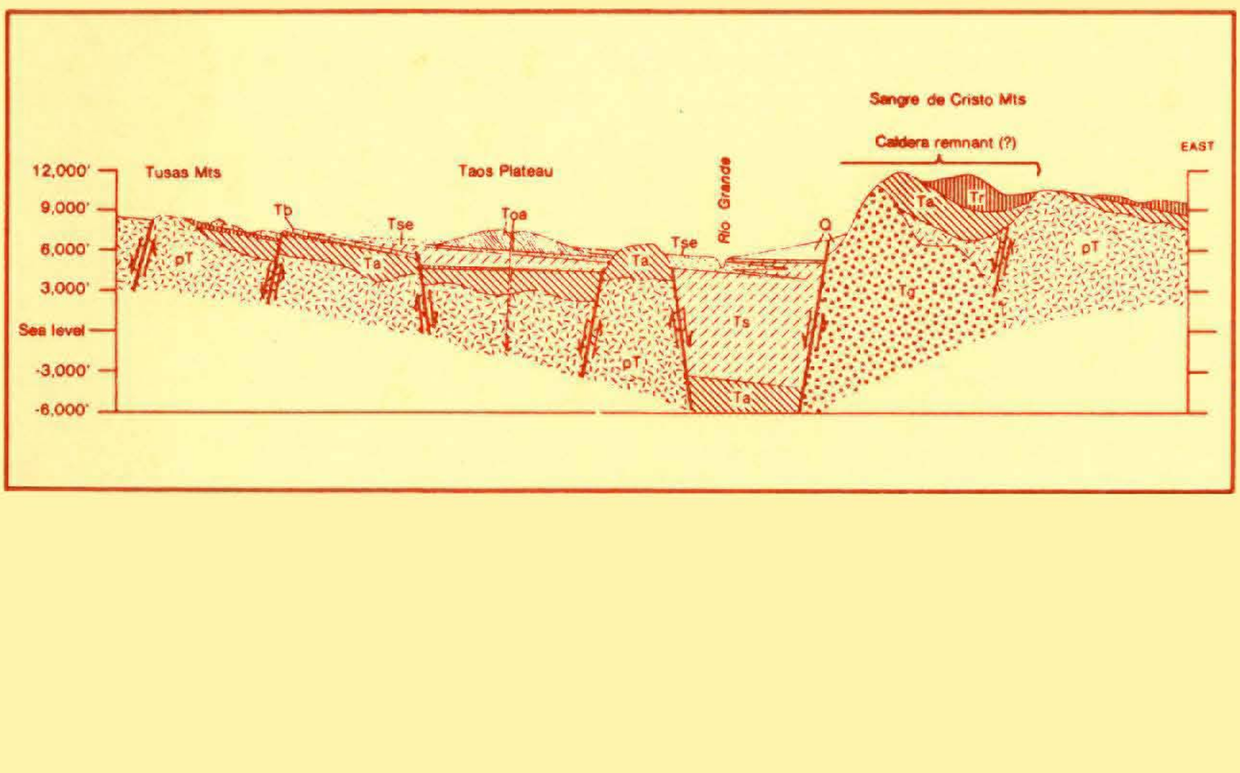
WORKSHOP ON

THE RIO GRANDE RIFT:

CRUSTAL MODELING AND APPLICATIONS OF REMOTE SENSING



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WORKSHOP ON

THE RIO GRANDE RIFT:

CRUSTAL MODELING AND APPLICATIONS OF REMOTE SENSING

Editor:
Douglas P. Blanchard

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Contents

Introduction

This volume contains abstracts of talks presented at a Workshop on the Rio Grande Rift held at the Lunar and Planetary Institute on April 21–23, 1980. Related materials, also found in this volume, include a summary of the workshop, results of the working sessions, the program, and participant list.

This workshop was organized by Douglas Blanchard of the Planetary and Earth Sciences Division of the Johnson Space Center as part of their Program on Continental Rifts, run under the auspices of the NASA Office of Space and Terrestrial Applications Branch of Non-Renewable Resources. William Muehlberger of the University of Texas, Austin served as chairman of the sessions.

Participants were asked to consider two questions: (1) What are the important problems associated with regions of continental rifting, and how are they important to the goals of the OSTA Non-Renewable Resources Program? (2) Which of these important problems are associated with the Rio Grande Rift, and how can they best be approached?

The goals of the workshop were: (1) To outline the elements of a program that could address significant earth science problems by combining remote sensing and traditional geological, geophysical, and geochemical approaches; (2) To identify specific areas and tasks related to the Rio Grande Rift which fit into such a program; and (3) To promote dialogue between ground-based and remote-sensing-based geoscientists.

A functional definition of the Rio Grande Rift

The more or less narrow linear belt extending from Leadville, Colorado, at least to El Paso, Texas, in which geologic and geophysical evidence suggests that the crust of the earth has been pulled apart and extended beginning about 26 My ago.

The rift region includes all those parts of the crust and mantle affected by this extension and related processes during that interval of time.

Workshop Summary

Douglas Blanchard

The "Workshop on the Rio Grande Rift: Crustal Modeling and Applications of Remote Sensing" was convened as part of Johnson Space Center's effort to define a project which advances the goals of the Non-Renewable Resources Branch of NASA's Office of Space and Terrestrial Applications. Approximately 45 scientists from a variety of geologic, geophysical, geochemical, and remote sensing areas of expertise attended the three day workshop. Nearly all the participants have been actively involved in research in the Rio Grande Rift. A list of participants is included in this report.

The workshop was divided into 2 parts: (1) presentation and discussion sessions intended to familiarize attendees with the present state of knowledge about the Rio Grande Rift (RGR) and (2) working sessions intended to define topical problems, assess the potential contributions of various disciplines, especially remote sensing, and identify the best next steps for continued research.

Monday was spent in a plenary session of information and discussion. Tuesday morning, the workshop split into two working groups, each with the same task: to make a nonprioritized list of significant geoscience and resource problems that can be addressed by the study of continental rifts, specifically the RGR. The unabridged lists are included in this report. The lists are somewhat uneven in level of detail and scale of problems, but they are inclusive.

Tuesday afternoon was devoted to discipline oriented presentations on remote sensing techniques. The Tuesday evening session was an informal gathering with, for the most part, unstructured discussion among the various scientists and groups.

Wednesday morning the group met in plenary session to categorize the questions formulated on Tuesday into topical research areas. After some discussion, the group agreed upon four topical areas:

History of crustal deformation
Configuration of the crust and mantle
Composition and physical state of the crust-mantle system
History of magmatism

Having agreed on the broad topical areas of research, the group then listed the various disciplines which could be brought to bear on these problems. They then engaged in a somewhat artificial exercise to rank the potential for contribution of each discipline to each of the topical areas of research. The numerical ratings are presented in Table 1. The rankings are interesting, but the real value in the exercise was the discussion of the possibilities for interdisciplinary research that evolved. Recorders for each discipline were appointed to summarize the discussion; their comments are also included in this report.

Finally, the group compiled a list of things that they felt were needed to advance the state of knowledge regarding the RGR and would foster fruitful interdisciplinary interaction. This list is also included.

Discussion

The workshop accomplished the entire process of information exchange and work laid out for it. This is a compliment to the participants who steadfastly stayed with the process and contributed to it throughout.

The workshop was successful in some areas but frustrating in others. It was successful in its goals of bringing traditional geoscientists and remote sensing scientists together in fruitful exchange, outlining a research approach to the RGR, and identifying significant problems to be worked on. However, the workshop was much less successful in identifying ways in which remote sensing could be utilized meaning-

Table 1

	Crustal Deformation	Crust-Mantle Configuration	Crust-Mantle Composition & Physical Prop.	Magmatism
	A	B	C	D
Electromagnetic R-S (1)*	2	1	1	2
Potential Field Magnetism (2)	1	1	1	0
Potential Field Gravity (2)	1	1+	1	0
Chemistry/Petrology (3)	0	2–	2	2
Geochronology (3)	2	2	2	2
Structural Geology (4)	2	1	0	1
Geomorphology (5)	2	1–	0+	2
Stratigraphy (5)	2	1–	1	2
Gravity (6)	1	2+	2	1+
Seismic Refraction				
Reflectance (7)	2	2	2	2
Other				
Electromagnetics (8)	1	2	2	2–
Magnetics (9)	0-1	1	2	1
Heat Flow (10)	1	2	1+	2
Geodetics	2	1–	0	1–
Paleoelevation (11)	2	0	0	0
Deep Drilling	1	2	2	2

*Numbers in parentheses reference discussion summaries.

Key 0 — not applicable
1 — some applications
2 — directly applicable

fully in an integrated interdisciplinary approach. Consequently, the approach we outlined did not clearly address the primary goals of the Non-Renewable Resources Program.

Remote sensing (R-S) was seen as a potential overview tool to delineate large scale regional features in early stages of an investigation. The topical research areas most directly addressable with R-S information are those that depend on interpretation of faulting patterns and topographical information. Far less optimism was expressed for meaningful rock type identification or geologic unit definition based on spectral reflectance and emittance properties. Geobotanical applications were discussed in general, but no applications specific to the RGR were identified.

There was the general opinion that R-S could be useful in remote, inaccessible areas about which we have little other information. For a region such as the RGR, the state of information and modeling has perhaps progressed beyond the point for meaningful additional contributions by remote sensing technology. The situation does provide the potential of a well known calibration area for remote sensing techniques, but, in terms of modeling the Earth's crust underlying the Rift, remote sensing seems to have little to offer directly.

The most interest and optimism was expressed in the potential use of large data base handling techniques that have been developed in conjunction with remote sensing data applications. Many of the needs perceived by the participants fall in the category of data base compilations and multiple data base correlations. This application of remote sensing related technology, which may or may not involve actual remote sensing data, is an important mechanism for interdisciplinary collaboration. The conceptual merging of discipline derived crustal models requires a different type of interaction, but it may well be stimulated by the physical merging of the data sets. Establishing a multiple data base geological information system for an area as well characterized as the RGR should represent a best possible test case for the applicability of remote sensing information. Nevertheless, there is no assurance of success in proportion to the considerable effort required to establish a data base system.

In summary, the workshop succeeded in its goals of information exchange and communication among investigators of widely varying disciplines. It was not successful in defining a meaningful remote sensing activity which would significantly advance our understanding of the crust and mantle in the region of the Rio Grande Rift.

