9950-706

# PATTERN, AGE, AND ORIGIN OF STRUCTURAL FEATURES WITHIN THE OZARK PLATEAU AND THE RELATIONSHIP TO ORE DEPOSITS

Final Report NASA Subcontract NAS7-100
JPL Task Order No. RD-151
No. 955959

Raymond E. Arvidson, P.I.
Associate Professor
McDonnell Center for the Space Sciences
Department of Earth and Planetary Sciences
Washington University
St. Louis, Missouri 63130

Contract Period: 1/1/81-12/31/81

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, Sponsored by NASA under Contract NAS7-100

# 1. TABLE OF CONTENTS

## . 2. ABSTRACT

This report is a summary of work conducted under JPL contract 955959 to Washington University. We have constructed topography and gravity anomaly images for the continental United States, based on filtering over a half million discrete data points. We find evidence, based on gravity, remote sensing data, the presence, trend, and character of fractures, and on rock type data, for a Precambrian rift through Missouri. The feature is probably the failed arm of a triple junction that existed prior to formation of the granite-rhyolite terrain of southern Missouri.

## 3. INTRODUCTION

This document constitutes the final report for our work on integrating and analyzing a variety of remote sensing, potential field, and geologic data to better understand the regional structural geology of Missouri and the potential correlations with Pb-Zn-Cu and Fe deposits of the region. As noted in JPL contract No. 955959, we were to:

(a) Assemble, reduce, and compare the data and begin preliminary scientific analyses. We have obtained a large quantity of data, as listed in Table 1.

(b) Reformat the data to a common, geographically oriented digital data base. That activity has been accomplished.

(c) Begin analyses of the registered data, concentrating on correlations between structural features seen in the potential field data and features seen in the remote sensing and geologic data.

(d) Begin geophysical modeling of the basement structure of the Ozark Plateau. Both tasks (c) and (d) have been accomplished and reported in Arvidson et al., 1982 and in Guinness et al., 1982. A complete bibliography for work conducted under this study is attached, along with copies of the two papers quoted above.

## 4. PROCESSING FREE AIR AND BOUGUER ANOMALIES AND TOPOGRAPHY FOR THE CONTINENTAL UNITED STATES

As presented in Arvidson et al. (1982) (attached), we have generated free air and Bouguer gravity anomaly images of the U.S. from approximately 500,000 land station readings. The technique used involved a boxcar filter, where the mean of the data values within the boxcar was used to replace center value, but only if a real data point did not already exist at that location. NOAA 30 second topography was also displayed as an image for the U.S. In addition, color-coded values of the anomalies were digitally overlayed onto a shaded relief version of the topography to display correlations between altitude and anomaly values.

Our work was utilized in Science News (page 233, Oct. 10, 1981 issue), summarized in Science by Dick Kerr (March 5, 1982 issue) and touched upon by J. Oliver, Cornell University, as part of his invited presentation on the frontiers of geophysics, presented at the Spring 1982 American Geophysical Union meeting. In addition, the work was mentioned as an example of using space techniques to understand the Earth during testimony at the Senate Appropriations Committee hearings on the FY83 budget. Finally, our color maps appeared on the cover of the May 4, 1982 issue of EOS.

We generated continental scale images to properly display a feature, newly discovered from our images, that extends at least 700 km in length. The feature is about 120 km wide, has a -30 mg Bouguer amplitude, and extends at least from a break in the midcontinent gravity high in S.E. Nebraska to the Mississippi Valley graben. The intersection of the feature and the Mississippi Valley graben is the site of a structural horst (Pascola Arch) and location of the bulk of the seismicity associated with the New Madrid seismic high. The Viburnum trend, producing 75% of the Pb in the U.S., lies within the feature, which we have informally named the Missouri gravity low. The Missouri gravity low is also aligned with the North Platte River and with a set of fractures within the Precambrian of Wyoming. The Platte also demarcates a sharp break in the free air anomalies. Whether the Missouri gravity low is genetically related to the Platte and to the Wyoming fractures remains open to question.

## 5. CHARACTERIZATION OF THE MISSOURI GRAVITY LOW - FAILED ARM OF A PRECAMBRIAN TRIPLE JUNCTION

As presented in Guinness et al. (1982) (attached), our next step in the analysis was to characterize the Missouri gravity low using a variety of remote sensing and geologic data. Positive magnetic anomalies are associated with the northeastern flank of the gravity low. The low also cuts across the major Precambrian age and rock type boundary in Missouri, marking a change from older sheared granites and metasediments (northwest), to younger granites and rhyolites (southeast). The age of the older terrain is about 1.6 billion years, while the younger terrain is about 200 million years younger. The 30 mgal amplitude of the gravity low is too high to be explained by a thickened section of Paleozoic sedimentary cover. Rather, the anomaly is due to a basement inhomogeneity. Modeling of the anomaly suggests a crustal excess of 3 km over surrounding regions, or the incorporation of slightly less dense material in the upper 4 to 8 km of the crust. The gravity low is also the site of a re-entrant of older metasediments into the younger granite-rhyolite terrain. It is conceivable that the low is remnant from the set of events that formed the younger granite-rhyolite terrain. The metasediments could be valley fill deposits formed within a failed arm of a triple junction. It has been hypothesized by a number of authors that the granite-rhyolite terrain formed via continent-continent collision and subsequent heating. The Missouri gravity low may be the remnant of a failed arm of a triple junction that existed prior to the collision event.

We have also begun preliminary analyses of the correlations between the potential field anomalies and fractures mapped on the surface and detected in remote sensing data (Guinness et al., 1982, attached). We find that the Missouri gravity low is coincident with a number of linears seen on Heat Capacity Mapping Mission data. Some of the linears correspond to mapped faults in the Paleozoic sedimentary cover and some are extensions of mapped faults. The majority of the faults are extensional, indicating that the gravity low is the site of vertical readjustments, probably driven by isostasy. It is also conceivable that stresses induced by the orogenic events associated with the Appalachians and the Ouachitas have led to reactivation.

We are currently, as part of the 2 year project originally proposed to NASA Headquarters, including Landsat and Seasat data in a more detailed analysis of the area covering and surrounding the

St. Francois Mtns. We expect to submit a paper in the fall of 1982 to a special issue of Economic Geology devoted to remote sensing. The thrust will be to map fractures from the remote sensing data and to correlate them with Bouguer anomalies, aeromagnetic anomalies as provided from NURE data, and with locations of known Pb-Zn-Cu stratabound deposits. This work began in the fall of 1981 but was delayed due to the discovery of the Missouri gravity low and the work that was needed to document this important basement structure.

## 6. BIBLIOGRAPHY - PAPERS SUPPORTED BY JPL CONTRACT 955959

Arvidson, R.E. and E.A. Guinness, 1981, Integration of remote sensing, geophysical, and geological data sets to better understand the structural geology of the St. Francois Mtns., S.E. Missouri, and surrounding areas, 1981 Int. Geoscience and Remote Sensing Symp., IEEE Cat. No. 81CH1656-8, 895-896.

Arvidson, R.E., 1981, Basement structure of the midcontinent, paper presented at the NASA-sponsored conference on rifting, NAPA valley, California December, 1981.

Arvidson, R.E., E.A. Guinness, J.W. Strebeck, G.F. Davies, K.J. Schulz, 1982, Image processing applied to gravity and topography data covering the continental U.S., EOS, 18, 261-265 (attached).

Arvidson, R.E., E.A. Guinness, J.W. Strebeck, 1982, Linear basement structure in the midcontinent, U.S.A. - Gravity, topography, remote sensing, and seismicity data, EOS, 18, 432.

Arvidson, R.E. and E.A. Guinness, 1982, Structure of the midcontinent basement - topography, gravity, seismic, and remote sensing data, 24th Plenary Meeting, COSPAR, Abstracts Booklet, 87.

Davies, G.F., 1982, Missouri gravity low-Major basement rift, presented meeting of FOAM (Friends of Aeromagnetic Mapping) held at the Univ. Kansas, Feb., 1982.

Guinness, E.A., R.E. Arvidson, J.W. Strebeck, K.J. Schulz, G.F. Davies, C.E. Leff, 1982, Identification of a Precambrian rift through Missouri by digital image processing of geophysical and geological data, J. Geophys. Res., in press (attached).

Strebeck, J.W., 1982, Structure of the Precambrian basement in the Ozark Plateau as inferred from gravity and remote sensing data, Master of Arts Thesis, Washington University, 149 p.

Strebeck, J.W., E.A. Guinness, R.E. Arvidson, 1982, Linear structures in Missouri seen with Heat Capacity Mapping Mission (HCMM) data, EOS, 18, 432.

# APPENDIX I

## DATA ACQUIRED FOR USE IN RESEARCH RELATED TO JPL CONTRACT 955959

BOOK - USGS open-file report #78-560. Generalized geologic map of Rolla 1°x2° quadrangle.

BOOK - USGS open-file report 78-806. Simple Bouguer gravity anomaly map, Rolla 1°x2° quadrangle.

BOOK - USGS open-file report 79-1192. Simple Bouguer gravity map of Rolla 1°x2° quadrangle

THESIS - Gibbons, J.F. Tectonics of eastern Ozarks area ... 1975.

THESIS - Palmer, J.E. Some geological & magnetic characteristics of buried & resurrected Precambrian hills ... 1967.

THESIS - Sides, J.R. Study of the emplacement of a shallow granite batholith, St. Francois Mountains ... 1979.

THESIS - Wagner, R.J. Stratigraphic and structural controls and genesis of barite deposits in Washington County, Missouri. 1973.

TAPE - 9 Landsat scenes of Missouri on computer compatible tapes.

PHOTOS - Landsat photos of Missouri

BOOK - Continental Tectonics, by Geophysics Study Committee, National Research Council. (Studies in geophysics)

BOOK - Harvard Library of Computer Graphics Mapping Collection -- 11 volumes.

MAP - 17 topographic maps (scale 1:250,000) of Missouri.

BOOK - Digital Image Processing, by William K. Pratt.

TAPE - Elevation data for North America (30", U.S.) from NOAA -- 4 computer compatible tapes.

TAPE - Seasat image of southern Missouri -- computer compatible tapes.

TAPE - Gravity readings, southern Missouri -- 3000 station tape from DMAAC.

TAPE - Seismic data tape, southern Missouri -- from St. Louis University.

BOOK - MoGS RPI #26. Guidebook to the geology of St. Francois Mountain area.

BOOK - MoGS RPI #46. Ash-flow tuffs of Precambrian age in SE Missouri.

BOOK - MoGS RPI #47. Mafic intrusive rocks of Precambrian age in SE Missouri.

BOOK - MoGS RPI #51. Petrochemistry of a Precambrian igneous province, St. Francois Mountains, Missouri.

BOOK - MoGS RPI #56. Data on Precambrian in drillholes of MO including rock type and surface configuration.

BOOK - MoGS RPI #61. Studies in Precambrian geology with a guide to selected parts of St. Francois Mountains, Missouri.

BOOK - MoGS RPI #27. Annotated bibliography of Missouri Precambrian, 1959-1973.

MAP - Paleotopography of the buried Precambrian surface in Missouri.

MAP - Geologic map of the Precambrian of Missouri.

MAP - OFM-80-1-Gl -- Subsurface geology of Precambrian St. Francois terrane, SE MO.

MAP - USGS map I-1161. Geologic map of the exposed Precambrian rocks.

MAP - USGS maps MF-1001A & 1001B. Structure contour map of buried Precambrian basement rock surface.

MAP - 30 Missouri aeromagnetic maps -- scale 1:62,500.

TAPE - 8 NCIC digital terrain tapes produced by DMATC from the 1:250,000 series of maps for areas of Missouri.

BOOK - APSRS state base graphics catalog for Iowa/Missouri.

MICROFICHE - APSRS state base graphics catalog for Iowa/Missouri.

BOOK - USGS Professional Paper 1042 -- Geology of the Decaturville impact structure, Missouri.

BOOK - MoGS RPI #44. Exposed Precambrian rocks in southeast Missouri.

BOOK - MoGS RPI #62. Guidebook to the geology along Interstate-55 in Missouri.

BOOK - MoGS RPI #58. Guidebook to the geology and ore deposits of selected mines in the Viburnum Trend, MO. 2d reprinting.

BOOK - Dynamics of Plate Interiors, publ. by AGU.

MAP - USGS open-file report 78-330 -- Aeromagnetic form-line contour map of the east part of Rolla, MO, 1°x2° quadrangle.

BOOK - USGS open-file report 78-402 -- Spectrographic and chemical analyses of drill core from Precambrian igneous rocks of the St. Francois igneous province in SE MO.

MAP - USGS open-file report 79-966. Aeromagnetic map of the Rolla, MO, area.

BOOK - USGS open-file report 79-992 --Linear feature data derived from Landsat images of southeastern MO.

