perimeter of the Mississippi Valley graben. The gravity and magnetic anomaly patterns, and the observation that the gravity low cuts across rock and age provinces, provide strong evidence that the Missouri gravity low is a consequence of a major inhomogeneity within the crust.

RELATIONSHIPS BETWEEN FOLDS, FAULTS, AND LINEARS IN SOUTHERN MISSOURI AND BASEMENT STRUCTURE

In this section we describe relationships between the Missouri gravity low and the patterns of faults, folds, and linears that exist within the Paleozoic sedimentary rocks covering Missouri. The particular tack that we take is to map the patterns of linear features from HCMM thermal images, compare those linears to the distribution of known faults and folds, and finally we relate the trends for the structural data to the gravity low.

Figure 9 shows a HCMM thermal infrared image over southern
Missouri taken during relatively clear atmospheric conditions at approximately 1:30 p.m. on June 10, 1978. The frame has been contrast-enhanced and transformed to a Mercator projection. Water appears dark (cool) because it does not warm as quickly as vegetation, soil, or rock. A correlation plot between the apparent temperature seen in this image and a map of the magnitude of topographic slopes demonstrates that the dominate control on temperature is relief. Areas with high relief show as relatively dark (cool), while relatively flat regions are bright (warm). For instance, the bright polygonal zone centered at 37.6° N. lat., 90.5° W. long. corresponds to flat terrain underlain in part by igneous rocks of the St. Francois Mountains and in part by the surrounding Cambrian sedimentary rocks. The dark area to the southwest of this region corresponds to Ordovician carbonates that have been dissected by streams. Flood plains of the streams and the major rivers are flat and therefore relatively bright (hot). Finally, the relatively smooth, bright regions to the north of the Missouri River and east of the Mississippi River coincide with the glacial till deposits related to the Wisconsin and earlier periods of glaciation.

We also combined a shaded relief image of topography with the daytime thermal image by multiplying the two data sets on an element by element basis. The resulting product is shown in Figure 9. Clearly, linear features are enhanced in the merged data relative to either the shaded relief map or thermal images shown alone. The reasons are at least three fold. First, topographic linears can be readily discerned on shaded relief maps (Wise, 1976). Second, topographic linears associated with river valleys would be enhanced.
because of the higher temperatures for the valleys as opposed to the hills. Combining the thermal image with the shaded relief map provides, in effect, a nonlinear enhancement of the topography. Third, any linear thermal features not related to topography would remain in the data. This product was used as our primary base for constructing a linears map for southern Missouri. An apparent thermal inertia image was also constructed using the formulation of Price (1977) and overlayed onto the shaded relief image. However, this product did not provide a significant amount of additional information, probably because the nighttime thermal and the albedo data contain only 25% of 13% of the variance inherent in the 3 dimensional thermal day-thermal night-albedo data set.

Figure 11 is a sketch map showing linears from the processed HCMM data. Also shown are folds from a version of the Missouri structures map (McCracken 1971) and faults from the latest geologic map of the State (Anderson et al., 1979). The folds are thought to be drape folds over the Precambrian surface in areas with significant relief due to basement faulting (McCracken et al., 1971). Most of the faults are high angle normal faults, although some evidence for shear movement can be found (McCracken et al., 1971). The area occupied by the high temperature region of the St. Francois Mountains and surroundings is also drawn on Figure 11. Note that linears, faults, and folds generally strike in a direction parallel to the gravity low. Also, the sharp southwestern edge of the St. Francois Mountains is coincident with the northern flank of the low. Further away from the low the the azimuths of features tend to disperse. Clearly, the basement inhomogeneity associated
with the Missouri gravity low has had a pronounced influence on the pattern of faulting and folding that has propagated through the Paleozoic sedimentary cover. The preponderance of normal faulting in the area implies, as does the reentrant of older basement rocks along the gravity low, that the dominate structural activity associated with the crustal inhomogeneity beneath the gravity low has been one of vertical readjustment. Preferential uplift along the low is also consistent with the pattern of vertical displacements shown by the mapped faults in the area (Figure 11).