A Nonprioritized List of Major Scientific and Resources Problems Related to Continental Rifts in General and the Rio Grande Rift Specifically

1. Modeling of the Rio Grande Rift (RGR) needs to account for features inherited from earlier rift development. Knowledge of paleotectonics (basin evolution, paleogeomorphology and structural development) is necessary for constraining models that include time as a variable. Sedimentology, sedimentary petrology and stratigraphy will allow the basin history to be integrated with the tectonic evolution of the RGR.
2. RGR and Economic Commodities and Mineral Deposits — We need a fundamental understanding of the relationships of the economic resources in the RGR region (i.e., geothermal, metallic/non-metallic, petroleum) in relation to pre-rift, contemporaneous, and post-rift structure. We need to derive an understanding of the structural control introduced upon pre-rift mineralization by rift related structure and tectonism and to understand the paragenesis of mineralization in relation to kinematic processes throughout the "RGR" region.
3. Geophysics — crust-mantle, lithosphere-asthenosphere, magma body — Past and present models of the Rio Grande Rift are critically dependent upon the configuration of the crust-mantle-lithosphere and lithosphere-asthenosphere boundaries. These boundaries are controlling factors for the intrusion and emplacement of magma into the crust. The depth and lateral extent of contemporary magma bodies are important data relating to a possible unique feature of continental rifts.
4. The timing of volcanism associated with the rift appears to be episodic. What controls this periodic process? How do magma volumes relate to this episodic cycle? Is the episodic pattern inside and outside the rift the same? How do the types of volcanics vary with time and space (inside-outside, west vs east flank) during the episodic pattern?
5. We need to gain a clearer understanding of the relation of mineral deposits to early-stage rift volcanism —especially to the clustering of ore bodies around calderas and in subvolcanic environments.
6. The axis of 10 my — recent volcanism lies in a NE trend, the so-called Jemez lineament, whereas the trend of the structural grabens is N-S. There are available data on the petrology of the volcanic trend, but geophysical data is concentrated within and in the vicinity of the structural rift. Broad scale and detailed geophysical measurements are needed along cross sections of the volcanic and structural trends. These might include gravity, conductivity, magnetics, etc. The most significant of such cross sections might be E-W ~ 20mi south of the New Mexico-Colorado border from Oklahoma to Farmington, emphasizing going far enough out to get into definite non-rift affected crust and lithosphere.
7. Displacement vectors: total and instantaneous. One of the basic data sets required for modeling of the rift is a picture of the rifting movement. These vectors are directed at obtaining a record of the movement. Knowledge of the rifting movement, lateral (rift), strike slip, and vertical (uplift), as a function of time, allows speculations and calculations concerning (i) driving mechanisms of the movement, (ii) interplay of lithosphere-asthenosphere, (iii) role of mid-crustal magma bodies, (iv) source regions of volcanism, (v) etc.
8. Can temporal and spatial geochemical-petrologic patterns of fundamentally basaltic volcanism be modeled in terms first of quantitative magma genesis processes and secondly in terms of the dynamic evolution of the crust-mantle system of the rift with time? Magma genesis reflects thermal perturbations

generated in the mantle, and individual magmas reflect specific conditions of genesis involving many parameters. Uniquely defining these parameters (depth of melting, degree of melting, source composition, volatile content and composition, etc.) requires multiple data sets including major and trace elements, isotopic systematics and petrography mineral chemistry studies. Ultimately, such detailed petrologic modeling offers the hope of monitoring changes in asthenosphere, lithosphere and crust with time as these materials are modified by transient thermal events associated with rift tectonics.

9. Tectonic geomorphology — A regional analysis of tectonic geomorphology on a quantitative basis might allow us to interpret paleotectonics (late Cenozoic) of the rift. Concepts and models developed by Bull (Univ. of Arizona) would be applicable at scales of 1:100,000 to 1:500,000. The resultant analysis will help block out both temporal and areal variations in tectonism, both uplift and extension
10. What controls the location of the rift?
11. Where and how is the rift independent of earlier structure? Why?
12. What is the magnitude of slip of earlier structure vs rift structure?
13. Which earlier structures are not used and why?
14. How does the RGR compare or contrast with other rifts?
15. What elements do the RGR have that are unique? ...in common with others?
16. What is the genetic relationship of igneous activity in the RGR and the rift itself?
17. What is the genetic relationship of the RGR and nonrenewable resources?
18. What is the RGR?
19. What is the relationship of uplift and mineralization?
20. What does the RGR have in common with mid ocean ridges?
21. What is the relationship of tectonic regime and mineralization?
22. How do hydrothermal systems relate to resources?
23. How is tectonic uplift related to resource exposure?
24. Is the rift caused by heat anomalies or tectonic causes?
25. How is "new" structure controlled by preexisting structure?
26. How much extension has occurred?
27. What is the temperature structure underlying the rift?
28. What are the characteristics of the unique midcrustal zones associated with the RGR?
29. What is the water distribution and content of the crust?
30. How is the heat flow associated with rifting?
31. How is the history of topographic evolution related to deep structure evolution?
32. What is the overall mass balance of the RGR in terms of sediments, erosional sequence, etc.?
33. What has been the drainage history?
34. What becomes of the rift to the north and south?
35. What distinguishes the RGR from basin and range?
36. How much material has been added to the RGR?
37. What is the tie between the RGR and the North American Cordilleron?
38. Upper mantle-crustal interaction — what and how much?
39. What mechanisms are operative in crustal thinning?
40. What is the extent of structural control on volcanics both in terms of compositions and placement?
41. What is the relationship of topologic surfaces to tectonic processes?

Summaries of Working Sessions

1. Electromagnetic Remote Sensing

D. Knepper, K.Meehan, M. Abrams and A. Kron

Introduction

Digital remote sensing data sets acquired from orbital altitudes can be statistically analyzed for regional terrain characteristics, as well as more localized phenomena. These analyses can be conducted relatively rapidly and, hence, could provide a substantial amount of geologic information at an early stage of investigation. Subsequent remote sensing studies could be focused on problematical areas defined by results from disciplinary studies and from the initial remote sensing study. Each remote sensing technique detects surface and/or near-surface phenomena; it is the synoptic view of surface features that makes recognition of regional patterns possible, and these patterns should be delineated at an early date. In no case can remote sensing analysis provide more than partial information, and this depends on many variables.

Crustal Deformation

Interpretation and analysis of image data can delineate regional fracture patterns that may identify unique regional structures or tectonic provinces, and provide necessary data for testing lineament tectonics theories in the Rio Grande Rift zone. Individual linear features can be examined for possible local structural significance. Spectral reflectance and emittance contrasts that define remote sensing terrain units (lithologic units, but not necessarily "formations") can be used to study rock type distribution in terms of local and regional structural features (i.e., offsets, basins, facies, unconformities). Regional cross-cutting relationships, both lineament-lineament and lineament-surface materials, can often be rapidly obtained from orbital data, particularly on a regional scale. Evidence of recent faulting, including scarps and anomalous drainage can be quickly scanned for orbital-scale data. Topographic relief, in that it may imply structure or structural relief, can be rapidly evaluated for a large region.

Crust-Mantle Configuration

Elements of structural geologic, geomorphologic, and stratigraphic information (most discussed above) can be interpreted from orbital remote sensing data.

Crust-Mantle Composition

Regional and local reflectance and emittance contrasts can be delineated to produce regional geologic maps of remote sensing units on areas of similar terrain characteristics. Inasmuch as surface morphology, vegetation, and reflectance and emittance characteristics of the terrain are a function of composition (in a general sense), rapid compositional characterization is possible. This capability is certainly applicable to the Rio Grande Rift zone region, and may be extremely important in studies of rift zones in other more primitive and inaccessible regions of the world.

Magmatism

Currently available MSS data can be used to detect limonite distribution rapidly, on a regional scale. Using other structural and geomorphic data from images, the delineation of limonitic alteration (or probable alteration) can be accomplished. Addition of Landsat-D spectral bands will increase the capability of detecting and mapping alteration. Relative ages of extrusive rocks can often be determined by cross-cutting relationships. Reflectance and emittance differences related to rock types can be used to map igneous rock distribution as well as more local manifestations of magmatism, including vents, cones, calderas, dikes, etc. Regional structures defined from orbital data (discussed earlier) can point to controls on distribution of magmatic materials. Thermal scanner data (when available at Landsat-like resolutions) could be useful for delineating regional structures via ground water variations as well as delineating rock type distribution through thermal inertia characteristics.

2. Remote Sensing Potential Fields

M. Mayhew and J. Hermance

Satellite Magnetic Anomalies

In crustal modeling we need to know the lateral variation in the form of certain physical property/depth curves, in particular, temperature, magnetization, and density. Such curves express the configuration of lithospheric layers and constrain models of their composition. Satellite magnetic anomalies, with the help of other data, can be used to model lateral variations in the magnetization/depth curve, and, in particular, the point at which that property goes to zero, the Curie temperature. This isothermal surface can, in principle, be mapped over large regions (e.g., the whole of the Rio Grande Rift zone), thus providing a constraint on thermal models at depth. Other data is handled as follows.

Studies on crustal xenoliths provide information on deep geothermal gradients and can be used to measure Curie points and identify magnetic mineralogy present. These are related to composition and oxidation state of the crustal rocks. Aeromagnetic data gives independent local estimates of the Curie depth. Heat flow measurements constrain thermal models at the surface, and, in combination with regional thermal models based on Curie isotherm mapping, may allow hot dry rock resources to be distinguished from hydrothermal resources. Independent estimates of Curie temperature and Curie depth suggest composition and degree of chemical fractionation of crustal rocks. Thermal models combined with models of composition and hydrous state indicate where in the crust magma is being generated and crustal deformation is concentrated.

Satellite Gravity Anomalies

Present GEM models are useful for giving the regional-residual field separation needed for subregional modeling. Long wavelength gravity anomalies obtained by Gravsat can be used to model lateral variations in the density/depth curve for the Rio Grande Rift zone. This provides the configuration of crust-mantle layers and, in combination with the distribution of other physical properties, suggests their compositions. The locus of the lowest density part of the uppermost mantle is likely the point of maximum crustal uplift, mantle heat flow, and the site of crustal melting leading to magma generation.

3. Geochemical and Petrologic Contributions to an Integrated Study of the Rio Grande Rift

S. Baldridge, D. Barker, M. Dungan, D. Phelps, J. Stormer, J. Wooden

A significant characteristic of the Rio Grande Rift and rifts in general is the occurrence of magmatism both within and on the flanks of the rifted area. An integrated study of the many aspects of this magmatism can contribute substantially to the problems of crust-mantle composition and structure, rift-related mineralization, heat flow and geothermal potential, and regional tectonics. Several specific studies of primary importance in understanding these problems are recommended below.

(1) The compositions of undifferentiated basaltic magmas are a function of the physical conditions of generation (P, T, vapor composition, etc.) and of the bulk composition of their source regions. Comprehensive petrologic and geochemical studies of the igneous rocks in the RGR can be used to place constraints on the depth of magma generation and the composition of the source region. When the constraints derived from petrologic studies are combined with geophysical constraints that provide information on crust-mantle configurations, additional fine details concerning the mineralogy and bulk composition of the asthenospheric and lithospheric mantle and the crust can be derived.

(2) Xenolith suites consisting of upper mantle and lower crustal material common to many alkali basaltic volcanic fields provide the only direct samples of the upper mantle and lower crust. Mineralogical and geochemical data obtained from xenoliths not only provide crucial information on the composition of the upper mantle and lower crust, but the data are also useful in defining the physical conditions (P, T, vapor pressure, etc.) of the upper mantle and lower crust through which the volcanic rocks passed on their way to the surface.