BOOK - USGS open-file report 79-1080 -- Uranium and thorium content of some sedimentary and igneous rocks from Rolla 1°x2° quadrangle, MO

BOOK - USGS open-file report 81-518 -- Metallic mineral-resource potential of the Rolla 1°x2° quadrangle, MO, as appraised in September 1980.

BOOK - USGS open-file report 77-787 -- Uranium in Precambrian granitic rocks of the St. Francois Mountains, SE MO, with comments on uranium resource potential.

BOOK - USGS open-file report 80-25 -- Spectrographic and chemical analyses of exposed Precambrian rocks, Rolla 1°x2° quadrangle, MO.

BOOK - USGS open-file report 80-1000 -- A possible favorable belt for mineral discovery in subsurface Cambrian rocks in southern MO.

TAPE - Aeromagnetic data, U.S., from NOAA.

BOOK - Economic Geology, vol. 72, no. 3 (May 1977): an issue devoted to the Viburnum Trend, southeast MO.

TAPE - 3 NURE tapes -- hydrogeochemical data for Dyersburg 1°x2° quadrangle and Poplar Bluff 1°x2° quadrangle, magnetic data for Poplar Bluff 1°x2° quadrangle.

BOOK - Map Projections for Geodesists, Cartographers and Geographers.

TAPE - HCMM digital tapes which were re-formatted and condensed onto 8 tapes.

TAPE - Missouri geologic map (on digital tape): red, green & blue filter versions.

TAPE - AEM-A image catalog, sorted by longitude/latitude. (Microfiche indexes also)

TAPE - Point gravity anomalies for the continental U.S. -- Generated by DMAAC.

TAPE - Topographic data set for Earth -- 2 digital tapes.

PHOTOS - Space Shuttle STS-1 onboard photos of Missouri areas.

MAP - Composite stratigraphic column for MO.

MAP - Geological highway map of the mid-continent region (AAPG)

MAP - Seismicity map of Missouri.

MAP - Structural features map of Missouri.

REPRINT - Aeromagnetic anomalies in Bonne Terre area of southeast MO mining district.

REPRINT - Depositional history of LaMotte sandstone of southeast MO.

BOOK - Bibliography of Missouri Precambrian.

MAP - USGS map MF-1004 A&B -- Generalized geologic and summary geochemical maps of the Rolla 1°x2° quadrangle, MO.

REPRINT - First-look analysis of geologic ground patterns on ERTS-1 imagery of MO.

BOOK - Geology in the area of the Eureka-House Springs anticline with emphasis on stratigraphy, structure, economics.

BOOK - Geology of the disseminated lead deposits of St. Francois and Washington Counties, MO.

REPRINT - Low-amplitude aeromagnetic anomalies in southeast MO.

REPRINT - Mineral-resource potential of the basement complex in MO.

REPRINT - Missouri's mineral resource base for future generations.

REPRINT - Standards of practice, MO Land Survey.

REPRINT - Tectonic features in the polygonal structure of Decaturville, west-central MO.

REPRINT - The 38th parallel lineament and its relationship to ore deposits.

REPRINT - Gravity and aeromagnetic anomalies over basement structure in the Rolla quadrangle and the southeast MO lead district.

BOOK - Viburnum Trend; 26th annual field trip of the Assoc. of MO Geologists.

BOOK - Central Mississippi Valley earthquake bulletin (from St. Louis University).

PHOTOS - HCMM photos (prints & transparencies) of mid-continent USA.

PHOTOS - HCMM photos (transparencies) of the Ozark Plateau.

PHOTOS - Landsat, Skylab, and NASA-Aircraft photos of east-central MO.

PHOTOS - Side-looking radar imagery of MO River area, east-central MO.

PHOTOS - JPL digitally processed Seasat radar images of the St. Francois Mountains, MO.

MAP - Subsurface geology of Precambrian St. Francois terrane, SE MO.

BOOK - Aeromagnetic lineament study of covered Precambrian basement, southeast MO.

BOOK - A field guide to the Precambrian geology of the St. Francois Mountains, MO.

BOOK - Major lineaments and possible calderas defined by side-looking airborne radar imagery, St. Francois Mountains, MO.

BOOK - Ortho-polygonal tectonic patterns in the exposed and buried Precambrian basement of southeast MO.

REPRINT - Granitic ring complexes and Precambrian hot-spot activity in the St. Francois terrane, midcontinent region, U.S.

MICROFICHE - 19 microfiche sets covering various aspects of the NURE-HSSR Program.

TAPE - Gravity data in National Gravity Data Base for Canada -- on digital tape.

BOOK - An analysis of haze effects on Landsat multispectral scanner data.

BOOK - Characteristics of TIROS, GOES, DMSP and LANDSAT systems.

MAP - USGS map MF-1011 -- Preliminary seismotectonic map of central Mississippi Valley.

BOOK - USGS open-file report 81-437 -- Proceedings of Conference XIII: Evaluation of regional seismic hazards and risk.

BOOK - Digital Image Processing for Remote Sensing.

TAPE - Aeromagnetic, hydrogeochemical, and reduced data for Rolla, MO, 1°x2° quadrangle from NURE -- 3 digital tapes.

MAP - Magnetic map of Missouri -- scale: 1 inch = 8 miles.

REPRINT - New gravity anomalies mapped from old data.

BOOK - Geologic application of thermal inertia imaging using HCMM data.

FILM - SIR-A image film master positives for STS-2 data takes 22, 24A & 24B -- 3 rolls of film.

THESIS - Strebeck, J.W. Structure of the Precambrian basement in the Ozark Plateau as inferred from gravity and remote sensing data. 1982

BOOK - ELAS: Earth resources laboratory applications software. (loose-leaf)

MAP - Geophysical data from FOAM II convenors.

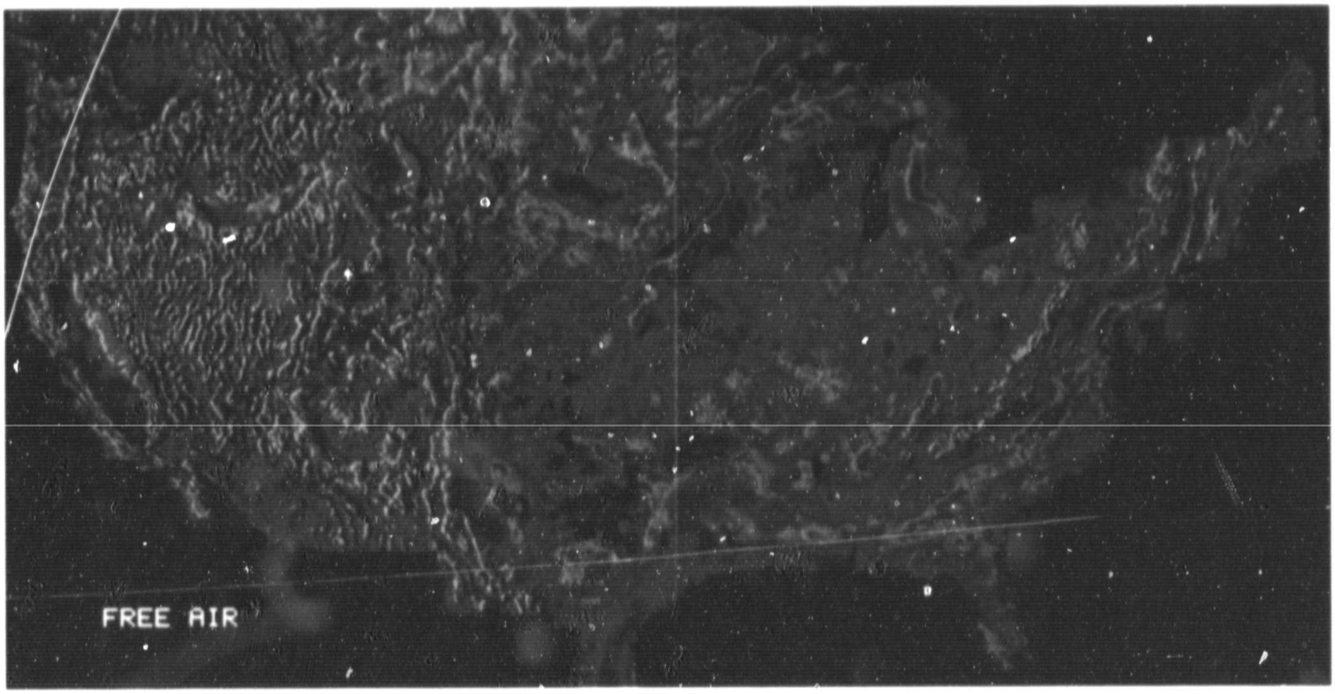
APPENDIX II

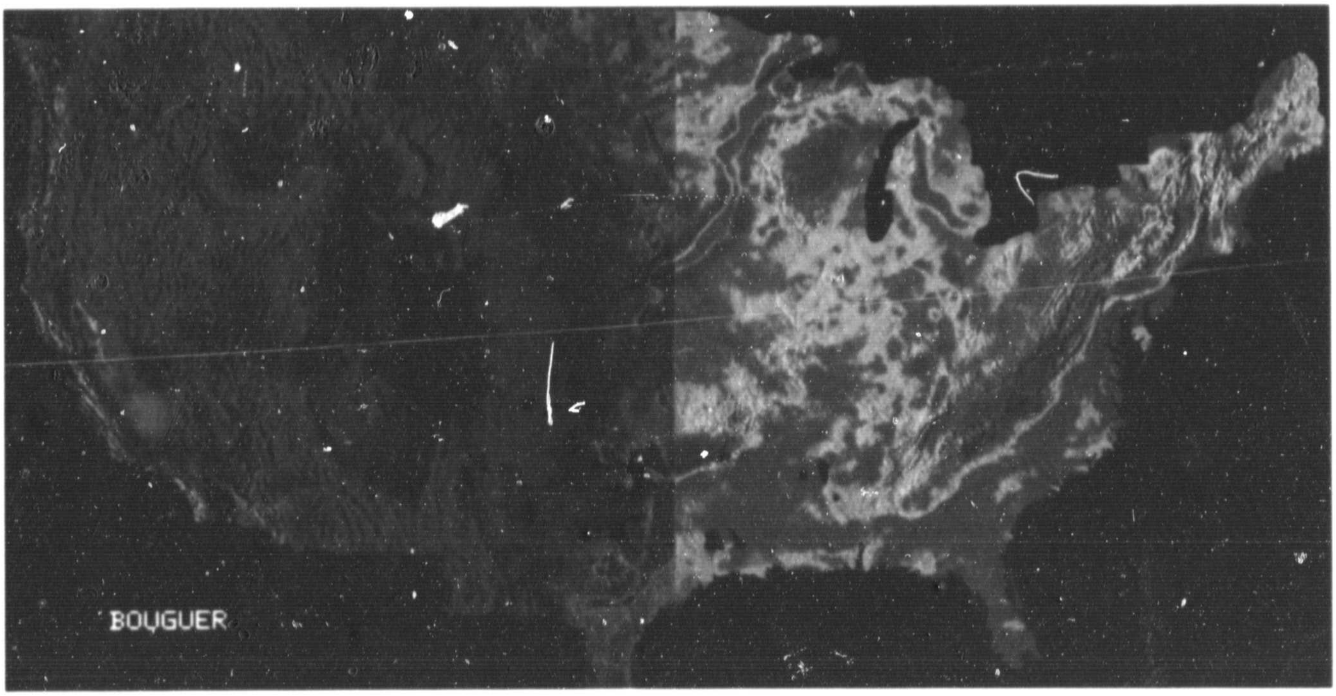
*The Oceanography Report*
*page 267*

ORIGINAL PAGE
COLOR PHOTOGRAPH

# EOS

Transactions, American Geophysical Union
Vol. 63 No. 18 May 4, 1982





EOS, Vol. 63, No. 18, Pages 261–265, May 4, 1982

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

***R. E. Arvidson, E. A. Guinness, J. W. Strebeck, G. F. Davies, and K. J. Schulz***

McDonnell Center for the Space Sciences
Washington University
St. Louis, Missouri

## 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 coterminus 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; *McNutt*, 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 *Moik* [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 Seeliger 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 [*Batson et al.*, 1975].