THE AGE, ORIGIN, AND EVOLUTION OF THE MISSOURI GRAVITY LOW

The Missouri gravity low must be older than the Paleozoic sediments that have been deposited over the reentrant of older rocks into the granite-rhyolite terrain. The reason is that any uplift and stripping of the younger granite-rhyolite rocks along the gravity low must have occurred before the Precambrian surface was buried. The oldest abundant sedimentary rocks in southern Missouri consist of Upper Cambrian sandstones called the Lamotte Formation (Anderson et al., 1979).

A number of events affected the region now occupied by the gravity low during the Precambrian including: (1) The set of processes that led to formation of the granite-rhyolite terrain of southern Missouri. Bickford et al. (1981) speculate that a rifting event or a convergent plate margin might explain formation of the granite-rhyolite units; (2) Rifting that was associated with the
opening of the Reelfoot basin, the Precambrian precursor to the Mississippi embayment (Ervin and McGinnis, 1975); (3) Rifting associated with formation of the midcontinent gravity high (Chase and Gilmer, 1973); and (4) The postulated continent-continent collision associated with the Grenville orogeny (Burke and Dewey, 1973).

At this point it is useful to summarize the characteristics of the Missouri gravity low. The feature has a negative Bouguer of about 34 milligals, a width varying from 120 to 160 km, it has a medial high for part of its length, and it extends about 700 km in length. The low is perhaps best expressed within the younger granite-rhyolite terrain of southern Missouri. The flanks of the feature exhibit magnetic highs, some of which are probably due to igneous intrusions. Finally, the feature controls the pattern of normal faulting in the Precambrian basement rocks and overlying sedimentary cover. Except for the lack of a discernable thickness of sedimentary fill overlying the granite-rhyolite terrain, such a description is consistent with an origin as the failed arm of a triple junction. In fact, there are examples of relatively recent rifts that have negative anomalies with no associated sediment fill, although Burke and Whiteman (1973) interpret these anomalies as being due to ponding of magmas at the base of the crust.

The Missouri gravity low could have formed as the failed arm of a triple junction that existed before formation of the granite-rhyolite terrain. The triple junction site would have been to the southeast, with the other two rifts becoming active spreading centers. Closure of that spreading center, with subsequent
continent-continent collision, may have been the most plausible method of generating the abundant alkalic igneous activity that produced the younger granite-rhyolite terrain. In the process, most of the sediment fill within the failed rift would have been metamorphosed, intruded into, and covered by the alkalic magmas associated with formation of the granite-rhyolite terrain. The metasediments found in the reentrant of older rocks in this terrain (Figure 7) may be the remnants of this valley fill. Subsequent events, such as the formation of the Reelfoot rift that is postulated to have occurred at approximately 1.2 Ga (Ervin and McGinnis, 1975), could have served to reactivate parts of the rift. Reactivation certainly occurred during the mid-Paleozoic to Mesozoic, when the southeastern end of the low was structurally active as the Pascola arch. We stress that our interpretation, although plausible, is by no means unique and serves only as a working hypothesis to be updated or discarded as new seismic, potential field, and rock-type data are acquired. It is of interest to note that an origin as a failed rift arm may provide a new perspective on the source of the Pb-Zn-Cu in the Paleozoic sedimentary cover, since base metal mineralization is a common process associated with rifting events (Burke and Whiteman, 1973).

SUMMARY AND IMPLICATIONS

1. Standard digital image processing techniques have been used to interpolate and display free air and Bouguer anomalies and topography as gray tone, color-coded, and shaded relief images
for the midcontinent as part of an analysis of how structural features within the Precambrian basement of Missouri relate to the broader structure of the midcontinent. In addition, the Precambrian basement rock type map of Bickford et al. (1981) and magnetic anomalies for Missouri have been digitally merged and displayed with the gravity data to facilitate examination of correlations. Finally, Heat Capacity Mapping Mission (HCMM) thermal image data covering southern Missouri have been enhanced and overlayed onto shaded relief versions of topography.