(3) Spatial and temporal variations in the composition of igneous rocks occur in most rift systems. These variations are the result of a number of interrelated variables such as the physical conditions of the site of magma generation, composition of the source region, thickness and composition of the crust through which the magma must pass, etc. Integrated petrologic and geochemical studies designed to evaluate the role of each of these variables in determining the composition of the rocks at the surface can provide information on the temporal and spatial changes in crustal thickness and in the mineralogical and chemical makeup of the crust and upper mantle. A necessary aspect in these studies is the acquisition of high quality geochronologic data.

(4) Primary basaltic magmas frequently undergo variable degrees of modification enroute to the surface or to shallow depths of emplacement as plutons. As a consequence of this differentiation, the magmas may substantially modify the crust, both thermally and chemically. The degree to which this occurs is proportional to the abundance of magma, its residence time in the crust, and the composition of crust and magma. Substantial portions of material may be left behind as crustal magma bodies during ascent and differentiation. These bodies are new components of the crust and major contributors to its properties.

4. Structural Geology

R. Belcher, U. Clanton, and W. Muehlberger

Structural geology is the only way to learn the history of crustal deformation. Events in the past have been recorded in various ways (i.e., faults, fractures, rift, grain, foliations, intrusions, etc.); one of the challenges is to separate the various contributors to the features seen today.

Structural geology can provide a lateral data base but not much depth data. Faults may show some depth/thickness relationships of upper crust but the lower boundary of the crust and the top of the mantle remain obscured. In conjunction with seismic data, some cross calibration is possible. Structural geology also provides clues to present and past stress/strain fields. Some clue is given to crustal deformations, but the view is somewhat restricted to the upper surface; depth information must be extrapolated.

Structural geology has no direct application in determining (surface down) crust-mantle composition, temperature and physical state, but the technique can define lateral extent of lithic units. The technique also provides information on the relation of adjacent (both vertical and horizontal) rock masses.

Structural geology is applicable to the extent that volcanic features and events are controlled by structure or that structural features are developed by the intrusion/extrusion of magmas.

5. Stratigraphic Studies — Geologic Studies

J. Reed

Stratigraphic studies of sedimentary sequences in the individual component grabens that comprise the Rio Grande Rift can provide invaluable information on the chronology of crustal deformation during the evolution of the rift. Such studies would depend both on surface mapping and subsurface data and should be supported by paleontologic, magnetostratigraphic, and tephrochronologic dating. These basin analyses should be integrated with quantitative geomorphic studies of adjoining uplands and structural studies of basic margins and flanking terrains.

In addition to studies of the component basics of the rift, stratigraphic analyses of adjacent areas in the high plains, the lower Rio Grande Valley and Neogene marine sequences in the western Gulf of Mexico should provide additional insight into the development and evolution of the Rio Grande Rift.

Orderly investigation of a major tectonic feature such as the Rio Grande Rift requires as an essential first step the preparation of modern, high quality geologic maps. Such maps serve both as a summary of available surface geologic information and as a statement of current interpretation of geologic and tectonic history. They form a fundamental data base that is critical both to the collection and interpretation of most types of geologic and geophysical data.

For a region of the size and complexity of the Rio Grande Rift, a series of maps at a scale of 1:250,000 would provide a useful synthesis with a reasonable amount of time and effort. Up to date maps of this scale are now available for parts of the rift region in Colorado and Texas. We suggest that the U. S. Geological Survey* and the New Mexico Bureau of Mines and Geology be asked to expedite compilation and publication of 1:250,000 scale geologic maps in the rift region in New Mexico and that NASA, as an adjunct to the RGR program, offer support in the form of remote sensing data, imagery enhancement, and interpretation to guide and facilitate the geologic mapping.

In conjunction with the compilation of the geologic maps, derivative and supplementary maps such as the following would be especially useful:

1. Tectonic-geomorphic map for use in evaluating temporal and spatial patterns of late Cenozoic deformation
2. Map showing distribution and age of rift-associated igneous rocks.
3. Compilations of existing gravity and magnetic data at the same scale.

6. Gravity

G. Jiracek and W. Peeples

Crust-Mantle Configuration

A major constraint on any configurational (structural) model of the crust and mantle is that the gravity data be satisfied. However, since gravity modeling is inherently non-unique it is important that seismic soundings or other geophysical data be used as tie points to reduce the non-uniqueness. Deep crustal-mantle

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*In this context it would be especially appropriate to approach M. W. Reynolds, Program Manager of the Geologic Framework and Synthesis Program in Reston.

gravity modeling includes asthenosphere-lithosphere considerations. The modeling must be performed on meaningful regional gravity anomalies obtained from complete Bouguer anomalies using known geology and well data.

Crust-Mantle Composition

A major constraint on any composition crust-mantle model is that the gravity data be satisfied. Again, as above, the gravity models are non-unique and the data must be processed carefully using known geological and geophysical facts.

The gravity data provide information regarding the present configuration of many structural features (faults, basins, etc.). Thus they are used directly in structural geology to deduce buried structure and infer temporal relationships.

Magmatism (generation, ascent, emplacement, cooling)

The gravity data can be used to delineate buried magmatic events and related volcanic landforms such as calderas, plugs, etc.

7. Seismic Studies

S. Kaufman and P. Morgan

Crustal Deformation

Passive seismic studies (microearthquake studies) directly locate and measure rates and direction of active faulting.

Crust-Mantle Configuration

There are three levels of detail in the seismic methods:

a. Very broad: surface wave and teleseismic P wave delay studies which essentially sample a volume of the crust/mantle and give broad regional structure/velocity layering.

b. Long profiles: seismic refraction which determines velocity layering along a profile 200-300 km in length. Average velocities in the layers are determined and dips of interfaces or reversals of the profiles are made.

c. Short profiles: seismic reflection/COCORP gives detailed spatial information on velocity contrasts and good velocity information down to the level where reflection quality is good, and gives an image that closely resembles geologic structure.

The MOHO is defined as a seismic discontinuity from refraction studies. (a), above, gives broad regional information on the depth to MOHO; (b) is the best technique for mapping depth to MOHO; and (c) gives information regarding the nature of the MOHO (chaotic, discontinuous reflector indicated on COCORP data).

The intracrustal geophysical anomaly ("Socorro magma chamber") was discovered by reflections from passive seismic studies, and its detail confirmed by COCORP data. The reflector is also prominent on refraction data ("Dice Throw Line") which has potential as a regional tool for looking for the reflector.

Our fundamental understanding of deep structure in the crust and upper mantle has derived from regional seismic studies: seismic refractions, teleseismic and seismic surface waves. Recently, seismic reflection studies, e.g., COCORP, have contributed to discriminating structural detail that have enormous implications for developing refined models of crustal processes. The utilization of seismic studies involves placing both braod regional constraints on structures in the crust and upper mantle as well as delineating sharp lithologic units in crustal units and on boundaries of such features as the intra-crustal geophysical anomaly.

Crust-Mantle Composition

Seismic velocity is a first order constraint on composition and /or phase.

Magmatism

a. Active seismic methods, primarily reflection but also refraction, can be used to map magma bodies—evidence of molten phases from implications on Poisson's ratio of reflection phase amplitudes.

b. Passive seismics indicate crustal deformation caused by intrusion (Socorro is the most active microearthquake area in the rift).

8. Electromagnetics

G. Jiracek and J. Hermance

One of the major deep continental discontinuities is the Rio Grande Rift conductive anomaly, discovered in the 1960's by Schmacher. The exact depth of this discontinuity has been the subject of considerable debate. At some locations the conductive layer is clearly intracrustal; beneath the rift, it may extend into the upper mantle or it may be a distinct and separate feature from a deeper upper mantle conductor. The relationship of these bodies to temperature, water content, and related petrology are critical to understanding the dynamic processes involved in continental rifting.

Magnetotelluric and related soundings are sensitive to electrical resistivity properties. These provide an additional important physical property measurement to interrelate with density, seismic velocity, etc., obtained from complementary geophysical measurements.

Magnetotelluric soundings individually yield electrical strike direction as a function of depth in the region surrounding the surface location. These strike directions reflect the structural fabric from a few hundreds of meters in depth to several tens of kilometers. Hence, to the extent that structural grain relates to stress, the deformational history from Holocene to Precambrian can be mapped in a widespread area. An additional contribution may be to complement gravity and shallow seismic studies to delineate shallow basin structures.

Deep electrical studies in some of the major rift zones of the earth (the Baikal, Rhine, East African Rift, Iceland and Rio Grande Rift), when interpreted in conjunction with seismic, gravity and heat flow studies, support a model where ascending masses of material from the mantle (mantle diapsis) are intimately coupled with the fractionations of a basalt melt and its accumulation at intracrustal levels within the earth. Available interpretations suggest that along interplate rifts, e.g., Iceland, the accumulation and chilling of melt at the base of the crust apparently leads to a significant component of crustal underplating. On the other hand, beneath intraplate rifts such as the Rio Grande, the emplacement of basaltic magma at intracrustal levels may lead to significant thermal perturbations of the crustal environment. The thermal regime may be modified by mobilization of hydrothermal fluids and perhaps even partial melting of crustal materials themselves. These have important implications for the genesis of economic ore deposits and for the high-level emplacement of geothermal reservoirs.

It is imperative that we refine our understanding of the vertical and lateral extent of these anomalous intracrustal features. Multidimensional analyses are required to provide meaningful interpretations of MT data.

9. Magnetics

L. Cordell and W. Peeples

Crust-Mantle Configuration and Composition

The magnetic data can be interpreted to obtain control on the Curie point depth and to obtain information regarding batolithic bodies in the crust.

Magnetic data can delineate structural grain in crystalline rocks covered by thick sedimentary cover. It can be used as a tool to determine unsuspected intrusives not otherwise observed because of obscuring sedimentary cover and thus is an indirect aid in magnetic studies.

10. Heat Flow

P. Morgan and M. Mayhew

Crustal Deformation

Thermal processes are generally thought to be either causative of or resultant from crustal deformation. They therefore represent a constraint on mechanisms of crustal deformation. The surface heat flow field should be used as a boundary condition for deformation models.

Crust-Mantle Configuration

Heat flow data can be used to determine the temperatures at depth and constrain maximum crustal thickness (cannot exceed melting point at base of crust). Lithosphere/asthenosphere can be defined by geotherm/solidus intersection.

Crust-Mantle Composition and Properties

The principle thermal parameter, temperature, can be derived from heat flow. An understanding of the thermal process is required. Crustal xenoliths indicate high (compatible with surface measured) geotherms. Marble xenoliths indicate a decrease in gradient in the mantle. Curie isotherms should be used to constrain subsurface temperatures. Hydrothermal processes (>3 Hfu) clearly are not related to conducted crustal heat flow. How does hydrothermal heat transfer confuse the basic heat flow pattern and contribute to the overall heat budget?