The gravity data were reduced to Free air and to Bouguer anomalies courtesy of the Geopositional Department, Defense Mapping Aerospace 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: $\Delta g_{FA} = g + 0.3086h - \gamma$, where $\Delta g_{FA}$ = Free air anomaly (mGal), $g$ = reading, $h$ = 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 gm/cm$^3$, using $\Delta g_{BA} = \Delta g_{FA} - 0.1119h$, where $\Delta g_{BA}$ = 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

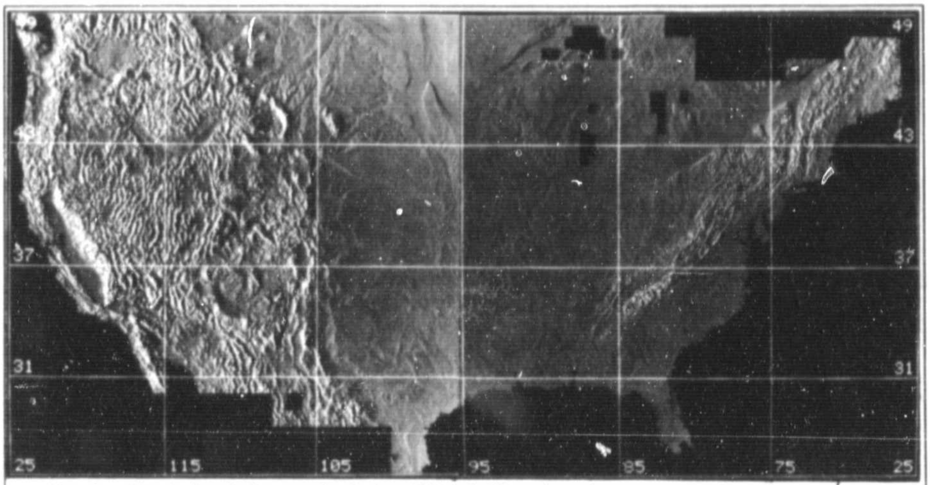


*Fig. 1.* Shaded relief map depicting NOAA 30-s elevation averages for the continental United States. Numbers running vertically along the sides of the image are degrees of north latitude, while numbers along the bottom are degrees of west longitude. This and other maps in the paper are Mercator projections. The simulated sun was set at 20° above the western horizon. Dark blocky areas are missing data.

0096-3941/82/6318-0261$01.00

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

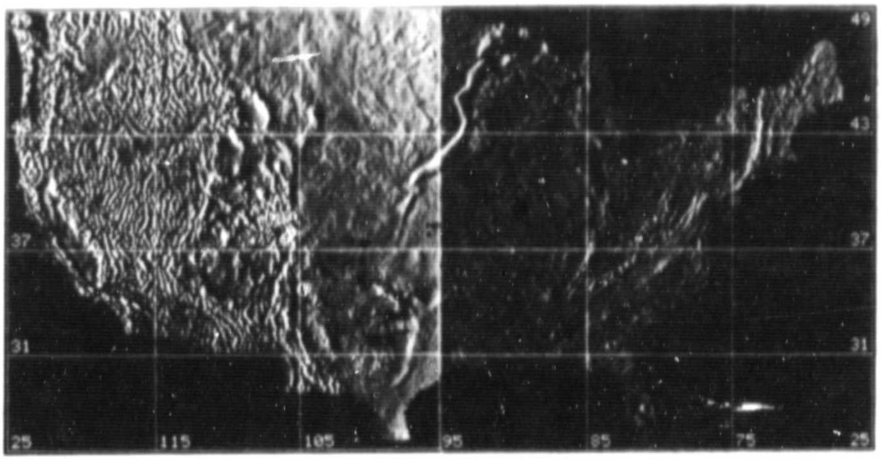


*Fig 2* Shaded relief map depicting filtered Free air anomalies. Black areas indicate regions containing either bad data or too little data to have statistically valid interpolations. The simulated sun was set at 15° above the western horizon. Variations in the anomalies are, in effect, illuminated as if they were a set of 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.

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 [*Eliason 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 postion 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 × 3 element filter and ending with a 21 × 21 element filter. The threshold was set such that at least 20% of the element locations at any given filter position must have had 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 × 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 operations 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 × 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 Bouguer anomalies, respectively. Comparison of these products with previously published contour maps [e.g., *Woolard and Joesting*, 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 overlayed onto the topography for a visual display of the correlations between the two variables. The technique that we used was to first convert the byte value for each element in the gravity arrays 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 overlayed onto a shaded relief map of the topography simply by re-

*All of the authors are with the Department of Earth and Planetary Sciences, Washington University.*

**Raymond E. Arvidson** *(far right) is an associate professor and received his Ph.D. from Brown University in 1974. He has been involved in planetary research and remote sensing for about a decade, including serving as team leader for the Viking Lander Imaging Team. He is currently a member of the National Academy of Sciences' Space Science Board and chairman of the board's Committee on Computation and Data Management. He is also an associate editor of JGR.*

**Edward A. Guinness** *(far left) received his Ph.D. in 1980 in planetary geology from Washington University and is now a senior scientist at the university's McDonnell Center for the Space Sciences. He spent a total of a year at the Jet Propulsion Laboratory, participating in the Viking mission operations. Guinness did his thesis research on the spectrophotometric properties of Martian surface materials, based on lander imaging data. He is continuing those studies, using data received from direct links from the Mutch Memorial Station (Viking Lander 1).*

**John W. Strebeck** *(second from right) received his master's degree from Washington University in 1982. His thesis topic involved geological and geophysical interpretations of the Missouri gravity low, a feature discussed in this paper. Strebeck is currently employed by Mobil Exploration Services, Inc., Dallas, Texas.*

**Geoffrey F. Davies** *(middle) is an associate professor and received his Ph.D. in 1972 from the California Institute of Technology. His research interest range from thermal evolution histories of the earth and planets to mantle convection and the tectonic evolution of continents. He has served on NASA advisory panels and is an associate editor of JGR.*

**Klaus J. Schulz** *(second from left) is an assistant professor and received his Ph.D. in petrology from the University of Minnesota in 1977. His interests range from the petrogenesis of the early continental crust to the effects that large impact events had on the subsequent thermal and tectonic regime of the earth's early lithosphere. Schulz will join the U.S. Geological Survey, Reston, Virginia, in June 1982.*

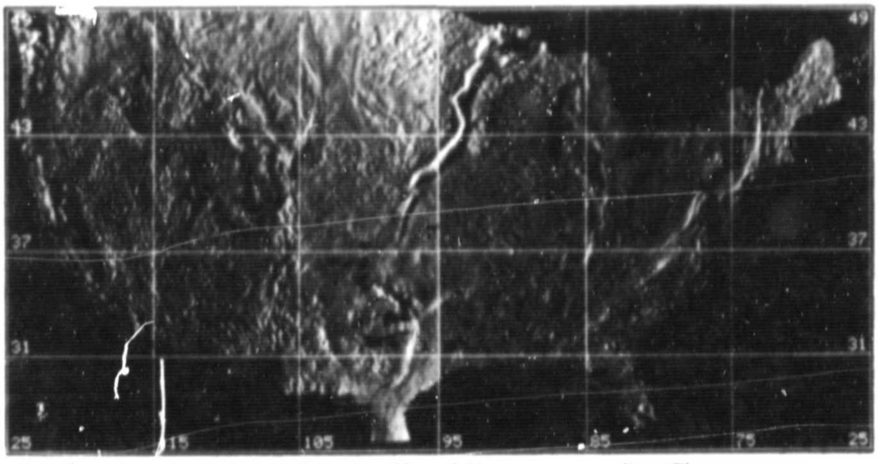


*Fig. 3.* Shaded relief map depicting filtered Bouguer anomalies. The map was produced in the same manner as the Free air anomaly map in Figure 2. No local terrain corrections were included in computing Bouguer anomalies.

placing the brightness component for each color with the brightness from the corresponding location in an array containing the shaded relief map. The net result is a color map where the brightness is modulated by the shaded relief map, while the color hue (dominant wavelength) and saturation (degree of purity) are controlled by the gravity anomaly values. Note that any color can be uniquely defined by a hue (dominant wavelength), saturation (purity), and brightness [*Slater*, 1975]. Such products are shown for both the filtered Free air and Bouguer anomalies on the cover of this issue of *Eos*. In both cases the maps were transformed to a Mercator projection, digitally reduced by a factor of 7, and then processed as discussed above.

## 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 Missouri gravity low and the Mississippi Valley graben, as defined by *Kane et al.* [1981] on the basis of gravity and aeromagnetic anomalies. The 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 [*Ervin and McGinnis*, 1975]. The low has a Bouguer 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 gm/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 [*Guinness et al.*, 1982].

The intersection of the Missouri gravity low and the Mississippi Valley graben has clearly served to control the emplacement of two mafic plutons defined by *Hildenbrand et al.* [1977]: the Bloomington 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 1000 earthquake epicenters recorded by the St. Louis University seismic network between 1974 and 1979 [*Stauder 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 genetically 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 Altyn Tagh of China [*Molnar and Tapponier*, 1975]. 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 and province boundaries defined by *Bickford et al.* [1981] in Missouri. For instance, the feature could have formed during the postulated collision event that produced the Grenville orogeny [*Dewey and Burke*, 1973].

## 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 radio-

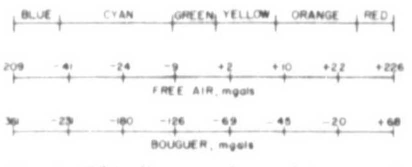


*Fig. 4.* This diagram shows the approximate color-coding scheme used to produce the color contours for the gravity anomaly maps shown on the cover of this issue of *Eos*. Histograms showing the fractional area occupied by each anomaly value were used to assign colors in such a manner that each color 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.

**Cover.** About a half million Free air and Bouguer anomalies for land stations covering the United States were spatially filtered to form a regular array of interpolated data. The anomaly values were then color-coded and overlayed onto a shaded relief map of topography. The simulated sun for the shaded relief map is from the west at 20° above the horizon. The color-coding scheme for the Free air data is approximately as follows: blue, less than −34 mGal; blue-green, −34 to −10 mGal; green, −10 to −3 mGal; yellow, −3 to +10 mGal; orange, +10 to +26 mGal; red, greater than +26 mGal. The color-coding scheme for the Bouguer data is approximately as follows: blue, less than −212 mGal; blue-green, −212 to −128 mGal; green, −128 to −84 mGal; yellow, −84 to −47 mGal; orange, −47 to −17 mGal; red, greater than −17 mGal.

*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.

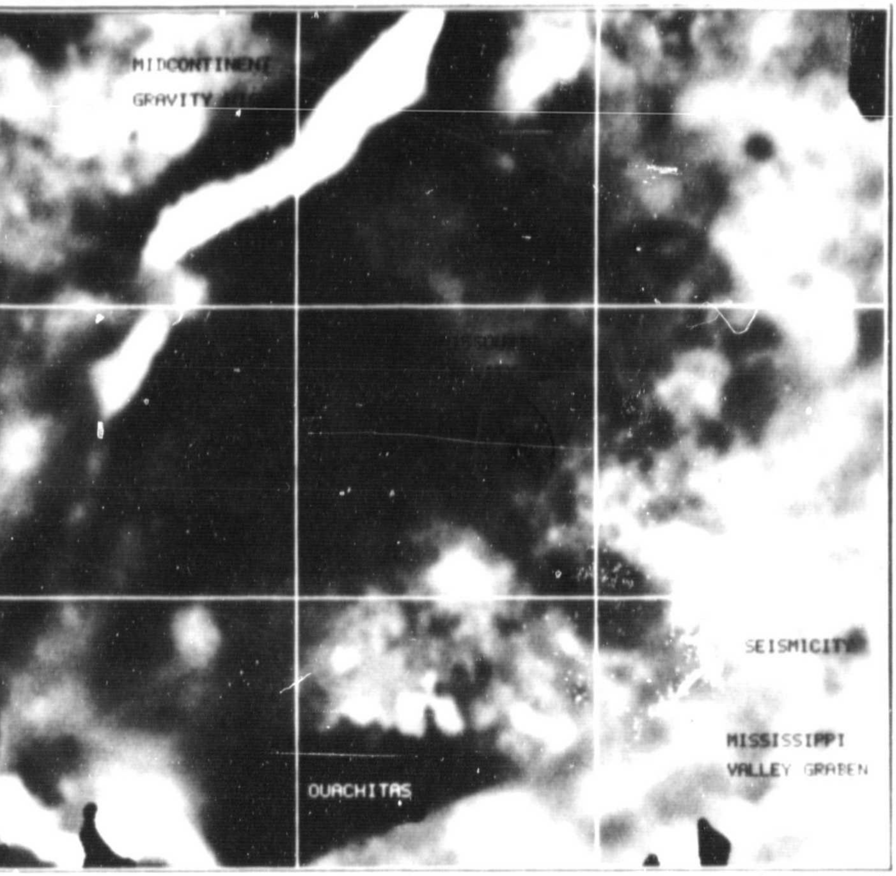


*Fig 6.* Gray tone version of the filtered Free air anomalies. The map boundaries extend from 34° to 43°N, 87° to 99°W. The two horizontal lines correspond to 37° and 40°N latitude, while the two vertical lines are 91° and 95°W longitude. In this map, bright areas have large Free air anomalies, while 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.

activity) data, aeromagnetic anomalies, and hydrogeochemical data for most of the continental United States. Such large data sets are aptly 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.