2. A major and previously unrecognized gravity anomaly (Missouri gravity low) in the midcontinent is a 700 km long, 120-160 km wide free air and Bouguer low, with a Bouguer amplitude of up to 34 milligals. The anomaly displays a medial gravity high for part of its length. The low begins at a break in the midcontinent gravity high in southeastern Nebraska, extends in a southeast direction through Missouri, and intersects the Mississippi Valley graben as defined by Kane et al. (1981). The northern and southern edges of the intersection of the Missouri gravity low and the Mississippi Valley graben are the sites of discrete positive gravity anomalies that are thought to be due to plutons. Also, many of the epicenters associated with the New Madrid seismic area are within the crustal block defined by the intersection of the gravity low and the Mississippi Valley graben. Discrete positive magnetic anomalies exist along the flanks of the Missouri gravity low. Finally, the gravity low is the site of a reentrant of older Precambrian metasedimentary
rocks into the younger granites and rhyolites that underlie much of southern Missouri. The amplitude of the low is too high to be related to thickening of Paleozoic sedimentary rocks. Rather the anomaly is probably due to a basement inhomogeneity. Two seismic refraction profiles (Stewart, 1968) cut across the low in two places in Missouri. In both cases, the seismic data are consistent with a slightly thicker crustal section beneath the gravity low. The magnitude of the gravity anomaly is consistent with a crustal excess of 3.3 km as compared to surrounding areas or with a crust that is slightly less dense (0.1 gm/cm³ contrast) in the upper 4 to 8 km.

3. A HCMM daytime thermal image was overlain onto a shaded relief image of topography covering the area underlain by the gravity low in southern Missouri. These data show that linears trend in the same direction as the low. On the other hand, linears tend to be dispersed in azimuth away from the gravity anomaly. Mapped faults (high angle normal faults, mainly) and drape folds over basement relief in the Paleozoic sedimentary cover of southern Missouri follow a similar pattern. Some of the HCMM linears correspond to the mapped structures, in some cases they are extensions of such features, and some linears do not correspond to mapped features. In any case, the correlation of the gravity low and the structural data suggest that the low is a major basement rift and that the structures in the Paleozoic deposits are due to vertical readjustments related to the crustal inhomogeneity that gives rise to the low.
4. The Missouri gravity low is older than the oldest Paleozoic sedimentary rocks that cover the reentrant of metasedimentary rocks into the younger granites and rhyolites. The oldest rocks correspond to the Upper Cambrian Lamotte Formation. The gravity low could be the present expression of a rift that formed as a failed arm of a triple junction occurring before or during the events that led to the younger granite-rhyolite terrain of southern Missouri. Emplacement of the igneous rocks would have effectively covered or metamorphosed sedimentary rocks that formed as valley fill with the rift. Reactivation of the rift has certainly taken place since it formed. Association of the Missouri gravity low with a unique history is difficult at this point because of lack of information on basement rock types, ages, and seismic controls on crustal configurations beneath the low.
ACKNOWLEDGMENT

This work was carried out with funding from the NASA Office of Space and Terrestrial Applications, Non-Renewable Earth Resources, through a contract (955959) from the Jet Propulsion Laboratory and by the Heat Capacity Mapping Mission Data Analysis Program, Goddard Space Flight Center under Contract NAS5-26533. Processing was conducted with a PDP-11/34 system located within the Washington University Regional Planetary Image Facility. Thanks are extended to St. Louis University for seismic data and to the Geopositional Division, Defense Mapping Aerospace Agency Center, St. Louis, Mo., for gravity data.
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261-296.


FIGURE CAPTIONS

Figure 1 - Digital shaded relief map of topography is displayed in this image with the simulated sun located at 20° above the northeastern horizon. A Mercator projection is used for this and the other images in the paper. Numbers running vertically on the right hand side are degrees north latitude and numbers at the bottom are in degrees west longitude. The particular area of concern is located in the box bound by 25 to 49° N. lat., and 80 to 110° W. long. The resolution of the image, measured as the width of a picture element (pixel) is about 7 km. At that resolution little structural control of topography is evident within the midcontinent.

Figure 2 - Gray tone image of free air gravity anomalies for the same area as displayed in Figure 1. Black areas correspond to regions where stations were spaced too far apart to allow reasonable interpolation. Bright regions correspond to positive anomalies, medium gray to areas with anomalies close to zero, and darker areas to regions with negative anomalies. The anomaly range goes from +66 to -360 milligals. A sketch map illustrating structural features evident in the image is shown in Figure 5. The midcontinent gravity high extends as a NE-SW trending linear high, flanked by lows, in the upper half of the image. Note the subtle linear low extending from a break in the gravity high, toward the
southeast, to about 36° N. lat., 90° W. long.