Magmatism

Surface heat flow is a constraint on volumes of recent plutonism. How much of the surface heat flow is residual magmatic heat?

11. Paleoelevation (by paleobotanical data)

L. Cordell

Crust-Mantle Configurations

Paleo-botanical data, treated as paleo-gravity, extend gravity modeling into the dimension of time.

Crustal Deformation

They provide the only long-term quantitative rate of uplift data as contrasted with short-term seismicity and repeat-leveling data.

Non-prioritized List of Things Necessary to Advance the Present State of Understanding of the Rio Grande Rift

1. Geochemical data base
2. Uniform map base (scale?)
3. More petrological/chemical/geochemical data
4. Development of fission track technique
5. Encouragement of drilling in the RGR
6. Current geological maps at 1:250,000
7. Joint compilation of published data
8. Remote sensing data from the RGR
9. Seismic shot to reverse the "dice throw" shot
10. Complete analysis of present seismic data
11. Pressure/temperature experimental petrology study, especially with respect to magnetic properties
12. Development of 3D-MT techniques
13. Agreement on common areas for work
14. Reduced heat flow data from Northern RGR
15. Drill holes for heat flow calibration
16. Gridded gravity data set
17. Completion of aeromagnetic data set
18. Aeromagnetic data base reduced to basement
19. Magnetic studies on xenoliths
20. Pilot study on paleo-elevation
21. Basin analysis
22. Magnetic properties, magnetic mineralogies, and Curie points of xenoliths
23. Chemistry and petrology of suites of crustal xenoliths within and adjacent to the rift

Program

Monday Morning, 21 April 1980

Introductory Comments and Welcome
Roger Phillips and Douglas Blanchard

Rifts of the World: Their Problems and Importance
William Muehlberger (Univ. of Texas, Austin)

Non-Renewable Resource Program—The NASA Perspective
Mark Settle (Program Scientist, NASA Headquarters)

Monday Afternoon, 21 April 1980

Overview of Geology of the Rio Grande Rift
William Muehlberger (Univ. of Texas, Austin)

Lineament Analysis
Scott Baldridge (Los Alamos Scientific Lab.)

Landsat Tectonics and Modeling
Daniel Knepper (USGS, Denver)

Computer Lineament Analysis
Kenneth Meehan (NASA Goddard Space Flight Center)

Tectonic History of Jencia Fault
Michael Machette (USGS, Denver)

Overview of Geophysics of the Rio Grande Rift
Lindrith Cordell (USGS, Denver)

Deep Thermal/Magnetic Structure of Rifts and Relationship to Major Volcanic Centers
John Hermance (Brown Univ.)

Applications of Satellite Data to Curie Isotherm Mapping
Michael Mayhew (Business and Technological Serv. Inc.)

Gravity Models for Rift and New MT Data over COCORP Area
George Jiracek (Univ. of New Mexico; now at San Diego State Univ.)

New COCORP Interpretations
Sidney Kaufman (Cornell Univ.)

Regional (Seismic) Structure of Rio Grande Rift
Randy Keller (Univ. of Texas, El Paso)

Snake River Plains Study
Kenneth Olsen (Los Alamos Scientific Lab.)

Overview of Petrology/Geochemistry of Northern Rio Grande Rift
Michael Dungan (Southern Methodist Univ.)

Overview of Petrology/Geochemistry of Southern Extension of Rio Grande Rift
Daniel Barker (Univ. of Texas, Austin)

Chronology and Magma Types
John Stormer, Jr. (Univ. of Georgia)

Taos Plateau Volcanics
Michael Dungan (Southern Methodist Univ.)

Xenoliths
Scott Baldridge (Los Alamos Scientific Lab.)

Tuesday Morning, 22 April 1980

Working Groups Meet

Tuesday Afternoon, 22 April 1980

Multispectral Scanning and HCMM
Michael Abrams (Jet Propulsion Laboratory)

Radar Applications to Tectonics
John Ford (Jet Propulsion Laboratory)

Passive Microwave Applications
Jack Paris (Johnson Space Center)

The LACIE Project Approach to Application of R-S Data Systems
Forest Hall (Johnson Space Center)

Satellite Magnetics and Gravity
Michael Mayhew (Business and Technological Serv. Inc.)

Advanced Plans and Concepts in Remote Sensing Technology and Applications
Mark Settle (NASA Headquarters)

Tuesday Evening, 22 April 1980

Informal Discussion on Modeling and Constraints

Wednesday, 23 April 1980

Working Sessions Meet

Participants

Michael Abrams
Mail Code: 183-501
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109

Carlos Aiken
Programs in Geosciences
University of Texas at Dallas
Dallas, Texas 75080

Scott Baldridge
Geosciences Division, MS 978
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

Daniel Barker
Department of Geological Sciences
University of Texas at Austin
Austin, Texas 78712

Robert Belcher
Earth Resources Branch
Mail Stop 923
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

Douglas Blanchard
Code: SN7
NASA/Johnson Space Center
Houston, Texas 77058

current address:
Code: SN2
NASA/Johnson Space Center
Houston, Texas 77058

Lawrence W. Braile
Department of Geological Sciences
Purdue University
West Lafayette, Indiana 47907

Joseph Bridwell
Geosciences Division
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

Uel Clanton
Code: SN7
NASA/Johnson Space Center
Houston, Texas 77058

Lindrith Cordell
Mail Stop 964
U. S. Geological Survey
Denver Federal Center
Denver, Colorado 8025

Pat Dickerson
Gulf Research and Development
P. O. Box 36506
Houston, Texas 77036

John Dornbach
Code: SF
NASA/Johnson Space Center
Houston, Texas 77058

Michael Duke
Code: SN
NASA/Johnson Space Center
Houston, Texas 77058

Michael Dungan
Department of Geological Sciences
Southern Methodist University
Dallas, Texas 75275

John Ford
Mail Code: 183-701
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109

Vivian Gornitz
Goddard Institute for Space Studies
2880 Broadway
New York, New York 10025

Forrest Hall
Code: SF2
NASA/Johnson Space Center
Houston, Texas 77058

Chris Henry
Bureau of Economic Geology
University of Texas at Austin
Austin, Texas 78712

John Hermance
Department of Geological Sciences
Brown University
Providence, Rhode Island 02912

Ray Ingersol
Department of Geology
University of New Mexico
Albuquerque, New Mexico 87131

George Jiracek
Department of Geology
University of New Mexico
Albuquerque, New Mexico 87131

current address:
Department of Geological Sciences
San Diego State University
San Diego, California 92182

Sidney Kaufman
Department of Geological Sciences
Cornell University
Ithaca, New York 14853

Dan Knepper
Mail Stop 964
U. S. Geological Survey
Denver Federal Center
Denver, Colorado 80225

Andrea Kron
G-4
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

Gary Lofgren
Code: SN6
NASA/Johnson Space Center
Houston, Texas 77058

Mike Machette
Mail Stop 913
U. S. Geological Survey
Denver Federal Center
Denver, Colorado 80225

Mike Mayhew
Business and Technological Services, Inc.
Aerospace Building, Suite 440
10210 Greenbelt Road
Seabrook, Maryland 20801

Kenneth Meehan
Mail Stop 923
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

Wendell Mendell
Code: SN6
NASA/Johnson Space Center
Houston, Texas 77058

John Minear
Code: SN6
NASA/Johnson Space Center
Houston, Texas 77058

current address:
Welex Corporation
P. O. Box 42800
Houston, Texas 77042

Paul Morgan
Department of Physics
New Mexico State University
Box 3D
Las Cruces, New Mexico 88003

current address:
Lunar and Planetary Institute
3303 NASA Road 1
Houston, Texas 77058

William Muehlberger
Department of Geological Sciences
University of Texas at Austin
Austin, Texas 78712

Kenneth Olsen
Mail Stop 676
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

Jack Paris
Code: SN7
NASA/Johnson Space Center
Houston, Texas 77058

Wayne Peeples
Department of Geological Sciences
Southern Methodist University
Dallas, Texas 75275

David Phelps
Code: SN7
NASA/Johnson Space Center
Houston, Texas 77058

Roger Phillips
Lunar and Planetary Institute
3303 NASA Road 1
Houston, Texas 77058

William Phinney
Code: SN6
NASA/Johnson Space Cneter
Houston, Texas 77058

John Reed
Mail Stop 913
U. S. Geological Survey
Federal Center
Denver, Colorado 80225

Ernest Schonfeld
Code: SN7
NASA/Johnson Space Center
Houston, Texas 77058

Mark Settle
Code: ERS-2
NASA Headquarters
Washington, D. C. 20546

Charles Simonds
Northrop Services, Inc.
P. O. Box 34416
Houston, Texas 77034

current address:
Texas Eastern Exploration Co.
P. O. Box 34416
Houston, Texas 77034

John Stormer, Jr.
Department of Geology
University of Georgia
Athens, Georgia 30602

Jeffrey Warner
Code: SN
NASA/Johnson Space Center
Houston, Texas 77058

James Wolleben
Gulf Research and Development
P. O. Box 36506
Houston, Texas 77036

Charles Wood
Mail Stop 922
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

current address:
Code: SN6
NASA/Johnson Space Center
Houston, Texas 77058

Joseph Wooden
Code: SN7
NASA/Johnson Space Center
Houston, Texas 77058

ABSTRACTS

THE ROLE OF REGIONAL LINEAMENTS AND PRE-EXISTING STRUCTURES ON THE LATE CENOZOIC RIO GRANDE RIFT, W. Scott Baldridge and Andrea Kron, Geosciences Division, Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545

The Rio Grande rift, extending from central Colorado through New Mexico to Chihuahua and West Texas, was initiated in response to extensional tectonics 25-30 m.y. ago. However, the rift follows pre-existing structural trends almost entirely (e.g., Chapin and Seager, 1975). The major grabens of the rift follow and are largely coincident with north-south trending Laramide (Paleocene and Eocene) compressional features. In West Texas southeast-trending basins of the southern rift coincide with the limit of Laramide thrusting. Grabens of the northern and central rift were also strongly affected by northwest-trending features of late Paleozoic age. In addition, the rift is intersected obliquely by a series of parallel, northeast-trending fracture zones (lineaments) (e.g., Chapin et al., 1978). These fracture zones, which are probably of Precambrian origin, extend for hundreds of kilometers and are variously characterized by faults and alignments of volcanic centers and intrusive bodies. Individual grabens of the rift are separated and offset from each other along these fracture zones.