## Acknowledgments

This work was carried out with funding from the NASA Office of Space Science and Applications, Nonrenewable Earth Resources, through a contract (955959) from the Jet Propulsion Laboratory. 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, to the Geopositional Division, Defense Mapping Aerospace Agency Center, St. Louis, Mo., for gravity data; and to NOAA for the topography data.

## References

Batson, R. M., K. Edwards, E. M. Eliason, Computer-generated shaded relief images, *J. Res. U.S. Geol. Surv.*, *3*, 401–408, 1975.

Bickford, M. E., K. Harrower, W. Hoppe, B. Nelson, R. Nusbaum, J. Thomas, Rb-Sr and U-Pb geochronology and distribution of rock types in the Precambrian basement of Missouri and Kansas, *Geol. Soc. Am. Bull.*, *92*, 323–341, 1981.

Dewey, J. F., and K. Burke, Tibetan, Variscan, and Precambrian basement reactivation: Products of continental collision, *J. Geol.*, *81*, 683–692, 1973.

Eliason, E., and L. A. Soderblom, An array processing system for lunar geochemical and geophysical data, *Proc. Lunar Planet. Sci. Conf. 8th*, 1163–1170, 1977.

Ervin, C. P., and L. D. McGinnis, Reelfoot rift: Reactivited precursor to the Mississippi embayment, *Geol. Soc. Am. Bull.*, *86*, 1287–1295, 1975.

Guinness, E. A., J. Strebeck, R. Arvidson, K. Schulz, G. Davies, Basement structure of the Ozark Plateau, Missouri-topography, gravity, seismic, and remote sensing data, submitted to *J. Geophys. Res.*, 1982.

Hildenbrand, T. G., M. F. Kane, and W. J. Stauder, Jr., Magnetic and gravity anomalies in the northern Mississippi embayment and their spacial relation to seismicity, *Misc. Field Stud. Map MF-914*, 2 sheets, U.S. Geol. Surv., Reston, Va., 1977.

Kane, M. F., T. G. Hildenbrand, and J. D. Hendricks, Model for the tectonic evolution of the Mississippi embayment and its contemporary seismicity, *Geology*, *9*, 563–568, 1981.

McGinnis, L. D., M. G. Wolf, J. J. Kohsmann, C. P. Ervin, Regional Free air anomalies and tectonic observations in the United States, *J. Geophys. Res.*, *84*, 591–601, 1979.

McNutt, M., Implications of regional gravity for state of stress in the earth's crust and upper mantle, *J. Geophys. Res.*, *85*, 6377–6396, 1981.

Moik, J. G., Digital processing of remotely sensed images, *Rep. SP-431*, 330 pp., Nat.

Aeronaut. Space Admin., Washington, D.C., 1980.

Molnar, P., and P. Tapponnier, Cenozoic tectonics of Asia: Effects of a continental collision, *Science, 189*, 419–426, 1975.

Pettengill, G., E. Eliason, P. Ford, G. Loriot, H. Masursky, Pioneer-Venus radar results: Altimetry and surface processes, *J. Geophys. Res., 85*, 8261–8270, 1980.

Slater, P. N., Photographic systems for remote sensing, in *Manual of Remote Sensing*, edited by R. G. Reeves, pp. 235–323, American Society of Photogrammetry, Falls Church, Va., 1975.

Stauder, W., M. Kramer, G. Fischer, S. Schaeffer, and S. T. Morrissey, Seismic characteristics of southeast Missouri as indicated by a regional telemetered microearthquake array, *Bull. Seismol. Soc. Am., 66*, 1953–1964, 1977.

Strebeck, J. W., Structure of the Precambrian basement in the Ozark plateau as inferred from gravity and remote sensing data, Masters thesis, Washington University, St. Louis, Mo., 1982.

Woollard, G. P., and H. R. Joesting, Bouguer Gravity Anomaly Map of the United States, U.S. Geol. Surv., Reston, Va., 1964.

# APPENDIX III

# IDENTIFICATION OF A PRECAMBRIAN RIFT THROUGH MISSOURI BY DIGITAL IMAGE PROCESSING OF GEOPHYSICAL AND GEOLOGICAL DATA

E.A. Guinness, R.E. Arvidson, J.W. Strebeck,
K.J. Schulz, G.F. Davies, and C.E. Leff
Department of Earth and Planetary Sciences
McDonnell Center for the Space Sciences
Washington University
St. Louis, Missouri 63130

SUBMITTED TO JGR: 11/1/81

REVISED: 5/28/82

# ABSTRACT

Digital free air and Bouguer gravity anomaly images have been constructed from approximately 287,000 station readings for the region bordered by 25° to 49° N. lat. and 80° to 110° W. long. 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 graben to form the Pascola arch. The anomaly varies from 120 to 160 km in width, extends about 700 km, and is best expressed in southern Missouri, where it has a Bouguer amplitude of approximately -34 milligals. The magnitude of the anomaly 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. Some of the discrete positive magnetic anomalies in Missouri are located 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 preceeded 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, topographic, 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.

## DESCRIPTION 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 kilometers 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 1943 map was checked against a new, unpublished map by I. Zietz and both maps were found to exhibit similar trends. The 1943 map was photographed onto film and the film was then scanned and 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 (one channel covering 0.5 to 1.1 micrometers) and in the thermal infrared (one channel from 10.5 to 12.5 micrometers) (Price, 1977). Each image element in the HCMM data covers about 500 m 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 the Lommel-Seeliger scattering law (Batson et al., 1975). The simulated sun 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 x N elements. The average of the valid data points within any given filter location is computed and used to replace the center 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 x 3 element filter and ending with a 21 x 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 are 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 entire 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 Bouguer 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 some of the major structural features seen in the free air anomaly images shown in Figures 2, 3, and in Bouguer image shown in Figure 4. 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 Keweenawan basalts that date at 1.1 billion years, 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 can 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-Arbuckle system are just a few of the other features that have a recognizable gravity signatures. For reference, the Ouachitas have minimum free air and Bouguer anomalies of -70 and -89 milligals.

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 (40.5° N. lat., 96° W. long.), strikes in a southeasterly direction, and extends to the Mississippi Valley graben as defined by Kane et al. (1981) (36° N. lat., 90° W. long.). The low varies between 120 to about 160 km in width, extends about 700 km in length, and is best expressed for the 300 km of its length closest to the graben. The feature also exhibits a irregular medial high (Figure 3) midway between the midcontinent gravity high and the graben. 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 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. The gravity low exhibits a Bouguer anomaly of -34 milligals for the region beneath the profile. 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 hundreds of 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 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 arguement 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 just to the southeast of profile A-A', 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. 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/cm3 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 within the crust cause the gravity anomaly, than the anomaly would be consistent with rocks that were 0.1 gm/cm3 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 additional seismic or rock type constraints on the crustal structure, 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 1.61 to 1.65 billion years old rocks composed largely of sheared granites and metasediments, and younger 1.38 to 1.48 billion years 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. Based on the rock-type data there also appears to be 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 structural 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. Some of the magnetic highs coincide with discrete gravity highs, such as in the area underlain by the Bloomfield intrusion in southeastern Missouri (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.

Previous work shows that magnetic highs in Missouri can be correlated with enrichment of magnetite in felsic volcanic rocks, and with the presence of mafic and therefore magnetite-rich intrusions (Allingham, 1964; Phelan, 1969; Cordell, 1979). In addition, local relief with the basement rocks also contributes to low amplitude anomalies (Allingham, 1964). The location of some of the discrete magnetic highs along the flanks of the gravity low suggests that the flanks correspond to zones of weakness where magmas have 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 the magnitude of topographic slopes demonstrates that the dominate control on temperature is relief. Areas with high relief are 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 a element by element basis. The shaded relief map is shown in Figure 10 and the overlay of the IR data onto the relief map is shown in Figure 11. 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. These products were 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 12 is a sketch map showing linears from the processed HCMM data. Also shown are folds from the Missouri structural 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, 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 12. 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 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 12).

## 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, 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 (Dewey and Burke, 1973).

At this point it is useful to summarize the characteristics of the Missouri gravity low. The feature has a Bouguer amplitude anomaly of about -34 milligals in southeastern Missouri, a width varying from 120 to 160 km and it extends about 700 km in length. The flanks of the feature are the locations of some of the magnetic highs in Missouri. 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 description of a failed arm of a triple junction (Burke and Whiteman, 1973). 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 1.1 billion years (Ervin and McGinnis, 1975) or recently proposed triple pronged northern extensions of the Reelfoot (Braile et al., 1982), 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. Reactivation events may be the cause of the variable characteristics of the feature along its length. 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.

## 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 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 infrared 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 700 km long, 120 to 160 km wide, and exhibits a Bouguer amplitude of -34 milligals in southeastern Missouri. 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. Some discrete positive magnetic anomalies exist along

the flanks of the Missouri gravity low. Finally, the gravity low is may be 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 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. Mapped faults (mainly high angle normal faults) 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 failed arm of a triple junction that existed 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 within 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. Thanks must go to L. Miller for providing much help in preparing this manuscript. Conversations with M.E. Bickford, E. Kisvarsanyi, O. Nuttli, and reviews by M. Londe, R. Batiza, M. Settle, and two anonymous scientists have played an important role in allowing us to integrate the information discussed in this paper.

# REFERENCES CITED

Allingham, J.W., 1964, Low-amplitude aeromagnetic anomalies in southeastern Missouri, Geophysics, 4, 537-552.

Anderson, K.H., 1979, Geologic map of Missouri, Missouri Geological Survey publication, 1 sheet.

Arvidson, R.E., E.A. Guinness, J. Strebeck, G. Davies, K.J. Schulz, 1982, Image processing applied to gravity and topography data covering the continental United States, EOS, 63, 261-265.

Batson, R.M., K. Edwards, E.M. Eliason, 1975, Computer-generated shaded relief images, J. Res. U.S. Geol. Surv., 3, 401-408.

Bickford, M.E., K.L. Harrower, W.J. Hoppe, B.K. Nelson, R.L. Nusbaum, J.J. Thomas, 1981, Rb-Sr and U-Pb geochronology and distribution of rock types in the Precambrian basement of Missouri and Kansas, Geo. Soc. American Bull., 92, 323-341.

Braile, L.W., G.R. Keller, W.J. Hinze, E.G. Lidiak, 1982, An ancient rift complex and its relationship to contemporary seismicity in the New Madrid seismic zone, Tectonics, 1, 225-237.

Burke, K. and A.J. Whiteman, 1973, Uplift, rifting, and break-up of Africa, in D.H. Tarling and S.K. Runcorn, eds., Implications of continental drift to the Earth Sciences, Academic Press, 735-755.

Chase, C.G. and T.H. Gilmer, 1973, Precambrian plate tectonics: The midcontinent gravity high, Earth Planet. Sci. Lett., 21, 70-78.

Cordell, L., 1979, Gravity and aeromagnetic anomalies over basement structure in the Rolla quadrangle and the S.E. Missouri lead district, Economic Geology, 67, 409-425.

Dewey, J.F. and K. Burke, 1973, Tibetan, Variscan, and Precambrian basement reactivation: Products of continental collision, J. Geology, 81, 683-692.

Eliason, E. and L.A. Soderblom, 1977, An array processing system for lunar geochemical and geophysical data, Proceed. Lunar and Planet. Sci. Conf. 8th, 1163-1170.

Ervin, C.P. and L.D. McGinnis, 1975, Reelfoot rift: Reactivited precursor to the Mississippi embayment, Geol. Soc. Am. Bull., 86, 1287-1295.

Evans, L.L., 1977, Geology of the Brushy Creek Mine, Viburnum Trend, Southeast Missouri, Economic Geology, 72, 381-390.

Gerdemann, P.E. and H.E. Meyers, 1972, Relationships of carbonate facies patterns to ore distribution and to ore genesis in the S.E. Missouri lead district, Economic Geology, 67, 426-433.

Grundmann, W.H., 1977, Geology of the Viburnum No. 27 Mine, Viburnum Trend, Southeast Missouri, Economic Geology, 72, 349-364.

Kahle, A.B. and A.R. Gillespie, and A.F.H. Goetz, 1976, Thermal inertia imaging - A new geologic mapping tool, Geophys. Res. Lett., 3, 26-28.

Kane, M.F., T.G. Hildenbrand, and J.D. Hendricks, 1981, Model for the tectonic evolution of the Mississippi embayment and its contemporay seismicity, Geology, 9, 563-568.

Kisvarsanyi, E.G., 1974, Operation basement: Buried Precambrian rocks of Missouri - Their petrography and structure, Am. Assoc. Petroleum Geologists Bull., 58, 674-684.