Figure 3 - Shaded relief image depicting free air anomalies as if they were hills and valleys illuminated by a sun located at 15° above the northeastern horizon. Note the correlation between the shaded relief of topography and this figure in areas of high relief. Note the linear gravity low that begins at the break in the midcontinent gravity high and strikes southeasterly toward 36° N. lat., 90° W. long. A Bouguer image displays a similar pattern for the linear gravity low.

Figure 4 - This color image combines a color-coded version of the free air image shown in Figure 2 with the shaded relief image shown in Figure 3. The effect is to be able to discern both the value of an anomaly for a given region and an indication of the local anomaly gradient. Red corresponds to free air values greater than 20 milligals; yellow to orange indicate a range from 0 to 20 milligals; green corresponds to -10 to 0 milligals; blue-green denotes -30 to -10 milligals; and blue corresponds to values smaller than -30 milligals. This figure was the base map used for constructing the structural features diagram shown in Figure 5.

Figure 5 - Sketch map showing major structures delineated in the free air images of Figures 2, 3, and 4 and equivalent presentations for Bouguer data. The Missouri gravity low is a subtle, but pervasive feature that extends from
the midcontinent gravity high to the Mississippi embayment. The location of the Mississippi Valley graben is in part from Kane et al. (1981). A-A' is the location of the profiles shown in Figure 6.

Figure 6 - Topography, free air, and Bouguer anomalies are shown for profile A-A' of Figure 5. The profile cuts across the Missouri gravity low.

Figure 7 - Rock types of Bickford et al. (1981) have been coded to discrete color values and overlayed onto a shaded relief version of Bouguer anomalies. Sun is from the west at 15° above the horizon. Color values are as follows: Medium blue - felsic rocks; yellow - granite; orange - rhyolite; purple - gabbro; dark blue - basalt; red - metasedimentary rocks; green - Sioux Quartzite; and light blue - Keweenawan sedimentary rocks.

Figure 8 - Vertical intensity magnetic anomalies with amplitudes greater than 600 gammas are shown as black splotches on gray-tone and shaded relief images of Bouguer anomalies for Missouri. Patterns of small black splotches near the southeastern edge of the state and in the upper right are spurious and are remnant from the original digitization of the Missouri magnetic anomaly map. Arrows point to the Bloomfield (lower right) and to the Salem magnetic highs (Phelan, 1969; Cordell, 1979). Both features are probably due to relatively mafic intrusions. Note that many of the magnetic highs are
clustered on the edges of the Missouri gravity low. The sun is from the west at 15° above the horizon for the shaded relief data.

Figure 9 - This figure is HCMM daytime thermal infrared image covering southern Missouri that has been contrast enhanced and transformed to a Mercator projection. Flat areas are brighten (warmer) that regions with high relief. HCMM frame ID A-A0045-19420-2.

Figure 10 - The HCMM contrast enhanced daytime thermal infrared image has been overlayed onto a shaded relief image depicting topography. The sun for the shaded relief image is from the west at 20° above the horizon. The overlay tends to enhance subtle topographic features while retaining linear thermal anomalies not associated with relief.

Figure 11 - Sketch map showing the Missouri gravity low, mapped faults and folds, and linears as mapped from the HCMM thermal image, and from the thermal-topography overlay. The structural trend is dominated by the trend of the Missouri gravity low. Azimuths of structures tend to disperse for regions far from the low.
HCMM Apparent thermal inertia has been color coded and overlain onto a shaded relief map depicting topography. Reds correspond to high A.T.I., blues to low values.

HCMM daytime thermal infrared brightness is coded as hue, albedo as saturation, and nighttime thermal infrared as intensity. Reds indicate relatively high values of daytime temperature.
The case is then made that the shock wave results reported by Brown and MacQueen, who reported the eyé phase transition at 780 GPa, favor the choice of Y-iron rather than O-iron. However, it is said to y-iron, a lighter element (such as 6°) must also be added to compensate for the increase in density resulting from the Ni.

**T21A-9**

Nov. Shock Wave Data for Pyrite and Its Relation to the Earth's Core

**THOMAS J. AHRENS and CHRISTOPHER R. KRAV90**

(Received address: Atlantic-Richfield Corp., Los Angeles, CA)

Now shock and release wave data in the 7 to 1000 Kbar pressure range and with a low (100 bars) value release phenomena detectable phase changes, over the unexpected. 