Two major fracture zones intersecting the central Rio Grande rift are the Jemez and Morenci zones. Both correspond to fundamental weaknesses extending through the crust into the mantle. The Jemez zone has previously been defined as an alignment of late Cenozoic volcanic fields, including Mount Taylor and the Jemez Mountains, extending from the Raton-Clayton area of northeastern New Mexico to the Springerville area of southeastern Arizona (Mayo, 1958; Laughlin et al., 1976). The Jemez zone has been more important in controlling late Cenozoic alkalic and tholeiitic basaltic volcanism than the rift itself (Luedke and Smith, 1979). This zone encompasses a nearly continuous belt of faults (dip-slip offset) extending from the Sangre de Cristo Mountains to Mount Taylor, a distance of more than 200 km. Northeast of Mount Taylor this zone is characterized by relatively high seismicity (Sanford et al., 1979). Between Mount Taylor and Springerville little geological evidence for tectonism along the Jemez zone was previously recognized. Preliminary analysis of SEASAT radar imagery indicates that two major fracture sets may be present in this area. A first set extends more than 60 km southwestward from the Zuni-Bandera lava field, parallel to the overall trend of the Jemez zone. A second set extends southward from the Zuni-Bandera field, on strike with alignments of vents and cinder cones within this lava field and parallel to a positive gravity anomaly underlying the lavas. Thus the Zuni-Bandera lava field, as well as other major volcanic centers along the Jemez zone west of the rift, is located at the intersection of large-scale fracture zones.

The Morenci zone, which extends from eastern central New Mexico to the vicinity of Morenci, Arizona, is manifested in part by the southwest-trending San Augustin basin of the Rio Grande rift (e.g., Chapin et al., 1978). A region of structural complexity, high seismicity, and possible magma intrusion occurs where this zone intersects the rift (Chapin et al., 1978; Sanford et al., 1979). Petrologic and isotopic data indicate that the Morenci zone represents a fundamental compositional boundary in the lithosphere (e.g., Aoki and Kudo, 1976; Everson, 1979). Detailed structural documentation of the Morenci zone is underway.

These transverse fracture zones may be periodically reactivated by changing stress fields. For example, the Jemez zone may have become reactivated in the last 12 m.y. because of the change from subduction to transform motion along the western boundary of the North American plate. Their persistence as lithospheric weaknesses may result from compositional or fabric inhomogeneities or from periodic reactivation in response to changing stress fields. They strongly affect volcanism, not only by acting as conduits where magmas leak to the surface, but possibly also by controlling magma genesis.

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PETROLOGY AND RESOURCE POTENTIAL, CENOZOIC IGNEOUS ROCKS, TRANS-PECOS TEXAS: D. S. Barker, Dept. of Geological Sciences, Univ. of Texas at Austin, Austin, TX 78712

From 46 to 16 m.y. ago in the Trans-Pecos region of far west Texas, igneous rocks were emplaced that compositionally resemble those in the Kenya, Oslo, and Gardar continental rifts. Silica-oversaturated and undersaturated rocks were interspersed in space and time. Among the quartz-normative rocks, basalt was extremely rare, trachybasalt and trachy-andesite formed widespread flows, and trachyte + rhyolite built shield volcanoes, at least 10 of which collapsed to form calderas with ash-flow deposits. Among olivine- and nepheline-normative rocks, basalt was rare, hawaiite and mugearite flows were extensive, and the more felsic rocks formed shallow intrusions of trachyte, phonolite, and nepheline syenite. Much of the felsic rock in both the silica-oversat-urated and undersaturated series is peralkaline. To the south-west, the quartz-normative rocks are less alkalic and appear to grade into the calcalkaline rocks of the same age span in Mexico.

Erosion has stripped away much of the volcanic cover to expose shallow intrusions, mostly sills and discordant sheets. At least 200 intrusions have outcrop areas exceeding 1 km^2. Most of these are compositionally homogeneous and, like the lava flows and ash-flow tuffs, present large, varied but individually uniform targets for remote sensing. Clusters of shallow intrusive bodies suggest underlying plutons that may be detectible by remote sensing geophysical methods.

More than 200 new major-element rock analyses have been made on precisely located samples. Representative analyses appear in Table 1. Trace-element XRF analyses are in progress. Trans-Pecos peralkaline rocks are significantly enriched in U, Th, Mo, Zr, Be and Li. Mines have produced Ag, Pb, Zn, Mo, U, Hg, and CaF_2 from Cenozoic Trans-Pecos igneous rocks and their contact aureoles. At least 15 large nepheline syenite bodies are promising sources of Al, in view of the intensifying search for domestic nonbauxite ores.

Trans-Pecos magmatism largely preceded, and was apparently unrelated to, normal faulting that represents a southeastern extension of the Rio Grande Rift. Present-day uplift, locally high heat flow, and seismicity cannot with any assurance be attributed to a rejuvenation of magmatism (Barker, 1979).

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TRANS-PECOS IGNEOUS ROCKS

Barker, D.S.

Table 1. Representative analyses, in weight percent

	1	2	3	4	5	6	7
SiO_2	49.83	54.91	59.07	71.20	47.27	48.46	61.30
TiO_2	1.62	1.89	1.42	0.16	2.56	2.74	0.31
Al_2O_3	16.35	16.23	17.60	13.37	16.60	16.30	17.95
Fe_2O_3	2.53	4.52	5.72	2.28	2.04	4.72	2.52
FeO	6.79	3.06	0.48	1.48	10.04	5.86	2.64
MnO	0.11	0.16	0.15	0.19	0.18	0.23	0.32
MgO	5.52	1.87	0.73	0.03	5.47	3.52	0.26
CaO	9.19	3.66	1.98	0.17	7.43	5.99	1.16
Na_2O	3.37	5.05	5.65	5.97	4.31	4.65	7.61
K_2O	0.82	3.85	4.54	4.69	1.24	2.61	4.93
H_2O^+	1.87	1.76	0.89	0.21	1.65	1.88	0.70
H_2O^-	1.03	0.98	0.41	0.13	0.21	0.54	0.10
P_2O_5	0.42	0.82	0.56	0.07	0.56	2.04	0.15
CO_2	0.25	0.28	0.01	0.00	0.02	0.12	0.10
Total	99.70	99.04	99.21	99.95	99.58	99.66	100.05

Silica-oversaturated series:
1. Trachybasalt, Bee Mountain "Basalt",Big Bend National Park
2. Trachyandesite,Alamo Creek "Basalt",Big Bend National Park
3. Trachyte, Paisano Pass
4. Peralkaline rhyolite, Mitre Peak

Silica-undersaturated series:
5. Hawaiite, Rawls Formation, Agua Fria quadrangle
6. Mugearite, Paisano Pass
7. Phonolite, Ranger Peak, Alpine South quadrangle

Analyst G. K. Hoops, Department of Geological Sciences, The University of Texas at Austin

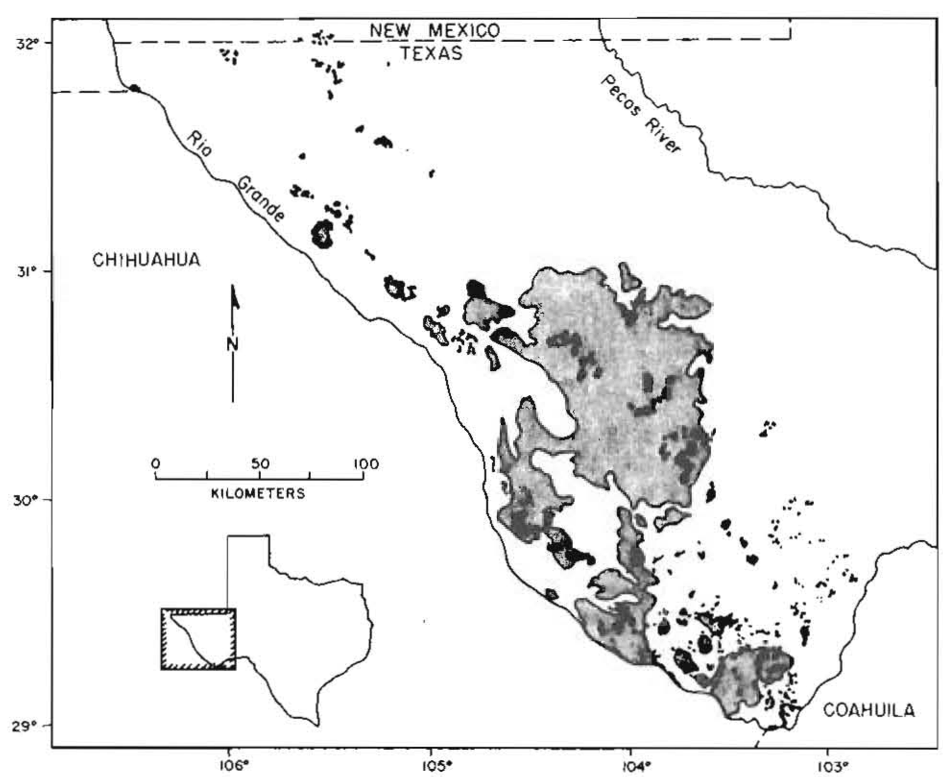

Figure 1. Distribution of Cenozoic igneous rocks, Trans-Pecos magmatic province. Intrusive rocks are shown in black; lavas and pyroclastic rocks are shown by stippled pattern. (Barker,1977)

QUANTITATIVE ANALYSIS AND DIGITAL PROCESSING
OF POTENTIAL FIELD DATA FROM
THE RIO GRANDE RIFT, COLORADO AND NEW MEXICO

BY

Robert C. Belcher
NASA/Goddard Space Flight Center
Earth Resources Branch, Code 923
Greenbelt, Maryland 20771

The crustal modeling group at Goddard Space Flight Center is conducting a multi-data type analysis of the Rio Grande rift area in Colorado and New Mexico. One of the goals of this effort is to construct a realistic crustal model of the rift region from both ground based and satellite derived data. Gravity and magnetics are of particular interest because they are geopoential data types directly affected by geometry of the crust and upper mantle, and by density and magnetization variations therein. At present the gravity studies are concentrated in three areas: investigation of optimum ground resolution for future gravity satellites, i.e., GRAVSAT; evaluation of different methods used to calculate Bouguer gravity anomalies; and theoretical two and three dimensional gravity modeling.

Optimum ground resolution for future gravity satellites is being investigated by upward continuing ground based gravity data for the rift area that has been gridded to cell sizes of 0.25, 0.5, 1.0, 1.5, and 2.0 degrees. The information content in each of these upward continued data sets is being analyzed to determine the most useful ground resolution for studies of geologic features the size of the Rio Grande rift area (approximately 9°x12°).

Several methods for calculating Bouguer gravity anomalies are being investigated to determine which procedures produce results that are least correlated with topography, and that are geologically reasonable. The standard method of Bouguer reduction, i.e., reducing to sea level and using a density of 2.67 gm/cm^3, produced a Bouguer gravity data set that has a correlation with topography of -0.91. This high degree of non-independece of the Bouguer gravity precludes it from being used with other data sets in multivariate statistical methods. Other Bouguer reduction methods being evaluated are residual Bouguer gravity procedures and variable Bouguer density calculations.