Kisvarsanyi, G. and E.B. Kisvarsanyi, 1976, Ortho-polygonal tectonic patterns in the exposed and buried precambrian basement of southeast Missouri, Proceedings of the First International Conf. on the New Basement Tectonics, Utah Geological Association, Pub. 5, 169-182.

Kisvarsanyi, G., 1976, Precambrian metallogenesis in the St. Francois Mtns. igneous province, S.E. Missouri, in Kisvarsanyi, E.G., ed., Studies in Precambrian geology of Missouri, Missouri Geological Survey, Rept. Inves. 61, 164-173.

Kobrick, M., 1982, Topography of the terrestrial planets, Astronomy, 10, 18-22.

McCamy K. and R.P. Meyer, 1966, Crustal results of fixed multiple shots in the Mississippi embayment, Am. Geophys. Union Monograph 10, 370-381.

McCracken, M.H., 1971, Structural Features of Missouri, Missouri Geological Survey Rept. Inv., No. 44, 68p.

McGinnis, L.D., M.G. Wolf, J.J. Kohsmann, C.P. Ervin, 1979, Regional free air anomalies and tectonic observations in the

United States, J. Geophys. Res., 84, 591-601.

Moik, J.G., 1980, Digital processing of remotely sensed images, NASA SP-431, 330 p.

Mouat, M.M. and C.W. Clendenin, 1977, Geology of the Ozark Lead Company Mine, Viburnum Trend, Southeast Missouri, Economic Geology, 72, 398-407.

Nuttli, O.W., 1976, Seismological studies of Missouri crustal structure, in studies in Precambrian Geology of Missouri Div. Nat. Resources, Rept. Inves. 61, 184-189.

Offield, T.W., 1975, Thermal infrared images as a basis for structure mapping, Front range and adjacent plains in Colorado, Geol. Soc. Am. Bull, 86, 495-502.

Paarlberg, N.L. and L.L. Evans, 1977, Geology of the Fletcher Mine, Viburnum Trend, Southeast Missouri, Economic Geology, 72, 391-397.

Pettengill, G., E. Eliason, P. Ford, G. Loriot, H. Masursky, 1980, Pioneer-Venus radar results: Altimetry and surface processes, J. Geophys. Res., 85, 8261-8270.

Phelan, M.J., 1969, Crustal structure in the central Mississippi Valley earthquake zone, Ph.D. Dissertation, Washington University, St. Louis, Mo.

Price, J.C., 1977, Thermal inertia mapping: A new view of the Earth, J. Geophys. Res., 82, 2582-2590.

Russ, D.P., 1981, The structure of the Reelfoot rift and its relationship to some regional midcontinent features, Geol. Soc. Am., Abs. with Programs, 13, 543.

Sabins, F.F., 1969, Thermal infrared imagery and its application to structural mapping in southern California, Geol. Soc. Am. Bull., 80, 397-404.

Simpson, R.W. and R.H. Godson, 1981, Colored gravity anomaly and terrain maps of the east central United States, U.S. Geol. Survey Open-File Report 81-846.

Stauder, W., M. Kramer, G. Fischer, S. Schaeffer, and S.T. Morrissey, 1977, Seismic characteristics of southeast Missouri as indicated by a regional telemetered microearthquake array, Bull. Seism. Soc. Am., 66, 1953-1964.

Stewart, S.W., 1968, Crustal structure in Missouri by seismic refraction methods, Bull. Seismol. Soc. Amer., 58, 291-323.

Strebeck, J.W., 1982, Structure of the Precambrian basement in the Ozark plateau as inferred from gravity and remote sensing data, Masters Thesis, Washington University, St. Louis, Mo.

Sweeney, P.H., E.D. Harrison, and M. Bradley, 1977, Geology of the Magmont Mine, Viburnum Trend, Southeast Missouri, Economic Geology, 72, 365-371.

VanSchmus, W.R. and M.E. Bickford, 1981, Proterozoic chronology and evolution of the midcontinent region, North America, Chapter 11, Precambrian Plate Tectonics, A. Kromer (ed.), Elsevier Pub. Co., 261-296.

Watson, K., 1981, Geologic applications of thermal inertia mapping from HCMM, 1981 Int. Geosci. and remote Sensing Symp., IEEE Cat. No. 81CH1656-8, 1182.

Wise, D.U., 1976, Sub-Continental sized fracture systems etched into the topography of New England, Proceedings of the First International Conf. on the New Basement Tectonics, Utah Geological Association, Pub. 5, 416-422.

Woollard, G.P., and H.R. Joesting, 1964, Bouguer gravity anomaly map of the United States, U.S. Geol. Survey.

# 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. Also 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 patten for the linear gravity low.

Figure 4 - This color image is a combination of a color-coded version of the Bouguer image with a shaded relief version of the same data. 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 anomaly values greater than -27 milligals; yellow to orange indicates a range from -74 to -27 milligals; green corresponds to -140 to -27 milligals; blue-green denotes -200 to -140 milligals; and blue corresponds to values smaller than -200 milligals.

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. Black lines delineate the edges of the Missouri gravity low as mapped in Figures 2, 3, and 4. The dashed line corresponds to the approximate boundary between older and younger basement rocks as shown in VanSchmus and Bickford (1981). Sun is from the west at 15° above the horizon. Color values are as follows: Medium blue - felsic rocks, mainly sheared granites; yellow - granite; orange - rhyolite; purple - gabbro; dark blue - basalt; red - metasedimentary rocks; green - Sioux Quartzite; and light blue - Keweenawan sedimentary rocks. Note that metasedimentary rocks exist to the southeast of the major rock type boundary (between older sheared granites and metasediments and younger granites and rhyolites) along the gravity low.

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. Arrow points to the Bloomfield magnetic high (Phelan, 1969; Kane et al., 1981). The Bloomfield feature is probably due to a relatively mafic intrusion. 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 brighter (warmer) than regions with high relief. HCMM frame ID A-A0045-19420-2.

Figure 10 - Shaded relief map depicting topography for southern Missouri and western Illinois, with the sun at 20° above the western horizon.

Figure 11 - 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.

ORIGINAL PAGE IS
OF POOR QUALITY

Figure 12 - 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. Heavy black lines indicate the borders of the Missouri gravity low as seen in the gravity anomaly images. 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.