Contrary to a few for with Shimok et al. data to 3000 kbar on iron and the pyrite by the present analysis, this led to results with the pyrite and pyrrhotite data, which do not include the transition of Cubic phase at ratio of 2.38 (C/P<1). This behavior is met with the results, which is not a transition high to the fine point at H<10, which may have a transition in the low-pressure state. When the new pyrite data and recent reanalysis of pyrite are used with shock wave data for iron and seismic data for the core the essentially new dataset is expected additivity to the molar volume of S and iron sulfides can be demonstrated. Depending on the pressure used, cases with 9 10 and 10 to 1328 are inferred in the liquid outer core. Further, the density and pyrhodina data, respectively.

**T21A-10**

Dynamics of Chemically Driven, Internally Generated Fluids

**HART P. EYE and DAVID A. YOON (Dept. of Geology, Arizona State University, Tempe, AZ 85287)**

It has been proposed that plumes are finitamente unsteady motions of mantle-derived thermal instabilities produced at the lower (hot) thermal boundary layer, owing to the destabilizing effects of flow superimposed on a temperature-dependent thermal boundary layer. When the primitive deep mantle is en- 

eralized in radiative heat sources from inhomogeneous planetary accretion (Anderson, 1975), then thermal instabilities may furnish a viable mechanism to extract the enthalpy sources into the upwelling, which is then propelled into the deep mantle, generating moving heat sources. 

Accordingly, we have modeled the thermal- momentum balances of these chemically un- 

reduced, subsurface plumes by means of boundary layer techniques in which both internal heating, with a localized thermal boundary layer and a strong- ly temperature-dependent thermal boundary layer, characteristic of mantle materials, are incorporated. 

The equations governing the conservation of energy and momentum are solved numerically:

**T22A-11**

T1:1 Dependence of Residual Density of Simple and Complex Fluids

**A. R. KOTI and L. S. BAKAT (Dept. of Terrestrial Magnetics, Carnegie Institution of Washington, 5241 Broad Branch Road, NW, Washington, D.C. 20015)**

A new method is described for determining the density of complex fluids, using a combination of high-pressure shock waves and shock tube techniques. The results of this method are compared with those obtained using other techniques, and the agreement is found to be within 1%.

**T21B-2**

New Deep-Sea-Oceanic Mantle Map of Arizonian

**M. R. HONG (Center for Lithospheric Studies, The University of Texas at Dallas, Richardson, Texas 75080)**

A new deep-sea-oceanic mantle map of Arizonian age is presented. The map is based on the interpretation of gravity data and magnetic anomalies, and provides information on the structure of the oceanic crust.

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Image Processing Applied to Gravity and Topography Data Covering the Continental U.S.

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Introduction

A great deal of digital topographic information and gravity data exist that cover the continental United States. For instance, data sets that can be purchased from the National Oceanic and Atmospheric Administration (NOAA) include (a) elevations averaged over 30 s of latitude and longitude for the conterminous United States and (b) over a half million gravity readings from stations distributed across the entire country, although in an irregular manner. Both the topography and the gravity data sets are fundamental to the understanding of the structure of the crust and lithosphere, and especially to the understanding of the relationships between topography and structure [McGinnis et al., 1979; McVitt, 1981; and others].

The intent of this work is to show the applicability of fairly standard image-processing techniques to processing and analyzing large geologic data sets. In particular we have utilized image-filtering techniques to interpolate between gravity station locations in order to produce a regularly spaced data array that preserves detail in areas with good coverage and that produces a continuous tone image rather than a contour map. We have used standard image-processing techniques to digitally register and overlay topographic and gravity data, and we have displayed the data in ways that emphasize subtle but pervasive structural features. In this paper we discuss the techniques used, briefly describe the products, and illustrate the potential of the methods by discussing subtle linear structures that appear in the processed data between the midcontinent gravity high and the Appalachians.