Theoretical two and three dimensional gravity modeling techniques are being used in conjunction with observed gravity data to predict geometries and density variations for the crust and upper mantle in the rift area. Two dimensional gravity modeling produced a Bouguer gravity anomaly profile that generally approximated observed Bouguer gravity profiles near Albuquerque, New Mexico. The crustal model used was composed of two bodies. The first was a mantle upwarp (density contrast = 0.5) varying in depth (west to east) from 40km beneath the Colorado Plateau, to 28km beneath the rift, to 50km beneath the High Plains. The second body was a 7km deep asymmetric graben (density contrast = -0.5) centered over the mantle upwarp. The first attempt at three dimensional gravity modeling produced a Bouguer gravity anomaly map that only in a general sense resembled the observed Bouguer gravity map near Albuquerque. Both maps exhibit a high on the east flank of the rift and a linear low over the rift. The theoretical gravity map shows a local high caused by a volcanic pile on the west flank of the rift, which is not present on the observed Bouguer gravity map in the area of the Jemez volcanic pile. The crustal model used for these theoretical calculations was composed of the following three bodies: the mantle upwarp discussed above but extended 100km horizontally along the rift, and dipping to the north; two 7km deep asymmetric grabens (density contrast = 0.5) having opposite throw; and a volcanic pile (density contrast = 0.2) along the west flank of the northernmost graben. The agreement of these modeling results with observed data is not good. This indicates that those crude, first cut models must be made more realistic by the inclusion of additional geologic information such as igneous intrusions, density variations, and different structural configurations.

TECTONIC INTERPRETATION FROM SEASAT RADAR IMAGERY: SOUTHERN APPALACHIANS.

J. P. Ford, Jet Propulsion Laboratory, Pasadena, CA 91103

Seasat synthetic-aperture radar (SAR) images taken in two different look directions in summer 1978 are analyzed for geologic mapping and image interpretibility, and compared with a selected Landsat multispectral scanner (MSS) image. Both forms of imagery provide orbital synoptic coverage of the study area. Textural patterns mapped from the SAR images show a close correlation with broad classes of topography. The topography of the area reflects the distribution of layered rocks that have differing resistance to erosion, and provides some structural information. Lithologic and structural interpretation from the images requires some a priori knowledge of the field geology combined with supportive field checking.

Geomorphic lineaments mapped from the SAR and MSS images consist of a number of major linear features many tens of kilometers in length, and numerous minor linear features generally less than 10 km long. The major lineaments are formed by linear valleys and ridges that parallel the regional strike, and by elongated mountains that are oriented in two different directions across the regional strike. The minor lineaments consist of segments of rivers and small valleys, some of which are aligned over many kilometers, and drainage channels that occur in closely-spaced sub-parallel swarms. The traces of many of the major lineaments correlate with mapped faults from published sources. The majority of the minor lineaments are uncorrelated geologically.

The major lineaments appear about as clearly on both the SAR and the MSS images. The minor mostly uncorrelated lineaments are more readily perceived and are mapped in greater abundance from the SAR images. Analysis of the lineament orientations reveals several preferred directions. The distribution of lineaments in the three most favored directions shows that there is a close coincidence of some aligned disconnected segments of rivers and small valleys with known structural features, and with geophysical anomalies in the basement. The swarms of closely-spaced drainage channels are erosional features with no apparent structural relationship. The distribution pattern of the minor lineaments revealed from the SAR images provides a basis for further geologic studies.

The high image-contrast that facilitates lineament perception and highlights topography on the SAR images reflects the high sensitivity of the Seasat SAR to change in terrain slope. In the study area this sensitivity is due largely to the low inclination off nadir of the Seasat imaging radar beam. Terrain slopes which exceed this inclination angle (about 20°) are geometrically distorted by layover on the SAR imagery. Both the Seasat SAR and the Landsat MSS sensors suppress geomorphic lineaments that are oriented at or near the illumination direction of the respective imaging systems. Lineament suppression by the SAR in a given look direction is largely compensated in the complementary look direction.

Noticeable error occurs in the orientation of geomorphic lineaments mapped from the Seasat SAR images where the linear features are short and have a slope greater than about 15°. Under such conditions a lineament appears to be rotated on the imagery relative to its true orientation. The advantages of the orbital SAR in highlighting topography and detecting

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Ford, J. P.

geomorphic lineaments are offset by the layover and geometric distortion introduced by the Seasat imaging geometry. The present study shows that future applications of orbital imaging radar for geologic mapping and interpretation demand an imaging geometry that reduces the effects of layover encountered on the Seasat SAR images but retains the topographic enhancement capability of the imaging radar system.

NEW GRAVITY AND MAGNETOTELLURIC STUDIES IN THE RIO GRANDE RIFT. G. R. Jiracek* and F. S. Birch**, Department of Geology, University of New Mexico, Albuquerque NM 87131
*Now at Dept. of Geological Sciences, San Diego State University, San Diego, CA 92182
**Permanent address: Dept. of Earth Sciences, Univ. of New Hampshire, Durham, NH 03824

The main purpose of our gravity studies in the Rio Grande rift is to determine the thickness of the low-density Neogene (or post-rifting) sediments. The thickness is required for numerical models of groundwater flow to be made by the U. S. Geological Survey, the sponsor of the research. A second purpose is to produce new complete Bouguer, regional, and residual gravity maps of the Albuquerque basin. The new maps are more useful than existing ones because of smaller contour interval (2 mgal) and explicit representation of measurement sites.

Gravity anomalies from an existing gravity map were interpreted by two-dimensional models constrained by mapped geology and available stratigraphic and density log data from wells. The regional field was defined as the complete Bouguer anomaly over large Precambrian outcrop areas outside the basin; also used were adjusted values at sites outside the basin where the sedimentary section is known from wells. The regional on the gravity profiles between these locations was found by interpolation using a physical spline.

Density logs and published values of densities from outcrops indicate that four distinct density units are needed. Appropriate values are 2.20 gm/cm^3 for the Neogene; 2.40 gm/cm^3 for the Paleogene, Cretaceous and Jurassic; 2.57 gm/cm^3 for the Triassic and Paleozoic; as well as 2.67 gm/cm^3 assumed for the Precambrian.

In the Albuquerque basin fifteen two-dimensional models show that the Neogene deposits average about 1.5 km thick and exceed 2.0 km in a north-south strip along the east side of the basin (Birch, 1980a). The thickness decreases to about 1.0 km between the Albuquerque and Santo Domingo basins whereas in the southern part of the basin it approaches or equals zero. These large thicknesses indicate that water quality rather than quantity will limit groundwater exploitation. With respect to rift genesis the isopachs do not support an origin as a rhombochasm.

Details of the new gravity maps are perhaps of only local significance but the regional field has interesting features with important implications concerning rift development (Birch, 1980b). The principal feature is an elliptical 50 mgal high (-210 to -160 mgal) under the deeper part of the Albuquerque basin. The long axis of this elliptical high is parallel to a line running southwest along the Tijeras fault, past Ladron Peak, and along the Plains of San Augustin branch of the rift rather than north to south along the Albuquerque basin. Another feature is that the regional field is higher (-165 mgal) east of the basin than west of the basin (-190 mgal). This relationship is opposite to what isostasy and the elevation of the Precambrian would suggest. In the vicinity of Socorro the regional high is essentially absent.

Gravity investigations of the same character and for the same purposes are presently being completed for the Tularosa, Jornada de Muerto, Mesilla, Palomas, San Marcial, and Mimbres basins and the Plains of San Augustin.

Magnetotelluric (MT) investigations have continued in New Mexico with National Science Foundation support to study suspected magma bodies and the deep structure of the Rio Grande rift. Twenty-five new MT soundings were recorded in the COCORP area in October, 1979 and two additional sites were occupied over 100 km east of the rift in the Great Plains province. Twenty-two of the new soundings were recorded as simultaneous station pairs with FM telemetry linking the remote site to the base recording site. Each station utilized a cryogenic (SQUID) magnetometer; the in-field MT system, including on-site processing, was developed and operated by Woodward-Clyde Consultants. In addition to recording five electric and magnetic fields from each site, at least two components of seismic signals, ambient temperature, wind speed, and wind direction were also digitally recorded. The latter measurements were made to study sources of magnetotelluric noise. Equipment for these experiments was furnished by the California Institute of Technology, Los Alamos Scientific Laboratory, and the U. S. Geological Survey.

The MT data have been processed to obtain tensor impedance estimates and corresponding parameters such as apparent resistivities, principal strike directions, tipper information, and coherency values. Results are generally of very high quality with coherency values exceeding 0.9 for much of the data. Soundings span the period range from 0.03 to 1700 seconds which provides depth sensitivity from a few 100 m to 10's of km.

Interpretation of the results has begun with initial one-dimensional modeling of each site followed by the preparation of MT pseudosections. Pseudosections provide strike direction information as a function of surface position and depth in the earth. Shallow strike directions in many instances show perfect correlation with surface geologic strike but significant deviations are evident. Deviations include pronounced variations of strike direction as a function of depth. Such directions indicate structural trends in the deep basement of the region.

Most soundings that sense to depths in excess of 10 km detect a conductive zone (< 10 ohm-m) in the crust. Such a zone appears to be characteristic of continental rifts (Jiracek et al., 1979) and may be related to magma at crustal depths, e.g. near 20 km depth in the COCORP area. The exact relation between MT conductive zones many kilometers thick and magma layers, apparently less than a kilometer in vertical extent, has not been established. Magnetotellurics can not resolve such a thin conductive layer at a depth of 20 km unless the resistivity contrast exceeds about 15. However, a thin magma layer could affect the electrical properties for a considerable distance above and below the actual body (Jiracek et al., 1979).

Magnetotelluric pseudosection results along COCORP lines 1A and 1 are easily correlated with the basement features detected by the seismic soundings. These features include the Lucero uplift on the west, a horst block extension of the Ladron Mountains, a more pronounced intrarift horst block on the east side of the rift, and the Los Pinos Mountains bounding the rift on the east. Deep conductive sedimentary basins are sounded between these features. Future multi-dimensional modeling of the MT results will provide more quantitative interpretations.

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SOME RESULTS OF COCORP SURVEYS IN THE RIO GRANDE RIFT AREA

KAUFMAN, S., et al.

Seismic reflection surveys carried out by the Consortium for Continental Reflection Profiling (COCORP) in the Rio Grande Rift near Socorro, N.M., have successfully mapped large-scale structural variations down to the base of the crust. Among the major features are (1) large-scale relief on the floor of the Albuquerque Basin, including a major intergraben horst standing over 3 km above the surrounding deep basin floors, and an extensive shallow structural bench beneath the southeast portion of the Basin;(2) well-developed, antithetic Tertiary normal faulting on the east side of the rift; (3) marked lateral and vertical variation in intrabasement reflection character, including relatively long correlatable events, distinct bands of short discontinuous reflections and seismically transparent zones; (4) a complex band of reflections from depths appropriate for the Moho; and (5) two zones of unusually strong, coherent reflections believed to be from active magma bodies emplaced in the area. The larger zone is at a depth of approximately 20 km and is confirmation of the existence of such a body, based on studies of microearthquakes by researchers from the New Mexico Institute of Mining and Technology. The smaller zone at a depth of approximately 7 km, hence of some possible resource value, is reported here for the first time.