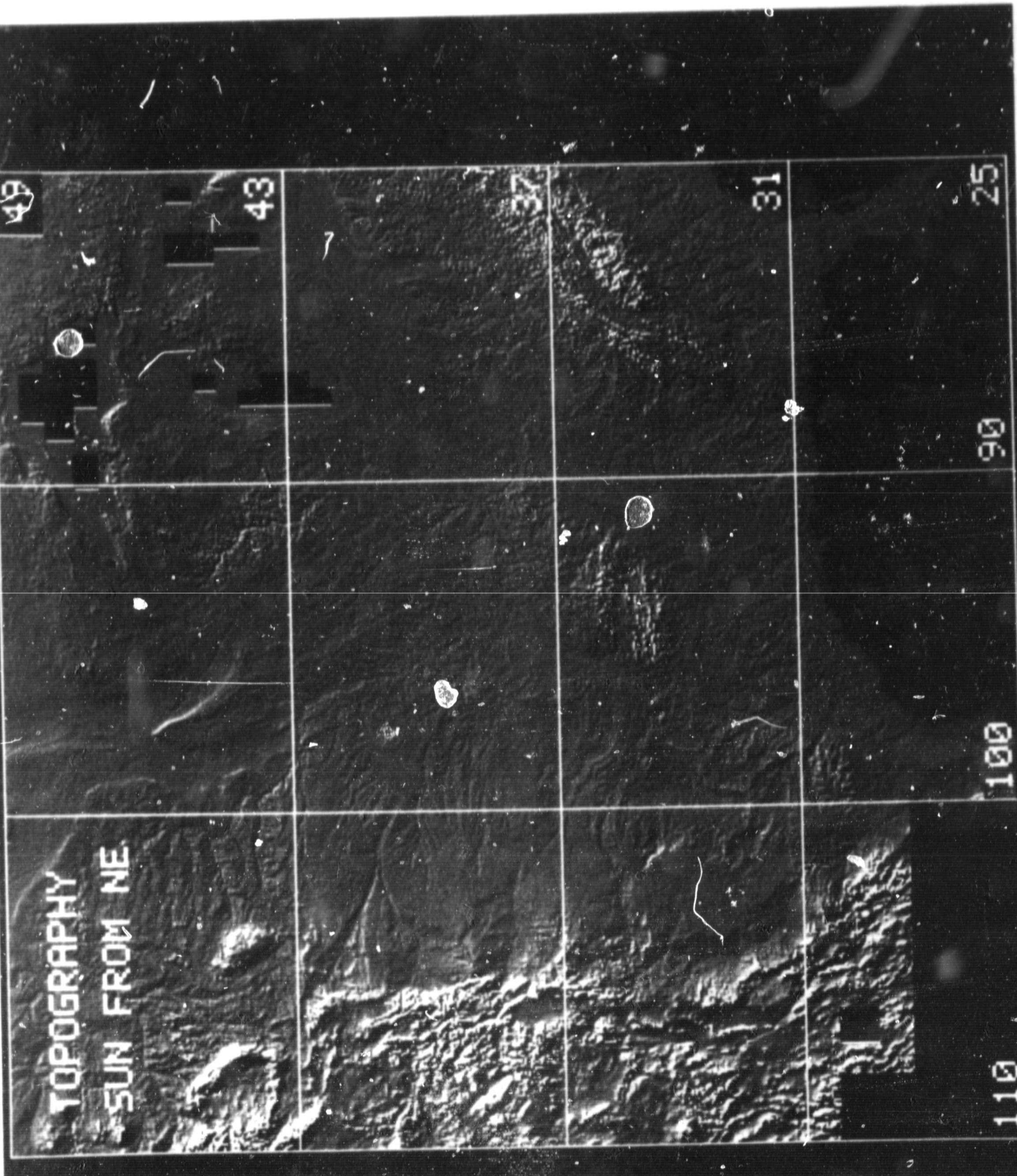


Figure 1

ORIGINAL PAGE

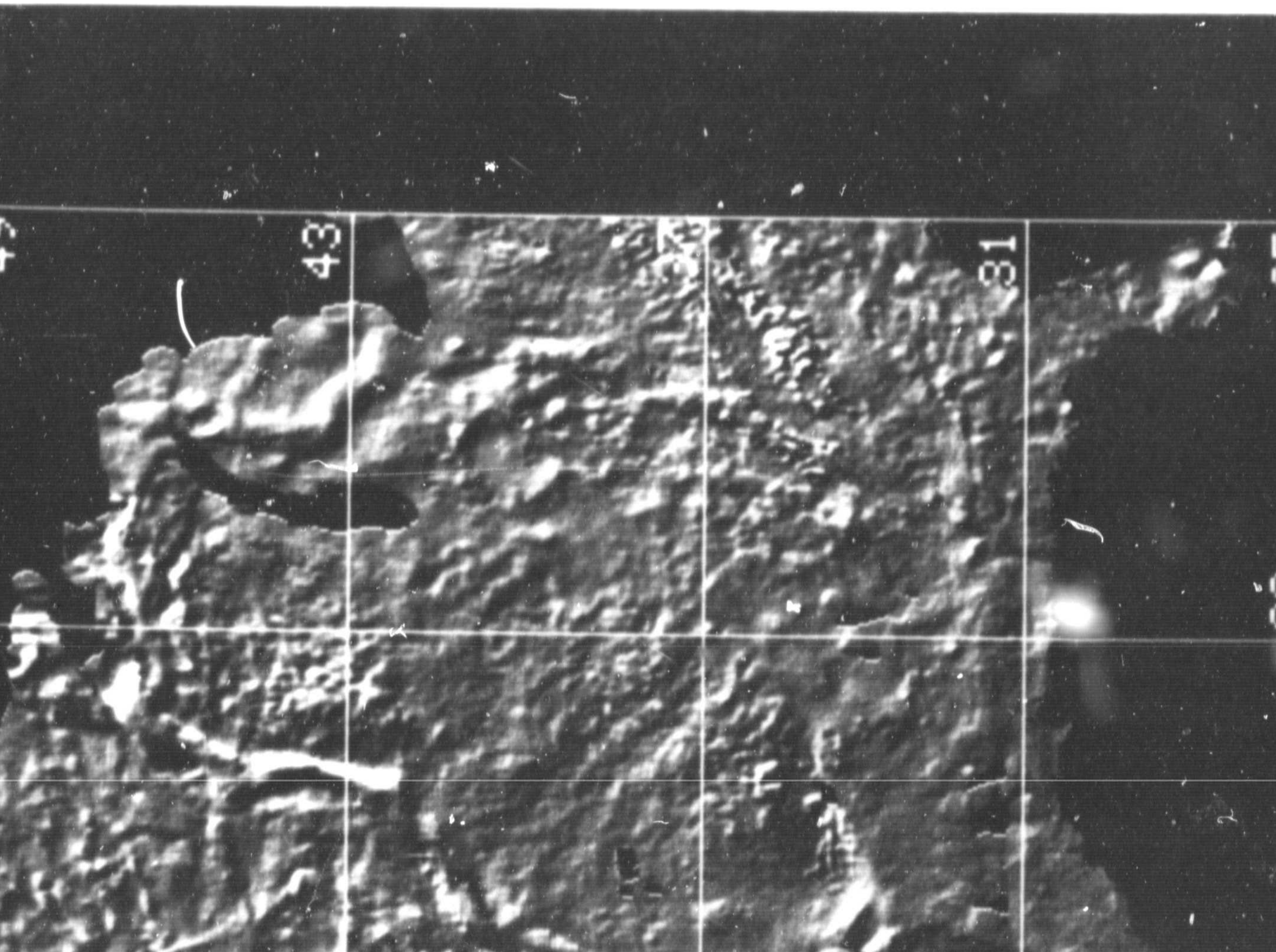


Figure 3

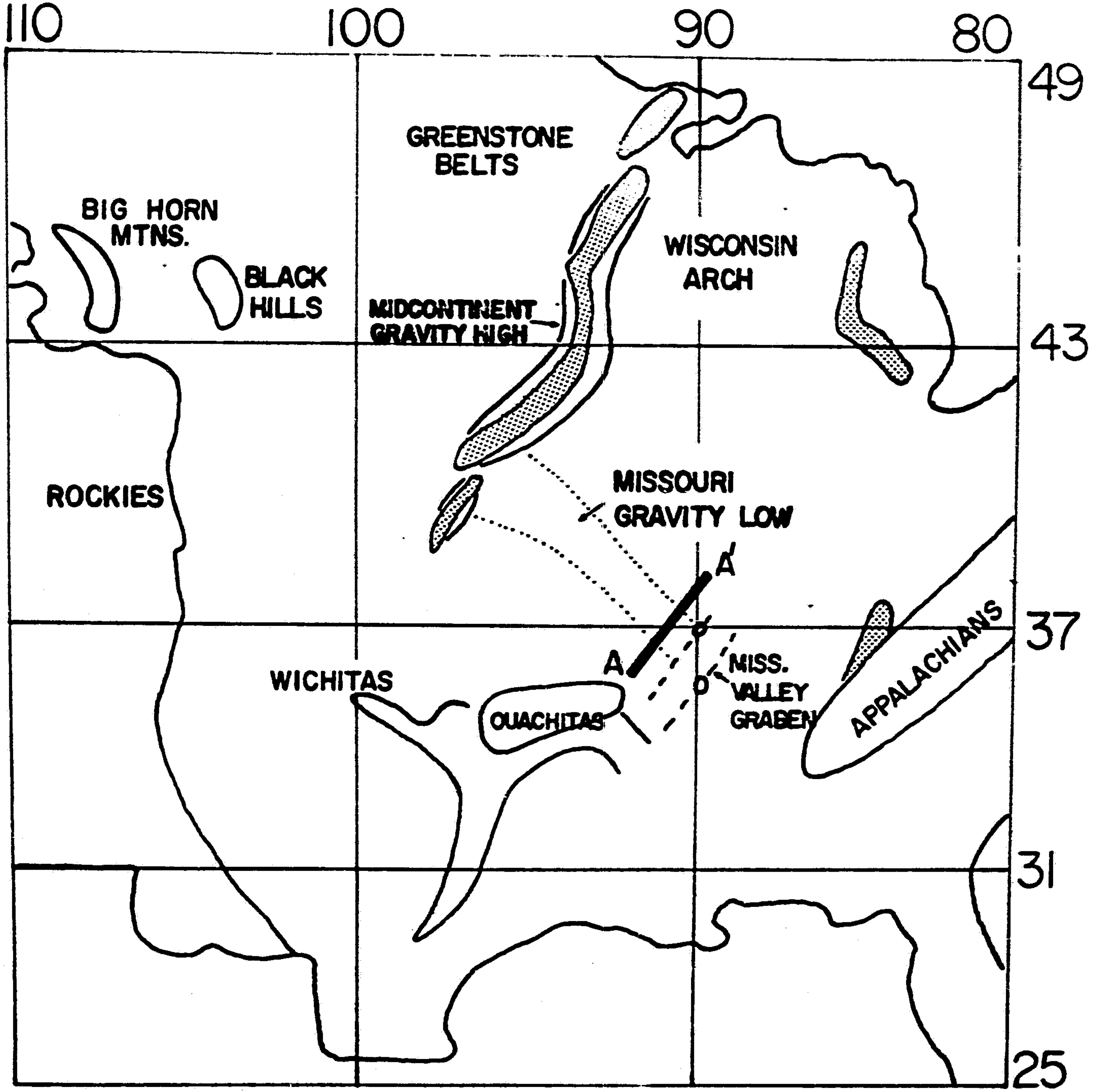

110
100
90
80
49
43
37
31
25
GREENSTONE BELTS
BIG HORN MTNS.
BLACK HILLS
MIDCONTINENT GRAVITY HIGH
WISCONSIN ARCH
ROCKIES
MISSOURI GRAVITY LOW
A'
A
WICHITAS
OUACHITAS
MISS. VALLEY GRABEN
APPALACHIANS

Figure 5

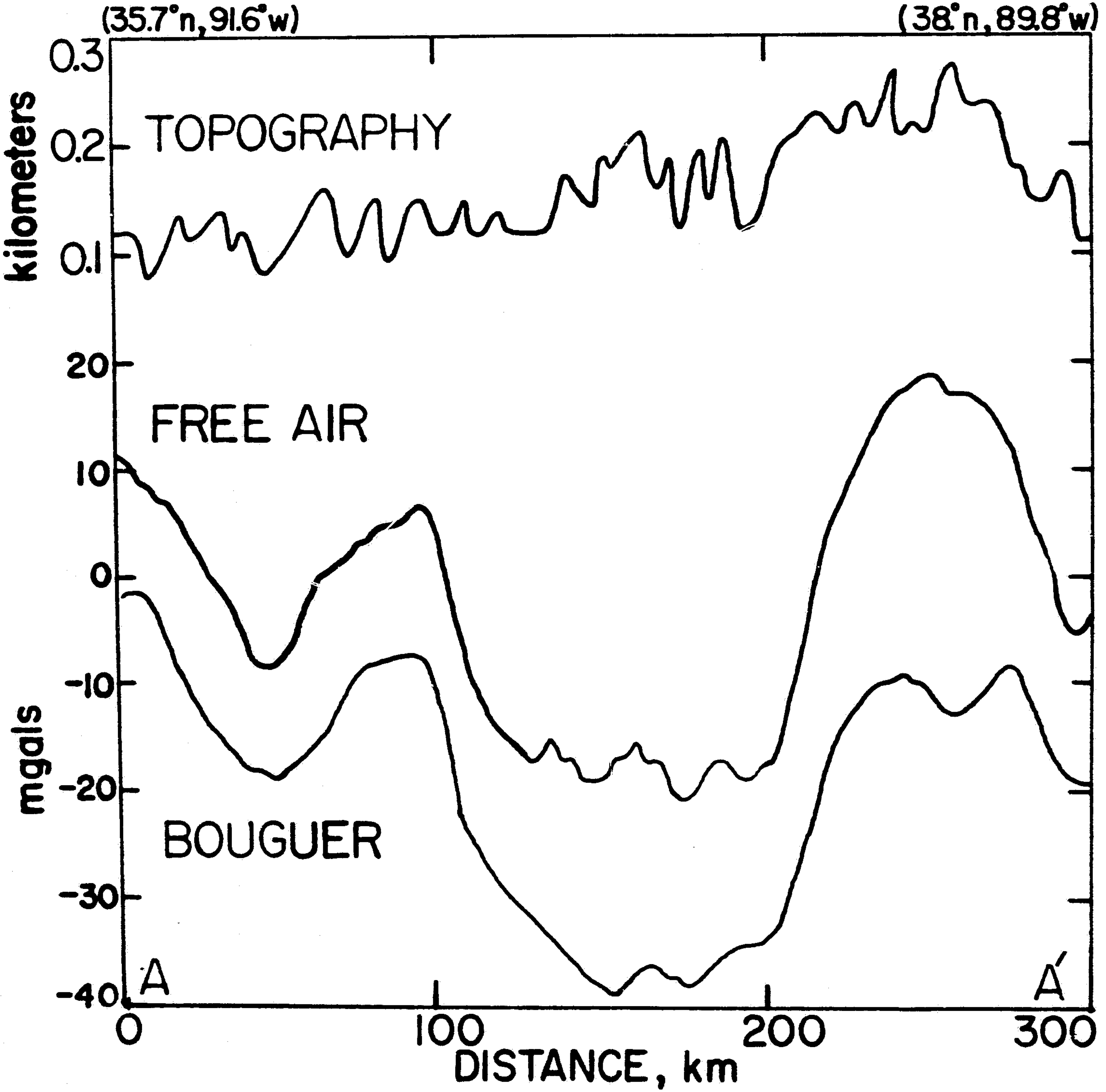

(35.7°n, 91.6°w)
(38°n, 89.8°w)
kilometers
0.3
0.2
0.1
TOPOGRAPHY
FREE AIR
BOUGUER
mgals
20
10
0
-10
-20
-30
-40
A
A′
0
100
200
300
DISTANCE, km