Data Processing Techniques

Data processing was conducted on a PDP-11/34 minicomputer with interactive image storage and display peripherals. Software is based on mini-VICAR, with a variety of applications programs to conduct filtering, enhancement, and geometric operations. The reader is referred to such standard references as Mok [1980] for further information about general techniques used in image processing. Our software was developed partly at the Jet Propulsion Laboratory, partly at the U.S. Geological Survey, Flagstaff, Arizona; and partly by us.

For purposes of this paper the dynamic range of both the topography and the gravity data were first scaled to fit within the range occupied by a byte variable (i.e., 8 bits or 256 discrete values). The byte-encoded data were then stored in data arrays, where the array element spacing was 30 s in both latitude and longitude. For the topography this procedure produced a regular array of byte-encoded data that had 2880 rows (latitude) and 7080 columns (longitude). The data arrays covered a latitude range from 25° to 49° N and a longitude range from 66° to 125° W.

The resulting topography data array could be displayed as an image if the byte-encoded data were converted to color or brightness values. An alternative and quite useful method of depicting topography is to generate a digital, shaded relief map. Figure 1 shows such a product, which was generated on a version of the data file that was first transformed to a Mercator projection, digitally reduced in size by a factor of 7, and then used to generate a relief map. The shading process is based on the assumption of a photometric function for the surface (Lommel-Seelig function in our case). The brightness assigned to a given array element location depends on the local slope magnitude and direction and is relative to an assumed solar azimuth and elevation [Hall et al., 1975].

The gravity data were reduced to Free air and to Bouguer anomalies courtesy of the Geopositional Department, Defense Mapping Agency Center, St. Louis, Missouri. The reference field at sea level that was used in the reduction was based on the 1967 International Gravity Formula, with all the data referenced to the 1971 International Gravity Standardization Net. Free air anomalies were computed from the following formulation:

\[ \Delta \phi_{\text{FA}} = g + 0.30968 \cdot \gamma, \]

where \( \Delta \phi_{\text{FA}} \) = Free air anomaly (mGal), \( g = \) reading, \( \gamma = \) elevation (positive down to geoid), and \( \gamma = \) theoretical gravity value. A second-order term was added to the elevation correction when the magnitude of the correction exceeded 0.1 mGal. Bouguer anomalies were computed on the basis of a slab with density 2.67 g/cm³, using \( \Delta \phi_{\text{B}} = \Delta \phi_{\text{FA}} - 0.111 \gamma \), where \( \Delta \phi_{\text{B}} \) = Bouguer anomaly in mGal. Local terrain corrections were not included in the Bouguer anomaly computations.

Generating images from the gravity data presents a more complicated problem than the topographic data since the gravity stations are not located along a regular grid. For both the Free air and Bouguer anomalies the data were first scaled to fit within a byte variable (i.e., 256 discrete values). The scaled data

Fig. 1. Shaded relief map depicting NOAA 30-s elevation averages for the continental United States. Numbers running vertically along the sides of the image are degrees of north latitude, while numbers along the bottom are degrees of west longitude. This and other maps in the paper are Mercator projections. The simulated sun was set at 20° above the western horizon. Dark blocks areas are missing data.
were placed into an array with the same element spacing (30 s) and geographic coverage as the topography data array. The element location closest to a given gravity station location was assigned the station value, thereby producing an array occupied in part by real data and in part by blank zones. We chose to use a conceptually simple, but powerful, filtering approach for interpolating between the real gravity data points. The technique was developed for processing lunar consortium data and was also used to produce altimetry maps from the approximately 100,000 elevation estimates obtained by the Pioneer Venus radar mapper [Elison and Soderblom, 1977; Pettengill et al., 1980]. The technique involves use of a spatial filter that generates a moving average through the data array. At any given position within the data array the filter occupies a box of \( N \times N \) elements. The mean value of the gravity anomalies for stations located within the box is used as the interpolated value for the box center only if an anomaly value does not already exist at that location. Shifting the filter over the array and repeating the operation for each element location results in a partially interpolated data set. Blank areas still remain in zones without any data and in zones with so little data that a user-defined statistical threshold was not met. The threshold is defined in terms of the fraction of elements within the box that must have valid data in order to replace the midpoint element with the average, assuming that the midpoint did not already have valid data.