The magma body reflections are among the most prominent deep events yet recorded by COCORP and their geometry and relationship to surrounding structural elements provide important constraints on the depth of brittle faulting and new insight on magma migration and accumulation.

The seismic character of other intrabasement features suggest particular igneous and/or metamorphic origins and support crustal models which emphasize lateral and vertical heterogeneity with depth.

REGIONAL CRUSTAL STRUCTURE OF THE RIO GRANDE RIFT G. R. Keller, Dept. of Geological Sciences, Univ. of Texas at El Paso, El Paso, TX 79968

In recent years, groups from the Los Alamos Scientific Laboratory, New Mexico State University, New Mexico Tech, Purdue University, the University of Texas at El Paso, the University of Wyoming, and the U. S. Geological Survey have been conducting seismic studies of the crustal structure of the Rio Grande Rift. Many of the results of these studies were presented in a volume recently published by the American Geophysical Union. These results and new unpublished data clearly document a thinning of the crust beneath the Rio Grande Rift. At a latitude of 35°N (Albuquerque), the crust thins from ~42 km beneath the Colorado Plateau to ~33 km beneath the rift and then thickens from south to north beneath the rift. Near Las Cruces, the crust of the rift is less than 30 km thick while near the New Mexico - Colorado border the crust is ~35 km thick. Upper mantle velocities (P_n) beneath the rift are less well known but reported values all fall in the range of 7.4 to 7.9 km/sec.

AN APPROACH TO CURIE ISOTHERM MAPPING USING LONG WAVELENGTH SATELLITE MAGNETIC ANOMALIES WITH APPLICATION TO THE RIO GRANDE RIFT M. A. Mayhew (BTS, Inc., Seabrook, MD. 20801)

A boundary condition on temperature at depth in the continental crust can in principle be obtained by mapping of the Curie isotherm where it forms the base of the magnetic crust. We describe an approach using high-elevation magnetic anomaly data obtained by the Pogo-series satellites, with respect to which the magnetic crust appears as a thin layer. Inversion of the anomaly data yields magnetization models expressing regional variations in the vertical integral of magnetization; this parameter is inversely correlated with regional heat flow in the western U.S., suggesting that areas of low apparent magnetization are areas of thin magnetic crust resulting from a shallow Curie isotherm. For a uniformly magnetized magnetic crust (or intra-crustal layer) Curie depth is linearly related to apparent magnetization. If the relation can be calibrated by two or more Curie depth estimates, the regional Curie isotherm configuration can be mapped. Alternatively, a family of Curie depth models can be computed using assumed magnetization values, and used as boundary conditions on heat flow models which can be compared with observations. Conductive heat flow models for the Rio Grande Rift are given as examples. Principal uncertainties are the magnetic mineralogy prevailing at depth and the uniformity of magnetization within the crust. The method will not work where the Curie isotherm lies below the crust, since the mantle is probably relatively non-magnetic. The method has possible application to aircraft data.

DIGITAL LINEAMENT ANALYSIS IN CRUSTAL MODELING

BY

Kenneth T. Meehan
NASA/Goddard Space Flight Center
Earth Resources Branch, Code 923
Greenbelt, MD 20771

The subcontinental region containing the Rio Grande Rift is being studied to assess the crustal stress relationships of this feature in relation to surrounding tectonically dissimilar blocks. This area including surrrounding crustal blocks of differing tectonic history and response to provincial stress regimes, is quite large and offers an ideal example of a major intraplate structural feature well suited to provide key explanations to crustal evolution. The Rio Grande Rift is itself just large enough to allow analysis and modelling with orbital potential field data in concert with more conventional spectral information (i.e. Landsat).

Lineaments have been plotted for all of 35 Landsat images that cover the Rio Grande Rift area of central New Mexico and Colorado. Lineament patterns for selected "type" tectonic areas will be analyzed at the pixel-to-pixel level to define their respective microtextural parameters or textural primitives. Larger primitives of perhaps greater complexity will be derived from these, which represent macrotexture. This macrotexture represents the collective, synthesized tectonic history of the crustal block, based upon its representation in those lineament patterns.

Subsequent analysis of the various components of the macrotextures will clarify individual paragenetic, deformational events and allow three-dimensional thematic classification of the crust. Under the assumption that the study of an areally and geologically complex feature, such as the Rio Grande Rift, could best be approached by an orchestrated investigation of its component parts, segregation of the region into tectonic regimes is done. Candidate classes for tectonic discrimination would include 1) the Great Plains, 2) Precambrian Colorado Porphyry Belt, 3) North, Middle and Southern sections of the Rio Grande Rift, 4) Colorado Plateau, 5) Basin and Range and 5) Datil-Mogollon Volcanic Field. This delineation provides boundaries to crustal blocks with a similar response to deformation(s) and clarifies relationships of geologic features to tectonic patterns and structural elements.

Individual deformational events with their related axial stress relationships may be derived for each tectonic region by quantiative analyses of their lineament patterns. These patterns are spatially correlated with gravity and aeromagnetic trends and gradients, defined by two dimensional autocovariance and power-spectral analysis. Probability estimates of those patterns being simply tonal anomalies identified at the surface, or fractures and conceivably faults, that would bear more significance to tectonic interpretation, are generated. Associations may then be drawn between lineaments and other geological features such as known mineralization, volcanic source areas, gravity and magnetic anomalies in order to determined causitive relationships.

RIO GRANDE RIFT OVERVIEW. William R. Muehlberger, Department of Geological Sciences, Univ. of Texas at Austin, Austin, TX 78712.

The Rio Grande flows within the axial depression of the rift from the San Luis Valley, Colorado southward to the Big Bend National Park, Texas, a distance of over 500 miles. To the north, the rift is recognized in the upper Arkansas River valley as far as Leadville, Colorado. The width of the rift-related features varies from the north where it is less than 100 miles to south of Socorro where it spreads from the Pecos River west into the Basin-and-Range Province and south across the transverse Texas Lineament zone.

Present axial rates of uplift range from 2 to 4 m/1000 years. Total uplift since Early Pliocene is several thousand meters in southern Colorado.

The location of the axial graben is controlled mainly by Laramide structures with offsets of individual basins controlled by Late Paleozoic and Precambrian structures and by the Jemez Lineament, a N56°E-trending zone of volcanic centers that extends from south-central Arizona to northeastern New Mexico. Most of the volcanism in or near the rift lies along this lineament. The relationships between the rift and the lineament need to be understood -- for example -- to determine whether mineralization is rift-related or lineament-related.

Graben development began about 25 m.y. ago as shown by the earliest rift-related volcanic rocks in southern Colorado, earliest bolson (closed-basin sedimentation) in New Mexico, and the abrupt termination of sedimentation from the ancestral Rio Grande system into the Gulf of Mexico. Immediately earlier the region had been planed to a surface of low relief with through drainage from west to east and southeast. The earlier episodes of rhyolite volcanism are mainly west of the rift (San Juan Mountains, Mogollon-Datil region) but the Trans-Pecos region lies within the rift (actually within the Texas Lineament zone).

Each basin along the axial region is tilted and adjacent basins reverse asymmetry across the bounding traverse structures.

The sedimentary history is best exposed in the Espanola Basin, but even here much of the earlier history must be inferred from limited exposures near the margin. The western half of the basin is now buried by the Jemez caldera and its ejecta. A prominent break in stratigraphic and structural style marked by an unconformity over the length of the rift occurred about 4.5 m.y. ago. This furnishes one convenient datum to measure younger deformation; earlier ones are mappable locally and contribute to the evaluation of deformation rates through time.

Rifts: A Brief Review

William R. Muehlberger, Department of Geological Sciences, Univ. of Texas at Austin, Austin, TX 78712

Rifts are linear zones of extension. The most extensive system is that of the mid-ocean spreading centers where new ocean crust is generated and where hydrothermal processes develop primary mineral resources. The processes that produce oceanic crust form the first step in the evolution of new continent.

Rifts bounded by continental crust are found in a variety of extensile regimes. The hot spot hypothesis of origin and its characteristic three-legged rift has dominated thinking concerning rifts. The fragmentation of Gondwana appears to furnish the best examples of this style. Failed arms that have yet to undergo a collision phase are abundant along the present Atlantic margin (Niger, Amazon, etc.) and those with a later collision phase (aulacogens) are abundant in older orogens (southern Oklahoma, Mississippi, Belt, and Athapuscow among others in North America). Other rift sytems have used pre-existing zones of weakness or are related to oblique extension, and thus are not related to hot spots. Many of the rifts bounding the North Atlantic and in northwestern Europe appear to have origins of this type, as does the Rio Grande Rift of the Western United States.

The complex interplay of divergent transcurrent (or transform) faults and their related subsidiary faults produces a wide array of depressions, the "rifts", "pull-apart structures", or "rhomb grabens" of many transform systems: Gulf of Aquaba, Dead Sea and Lake Amike basins along the Levantine fault zone; Salton Sea depression of the San Andreas fault system; Lake Izabal depression of the Polochic-Motagua fault zone; and those along the Marlborough fault sytem in New Zealand. Continent-continent collisions also produce rifts that strike nearly perpendicular to the collision: Rhine graben and Lake Baikal graben are good examples (the "impactogen" of Kevin Burke).

Each of these rift types has had a different geological history which in turn develops its own characteristic association of mineral and fossil fuel resources. Why are some rifts (or segments of rifts) almost smothered by igneous activity whereas others are nearly free of volcanism? What are the effects of changing spreading rates or directions? Or stopping and restarting of spreading? What differences in the history of a rift will develop as a result of plate migration from one climatic belt to another. Answers to these questions can only be obtained by massive coordinated research programs using all available tools to probe the surface and the deep interior that furnishes the driving mechanisms to the continental rifts on which we depend for all our food, water, and mineral needs.