Figure 6

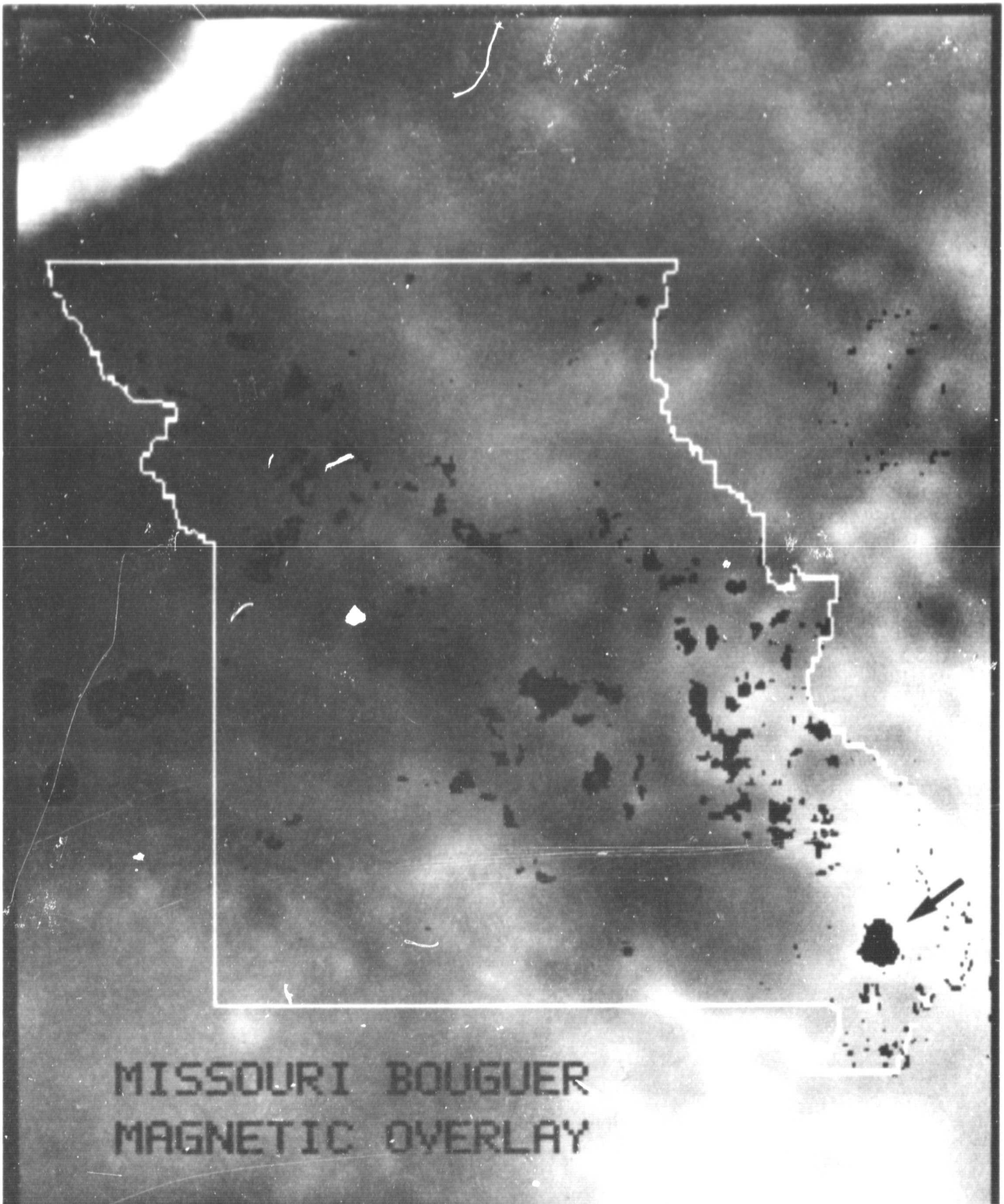


Figure 8a

ORIGINAL PAGE

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

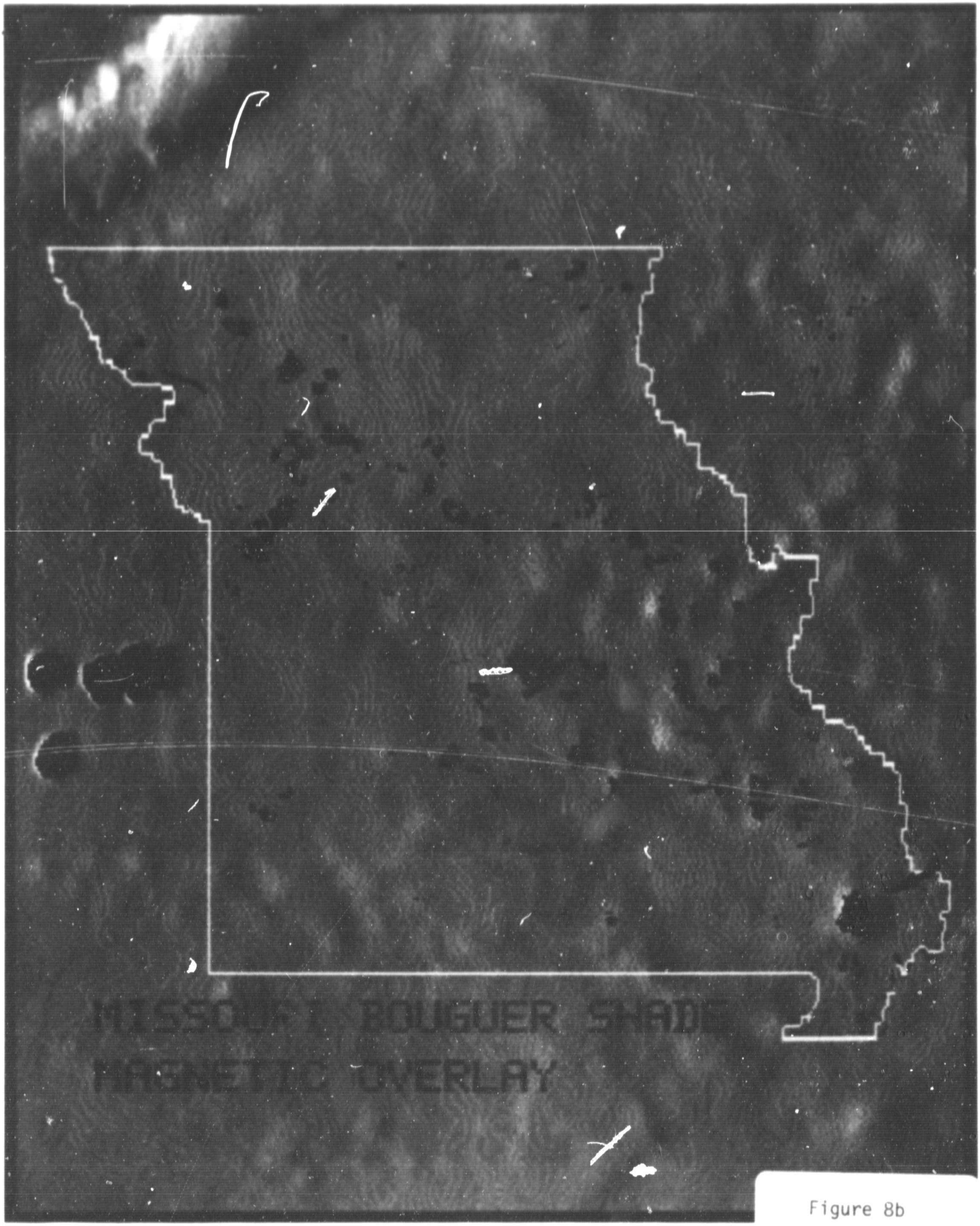


Figure 8b

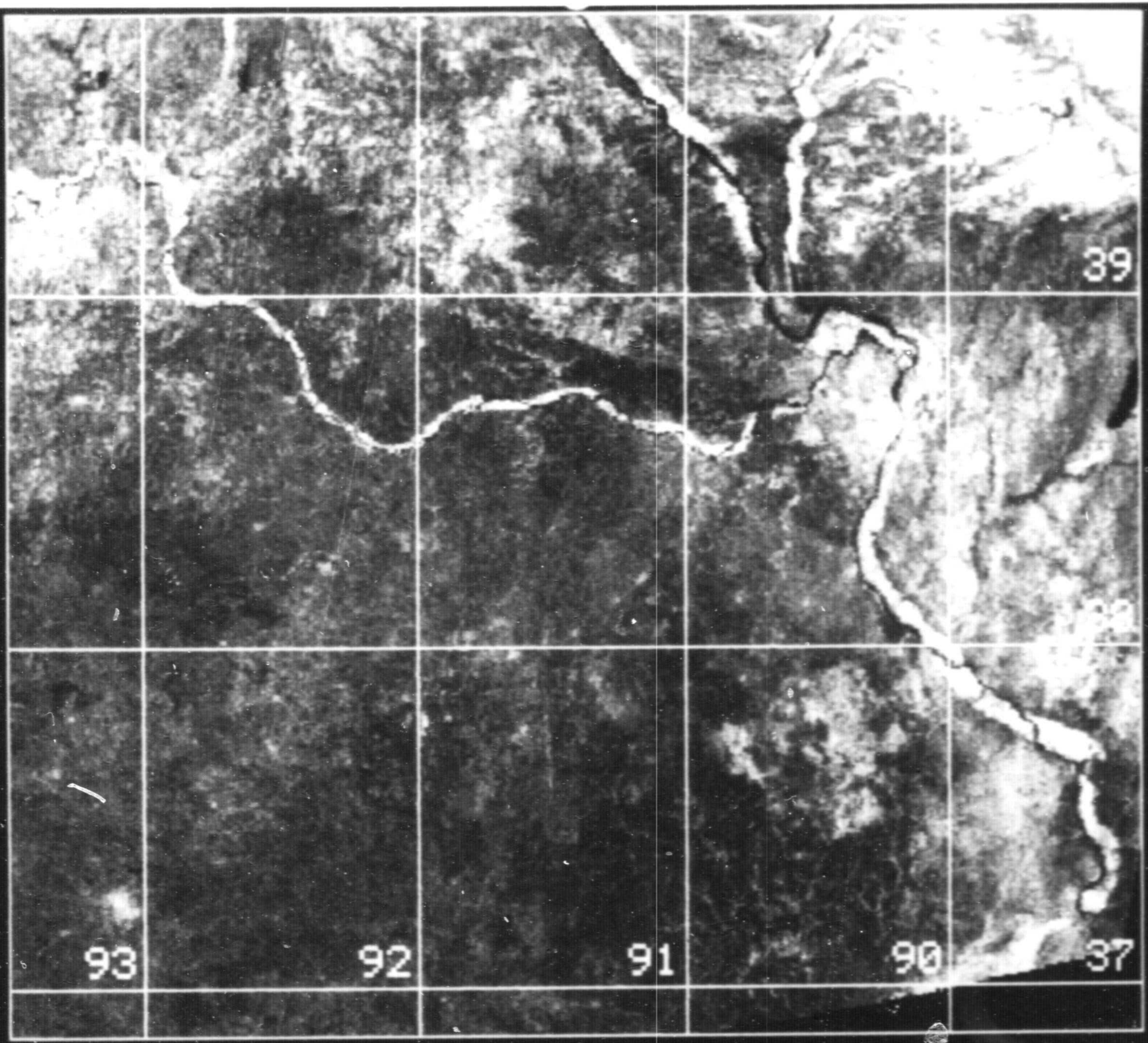
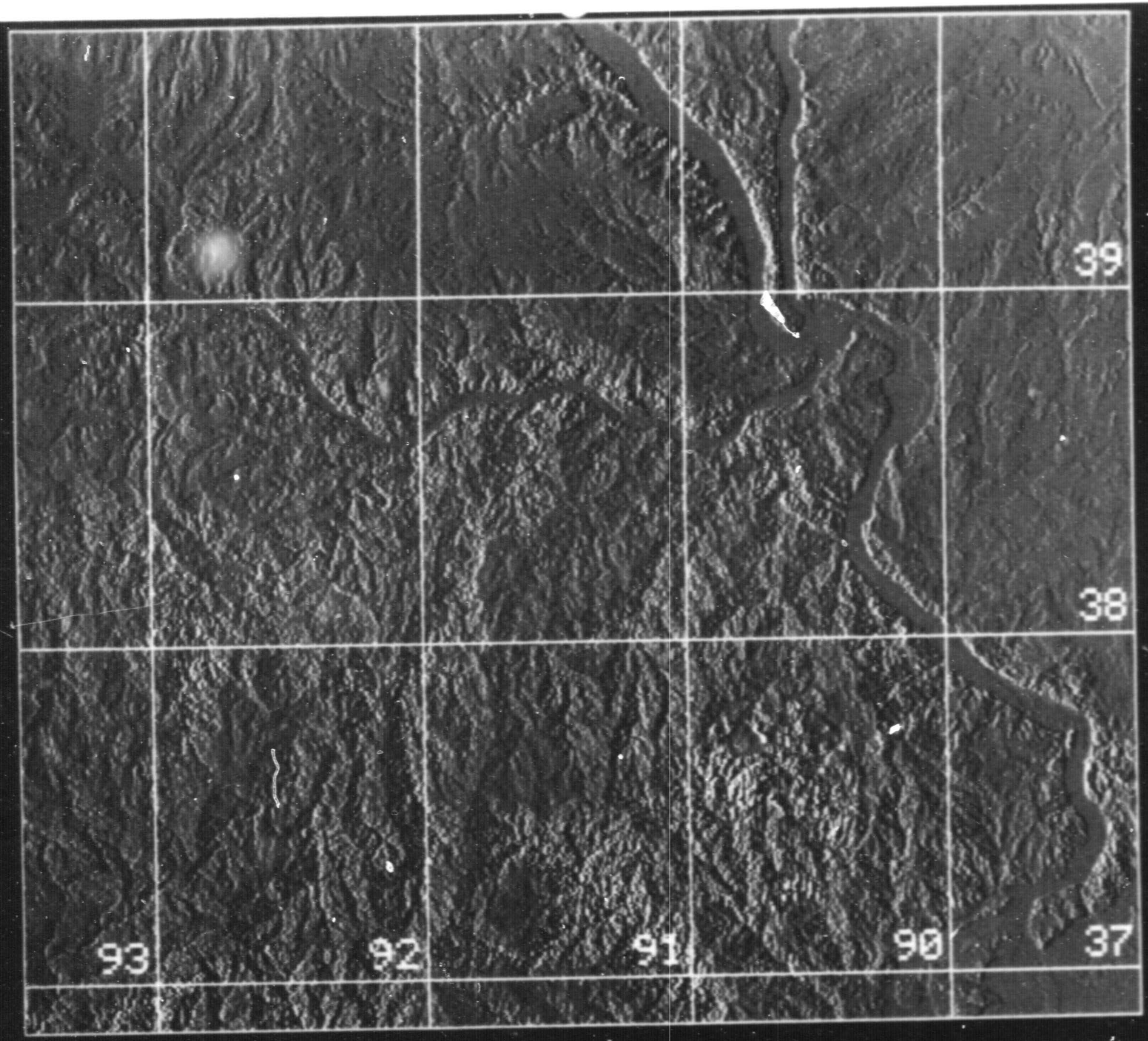