In practice the gravity data were processed by using several filter widths, beginning with a \( 3 \times 3 \) element filter and ending with a \( 21 \times 21 \) element filter. The threshold was set such that at least 20% of the element locations at any given filter position must have valid real data values to be interpolated. The choice of filter sizes was governed by the station spacings, which averaged several kilometers but varied from hundreds of meters to several tens of kilometers. A \( 3 \times 3 \) element filter, for instance, covers 90 s of arc in both latitude and longitude, or about 3 km along a line of latitude. Note that regions with relatively small distances between gravity values were interpolated only over relatively short distances, since once an element was assigned a data value it was not affected by later filter passes. The net effect of the filtering operation was to generate a regular array of gravity data, with original data left intact and with interpolated data between the original values.

Some areas in the array, even with a \( 21 \times 21 \) element filter, still had too little data to allow interpolation. Those areas appear black in all of our displays.

The filtered gravity anomalies could be displayed as gray tone or as color-coded images. As with topography, we find that a very effective visual display is a shaded relief map. Figures 2 and 3 depict shaded relief maps for the Free air and Bouger anomalies, respectively. Comparison of these products with previously published contour maps [e.g., Woulard and Josset, 1964; McGinnis et al., 1979] show similar broad-scale patterns. However, the maps shown in Figures 2 and 3 display inherently more information. The reasons are threefold. First, a finer grid spacing was used to interpolate between station readings than any published map we have been able to examine. Second, there are as many contour intervals as there are values in a byte variable (i.e., 256). Most contour maps typically have a dozen or so contour intervals.

Third, areas with a large number of closely spaced stations retain details of the anomaly patterns.

The filtered gravity anomalies can also be digitally overlaid on the topography for a visual display of the correlations between the two variables. The technique that we used was to first convert the byte values for each element in the gravity array to a given color (Figure 4). The colors were chosen in such a manner that blue corresponded to the most negative anomalies and red to the most positive anomalies. Oranges, yellows, and greens were chosen to represent intermediate values. Color-coded images depicting the anomaly patterns were digitally overlaid onto a shaded relief map of the topography simply by re-

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**Fig. 2.** Shaded relief map depicting filtered Free air anomalies. Black areas indicate regions containing either bad data or too little data to have statistically valid interpolations. The simulated sun was set at 12° above the western horizon. Variations in the anomalies are, in effect, illuminated as if they were the topographic ridges and valleys. For example, the midcontinent gravity high (43°N, 94°W), which is a positive anomaly, stands as a ridge, while the great valley of California (37°N, 120°W), which is a negative anomaly, appears as a trough.
Fig. 3. Shaded relief map depicting filtered Bouguer anomalies. The map was produced in the same manner as the Free air anomaly map in Figure 2. No local terrain corrections were included in computing Bouguer anomalies.

Fig. 4. This diagram shows the approximate color-coding scheme used to produce the color contours for the gravity anomaly maps shown on the cover of this issue of EOS. Histograms showing the fractional area occupied by each anomaly value were used to assign colors in such a manner that each color value occupies an area comparable to any other color value. About 45 discrete color values (i.e., discrete hue and saturation values) were used in each anomaly map. On the other hand, the shaded relief map versions of the anomalies each contain 256 shades of gray.

Discussion

A sketch map showing some of the major structures evident in the color and shaded relief maps is shown in Figure 5. For this paper we will restrict our discussion of the processed data to a portion of the midcontinent, where we have a continuing interest in the crustal structure and the relationships between basement fractures and ore deposits. Such a discussion also serves to illustrate the kinds of information that can be gleaned from topography and gravity data that have been processed in image format.

The dashed lines in Figure 5 define two major structures in the midcontinent: a newly discovered feature we call the Mississippi Valley graben, as defined by Kane et al. [1981] on the basis of gravity and aeromagnetic anomalies. The

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Missouri gravity low can be seen on the color and shaded relief maps as a 140-km-wide feature that begins at a break near the southern edge of the midcontinent gravity high and extends across Missouri and into the Mississippi embayment. In the embayment the low takes the form of a horst block called the Pascola Arch [Ewen and McGinnis, 1975]. The low has a Bouger amplitude of about 30 mGal for the region just to the northwest of the embayment. The magnitude of the anomaly suggests a deep basement structure. In fact the anomaly is consistent with an increased crustal thickness of 3 km at the Moho or with a crust that has a density of 0.1 g/cm$^3$ less than the surrounding areas for the first 4 to 8 km below the surface [Strebeck, 1982]. Analyses of remote sensing data and ground studies for areas overlying the gravity low demonstrate that the regional fracture trends are coincident with the strike of this deep basement feature, suggesting a fair degree of control over the pattern of faulting in the area [Gradwohl et al., 1982].