Figure 9



TOPOGRAPHY WITH SUN FROM WEST

Figure 10

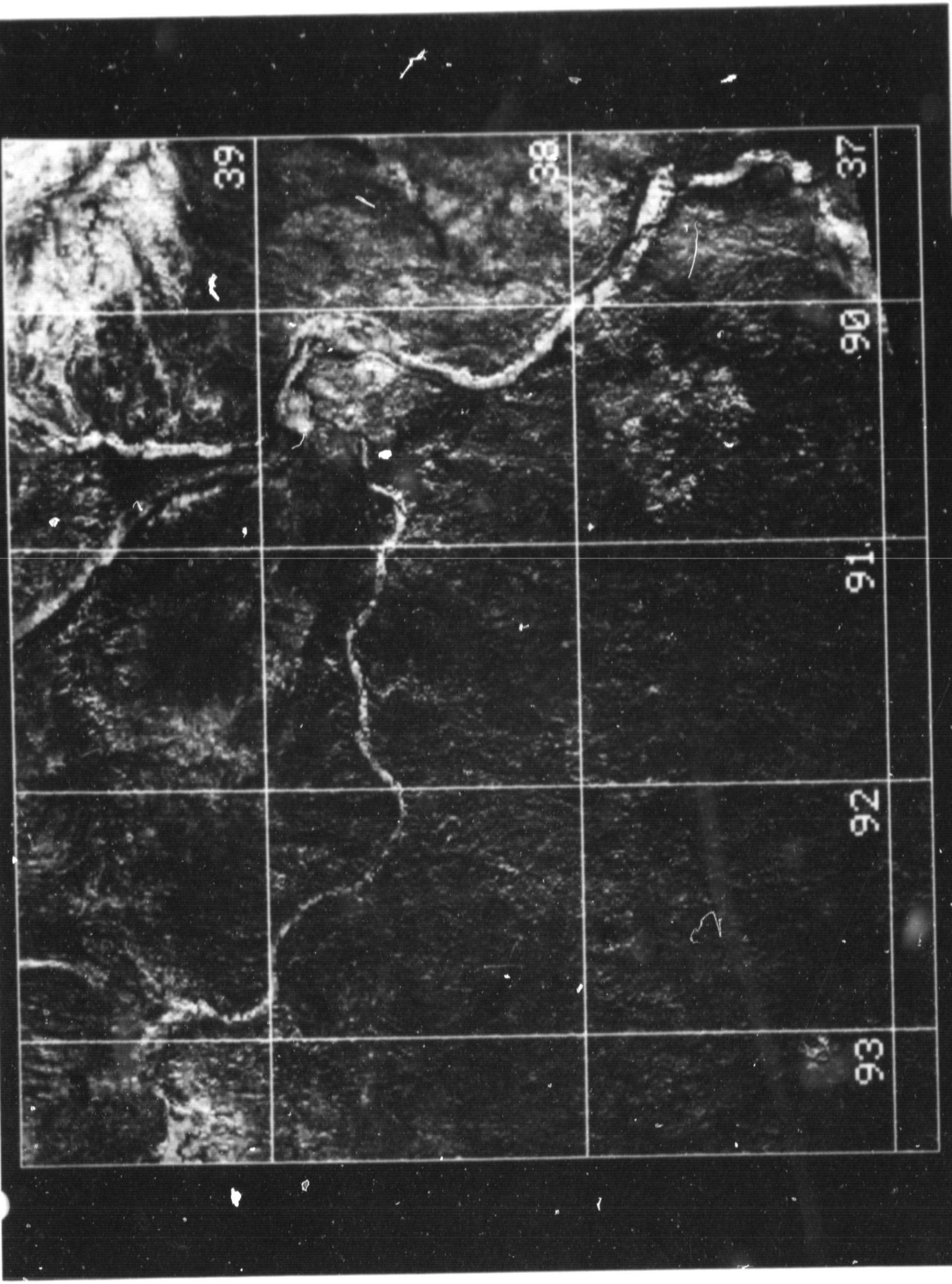


Figure 11

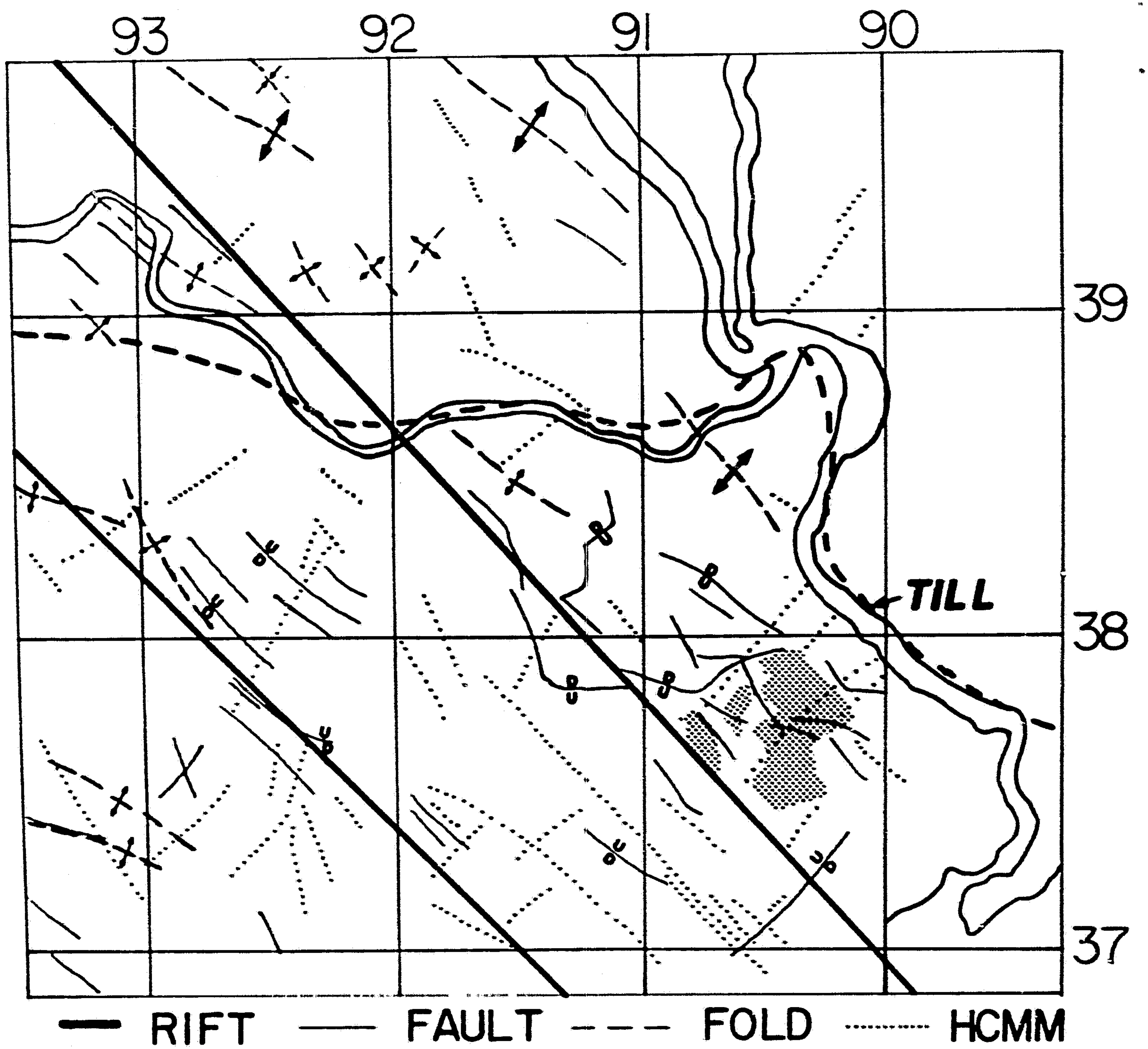


Figure 12

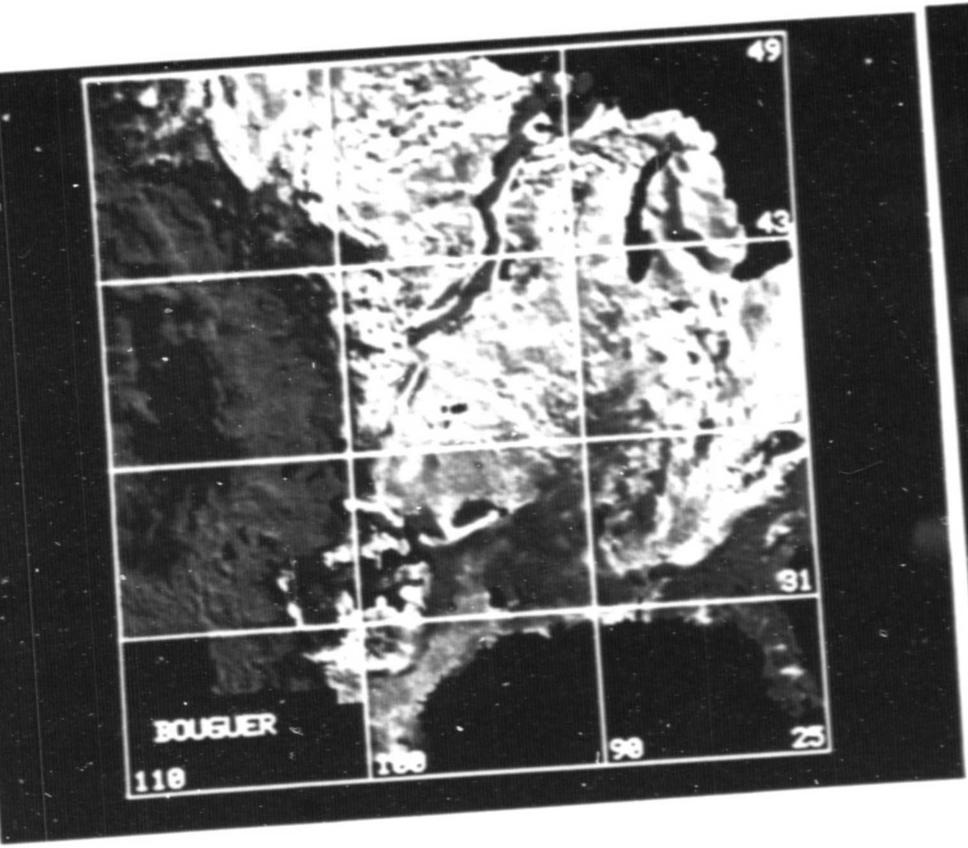


Figure 4

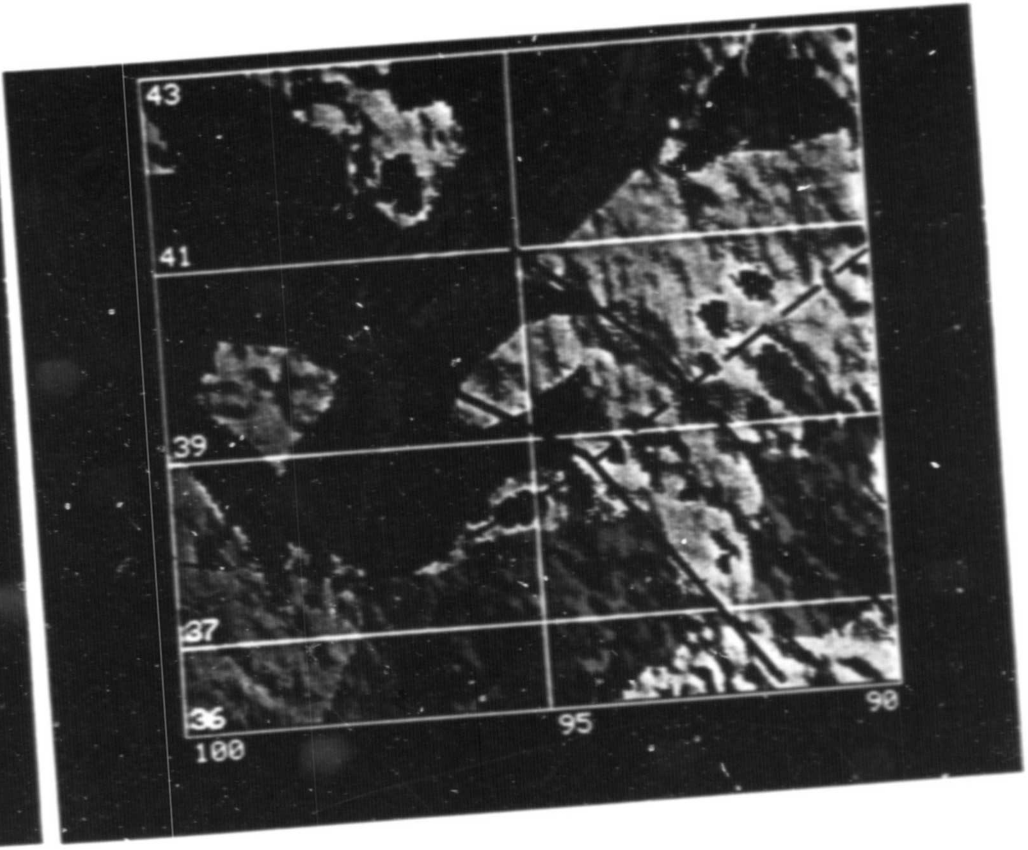


Figure 7

ORIGINAL PAGE
COLOR PHOTOGRAPH