The intersection of the Missouri gravity low and the Mississippi Valley graben has clearly served to control the emplacement of two major plutons defined by Hildenbrand et al. [1977]; the Bloomfield intrusion to the north and the Covington intrusion to the south. The two plutons can be seen as positive anomalies in the Free air color map and as bumps on the shaded relief maps. Additionally, Figure 6 is a gray tone image of the filtered Free air data that has been contrast enhanced to show the variations in the midcontinent. In such a display the most negative anomalies are dark, and less negative anomalies are bright. The Missouri gravity low is clearly discernible, and there is a suggestion of a NE-SW trending structure that, in fact, outlines the Mississippi Valley graben. The white dots represent over 1500 earthquake epicenters recorded by the St. Louis University seismic network between 1974 and 1979 [Stauber et al., 1977]. Clearly, the epicenters, which delineate the New Madrid seismicity high, are concentrated in the crustal block defined by the intersection of the Missouri gravity low and the Mississippi Valley graben. Thus the intersection of these two crustal structures seems to have provided both a zone of weakness for the emplacement of plutons and a focus for release of strain energy via earthquakes.

Examination of the Free air color map suggests an extension of the Missouri gravity low from the midcontinent gravity high to the northwest, perhaps as far as to the Big Horn uplift in Wyoming. The suggestion is based on an alignment of a sharp break in the Free air anomalies with the North Platte River valley in Nebraska and with fractures in Wyoming. The reality of such an extension must remain open to question until further study. If the extension is geographically related to the Missouri gravity low, the combined lengths of the two features would be over 1500 km. There are other structures of comparable length on the earth, namely transcurrent faults such as the East Tethys. It is conceivable that the Missouri gravity low and the extension into Wyoming are part of a transcurrent fault system, sections of which have been reactivated during various time periods. Such an origin is also consistent with the observation that the structure cuts across the basement age

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**Fig. 5.** Sketch map showing some of the major structures seen in the gravity anomaly maps presented in this paper. The Missouri gravity low can be seen best on the shaded relief map versions of the anomalies. The two plutons are the Bloomfield pluton to the north and the Covington pluton to the south. They can be seen as red dots on the Free air color maps and as bumps in the shaded relief anomaly maps. The Bloomfield intrusion is located at about 37°N, 90°W. The Mississippi Valley graben location is from Kane et al. [1981], although the outline can be seen in the shaded relief anomaly maps.

**Fig. 6.** Gray tone version of the filtered Free air anomalies. The map boundaries extend from 34° to 43°N, 87° to 95°W. The two horizontal lines correspond to 37° and 40°N latitude, while the two vertical lines are 91° and 95°W longitude. In this map, bright areas have large Free air anomalies, while dark areas have small (i.e., highly negative) values. The white dots are earthquake epicenters for the period from 1974–1979, as recorded by the St. Louis University seismic network. The Bloomfield and Covington plutons are the bright circular features just to the north and south, respectively, of the epicenter cluster. The Missouri gravity low extends from a break in the midcontinent gravity high, through Missouri, and across the Mississippi Valley graben. The intersections of the gravity low and the graben are the locations of the intrusions. In addition, most of the seismicity is concentrated within the crustal block defined by the intersection of the gravity low and the graben.
Implications for the Earth Sciences

The future will see an increased availability of a number of other large, geographically oriented data sets that are applicable to earth science problems. For instance, as part of the National Uranium Resource Evaluation Program, the Department of Energy has acquired airborne digital gamma ray (net radioactivity) data, aeromagnetic anomalies, and hydrogeochromal data for most of the continental United States. Such large data sets are amply suited for use with the kinds of techniques described in this paper. Of course, analysis of any data set requires, above all, the proper framing of scientific questions. Also, the right kinds of data must be accessible to answer the questions. However, we do feel that interactive digital image processing of a variety of geographically oriented data sets can lead to substantial advances in our understanding of the earth.

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