CRUSTAL STRUCTURE OF THE RIO GRANDE RIFT FROM SEISMIC REFRACTION PROFILING: SOME RESULTS AND FUTURE PROSPECTS. K. H. Olsen, Geosciences Div., Los Alamos Scientific Laboratory, Los Alamos, NM 87545

An unreversed seismic refraction profile extending northward along the axis of the Rio Grande rift was obtained in 1976 by a team of seismologists from LASL, UTEP, and USGS. The energy source for this experiment was a 600 ton chemical explosion - code named DICE THROW - which was detonated at the White Sands Missile Range (WSMR) in central New Mexico. The analysis of the DICE THROW record section (Olsen and others, 1979) that covered a 350 km long section of the rift between central New Mexico and the New Mexico/Colorado border has shown:

1. The crust-mantle interface (Moho) beneath the rift is at a depth of $\sim$33 km and the Pn velocity is in the range 7.6-7.8 km/s. This value of the Moho depth is in excellent agreement with results obtained from the COCORP vertical reflection profile that transects the DICE THROW line near Abo Pass. The 33 km depth represents a thinning of the crust by 10 to 17 km with respect to adjacent provinces (Colorado Plateau and Great Plains). Crustal thinning and anomalously low Pn velocities are also observed in other continental rifts.
2. The DICE THROW data also show a very strong intracrustal reflector is present in the central Rio Grande rift at a depth of $\sim$20 km. Synthetic seismogram modeling suggests this reflector is the top of a (thin?) zone of anomalously low shear wave velocity suggestive of high temperature and/or a partial melt layer. This layer appears to be an extension of a midcrustal magma body near Socorro that has been inferred and delineated by other seismic, electromagnetic, and surface deformation measurements. An interesting question pertinent to the structure and contemporary processes occurring in the rift is whether similar anomalous intracrustal layers can be found elsewhere beneath the rift.

Because available seismic sources from mine and quarry blasting are either not large enough or suitably located within the rift, the DICE THROW profile has not yet been reversed and data on dips, true seismic velocities, and the extent of major subsurface interfaces are still somewhat uncertain. Additional deep seismic refraction studies within the rift are required to remove these ambiguities.

Several geological and geophysical features such as microearthquake clustering in the vicinity of recent surface deformation, high heat flows, extensive surface volcanic formations, and preliminary indications of high electrical conductivities in the crust strongly suggest the presence of partial melt zones and/or possible magma bodies in the region of north-central New Mexico where the rift is intersected by the transverse shear zone of the Jemez Lineament. This region includes the areas of the Valles Caldera-Jemez Mountain Volcanic Field, the Espanola Basin, and (in part) the Taos Plateau Volcanic Field.

In order to help clarify the structure and crustal dynamics of this complex section of the rift, the LASL seismology group has submitted a proposal to the Department of Energy (DOE) to carry out a program of seismic refraction profiling during 1981 and 1982. This area is one of several locales of interest as possible deep drilling targets under the aegis of the Continental Scientific Drilling Program (CSDP) being developed for the 1980's by the US Geodynamics Committee. Extensive preliminary exploration by available geological, geophysical, and geochemical techniques will be required to properly define the scientific questions to be addressed by specific deep drill holes.

The principal objectives to be met by the proposed LASL seismic refraction study are: (1) Better definition of the dip, depth, and Pn velocity at the Moho by a reversal of the DICE THROW line; (2) Investigation of possible midcrustal "magma body" reflectors using wide angle reflections; and (3) Investigation of possible magma chambers beneath the Jemez volcanic field derived from indications of "shadowing" along a fan profile. In order to achieve these objectives, several specially sited borehole explosions in the Ojo Caliente-Petaca section of the Espanola Basin are proposed.

In addition to these proposed LASL seismic shots in the northern rift, the WSMR plans to repeat (in August, 1981) a 600 ton explosion at the same shotpoint in the central rift that was used for the 1976 DICE THROW event. Thus, these several explosions now in the planning stage present an opportunity for extensive seismic refraction profiling in the rift and for other coordinated geophysical studies. We are encouraging other seismologists to join in a consortium effort to obtain additional data from these shots in adjacent regions and to seek ways to supplement and to extend seismic profiles in the Rio Grande rift during this period.

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Paris, J. F., Earth Observations Division (SF3), NASA Johnson Space Center, Houston, Texas

The objective of the oral presentation to the Rio Grande Rift Workshop on the subject of "Passive Microwave Applications" was to give a tutorial on passive microwave sensing and applications to geology.

Due to the fact that the vast majority of remote sensing applications in geology depend upon spatial information (e.g., shape, size, pattern, shadow, texture and relationship to other objects in space), useful applications of passive microwave radiometry and imagery are few. From space platforms, the best spatial resolution obtainable with passive microwave imagers is on the order of tens of kilometers. This level of spatial resolution is unacceptable to geologists who prefer ground resolutions in remote sensing imagery on the order of tens of meters instead of kilometers. Passive microwave imagery is best thought of as being like a low resolution thermal infrared imager such as on meteorological satellites. Passive microwave imagers respond to changes in surface layer thermometric temperature and surface emissivity, as does infrared imagers, but the response function is quite different. A small change in thermometric temperature produces a large change in infrared radiance and a small change in microwave radiance. Another basic difference between infrared and microwave radiometry is that fact that the water content of the surface material has a dominant effect on microwave radiance through both the thermal inertia effect and the effect on surface emissivity whereas the effect of water content on infrared radiance is due only to the thermal inertia effect. As a result, the main application of passive microwave radiometry and imagery over land is the detection of changes in surface soil moisture and snow (liquid) moisture.

The future of passive microwave sensing in geology is open. One application that has been untested is the use of passive microwave sensors to aid in diurnal thermal infrared imagery for thermal inertia mapping such as is being attempted with the Heat Capacity Mapping Mission (HCMM) sensors. A scenario is envisioned wherein a passive microwave imager could be used to establish the absence of moderate or high levels of soil moisture in a geological test site area so that the thermal inertia map derived from thermal infrared imager data can be related strictly to differences in surficial materials and not to patterns of soil moisture in the area. Aircraft-based passive microwave imagers could be used for geology to image soil moisture patterns that might be controlled by faults since resolutions on the order of tens of meters are obtainable from low altitude. Some lithographic units have shown differences in microwave radiance in aircraft-based experiments.

MAGMA TYPES AND CHRONOLOGY IN THE RATON-CLAYTON VOLCANIC FIELD: ANALOGIES WITH THE TAOS PLATEAU. John C. Stormer, Dept. of Geology, University of Georgia, Athens, Georgia; David W. Phelps and Joseph L. Wooden, LOCKHEED, 1830 NASA Rd. 1, Houston, TX; Douglas P. Blanchard, NASA-Johnson Space Center, Houston, TX.

In a compositionally diverse volcanic field, such as the Raton-Clayton or Taos Plateau, the various rock types result from different petrogenetic processes. The fine details of chemical and chronologic comparisons between fields may well be obscured unless analagous magma types can be identified. The successful identification of coherent magma types can enhance the value of geochemical data for tectonic interpretation. Conversely, the comparative chronology and tectonic interpretation may usefully constrain possible models for magma genesis. The present paper represents an attempt to identify magma types in the Raton-Clayton field and to suggest analogs from the Taos Plateau volcanic field (TPVF) (Lipman and Mehnert, 1979).

Previous work in the Raton-Clayton field has not clearly separated the geochemical-petrographic magma types from stratigraphic formations based on relative ages (Stormer, 1972; Baldwin and Muehlberger, 1959; Wood et al., 1953). Therefore we are proposing redefined magma types (see below) for the Raton-Clayton volcanic field. Figure 1 illustrates the temporal relationships of the various magma types, and Table 1 presents pertinent geochemical data.

Alkali Olivine Basalt: These rocks occur as widespread flows of moderate thickness or as cinder cones with associated flows. Phenocrysts of olivine and clinopyroxene are common whereas plagioclase phenocrysts are rare. The alkali olivine basalts are moderately to strongly enriched in incompatible elements and contain 3-10% normative ne. Previously, rocks with these characteristics were included in the early Raton and late Clayton basalts. There are no analogous magmas in the TPVF.

Low-K Olivine Basalt: These occur as thin flows containing small phenocrysts of olivine in a diktytaxitic groundmass composed of predominantly plagioclase. The low-K olivine basalts are the least enriched in incompatible elements of any basaltic rocks in the Raton-Clayton field, and they are either slightly ne or hy normative. In the past, rocks of this composition were included in the late Raton and early Clayton basalts. The low-K olivine basalts are broadly comparable with the Servilleta basalts in the TPVF.

Mafic Feldspathoidal Volcanics: These consist of cinder cones with small flows of basanite to olivine mellilite. Phenocrysts of clinopyroxene, olivine, and hauyne in some varieties are set in a groundmass of nepheline and rare mellilite. These rocks are strongly enriched in incompatible elements and contain up to 20% normative ne. The feldspathoidal volcanics comprise parts of the late Clayton and Capulin flows. There are no equivalent magma types in the TPVF.

Silicic Alkalic Basalt-Olivine Andesite: These occur as cinder cones with associated flows. Large phenocrysts of olivine and resorbed sodic plagioclase and quartz occur in a fine-grained groundmass. These lavas form the majority of the Capulin basalts as well as a few late Clayton volcanos. Their counterparts in the TPVF are the silicic alkalic basalts, xenocrystal basaltic andesite, and olivine andesite.

Two-Pyroxene Andesite: These lavas form the Sierra Grande shield volcano. The rocks are characterized by large orthopyroxene (some with hypersthene cores), clinopyroxene, and smaller plagioclase phenocrysts in a glassy matrix. The two-pyroxene andesites are moderately enriched in incompatible elements. Comparable rocks in the TPVF are the transitional rhyodacites (San Antonio Mtn.).

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Red Mountain Dacites: These occur as several large domes, plugs, and thick flows. Phenocrysts of amphibole and plagioclase are characteristic, although biotite, apatite, and quartz are found at some localities. A more mafic rock type that contains rare resorbed amphiboles is tentatively included in this group. The dacites correspond to the quartz latites of the TPVF.

Tertiary Peralkaline Phonolite-Lamprophyre: These occur as sills and dikes of extremely peralkaline rocks similar to rocks of the Trans-Pecos region in Texas. Although the exact age of the peralkaline suite is unknown, they are considerably older than the Pliocene to recent volcanics. There are no comparable rocks in the TPVF.

The above redefined magma types are preliminary and additional study may result in significant changes. In general most of the magma types encountered in the Raton-Clayton volcanic field are more alkalic than those in the TPVF. However, there are significant similarities between some of the magma types found in both volcanic field that should not be overlooked.

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Table 1

	SiO_2	CaO	K_2O	P_2O_5	Rb	Sr	Ba	La_n/Yb_n
Alkali Olivine Basalt	45-48%	9-12%	≥1%	≥1%	<20 ppm	≥1000 ppm	≥1000 ppm	15-20
Low-K Olivine Basalt	48-50%	≤10%	≤1%	<0.5%	≤15 ppm	≤1000 ppm	≤1000 ppm	<15
Mafic Feldspathoidal Volcanics	36-45%	10-15%	1-1.5%	1-3%	20-30 ppm	1000-3000 ppm	1000-2000 ppm	15-35
Silicic Alkalic Basalt-Olivine Andesite	50-56%	<10%	>1%	~0.5%	20-30 ppm	<1000 ppm	≤1000 ppm	≤15
Two-Pyroxene Andesite	57-60%	≃6%	2-3%	≃0.5%	≤30 ppm	≤1500 ppm	≤1700 ppm	20-25
Red Mountain Dacite	60-69%	<5%	2-3%	0.1-1%	25-50 ppm	≤1000 ppm	≤1500 ppm	20-30

RATON-CLAYTON VOLCANIC FIELD

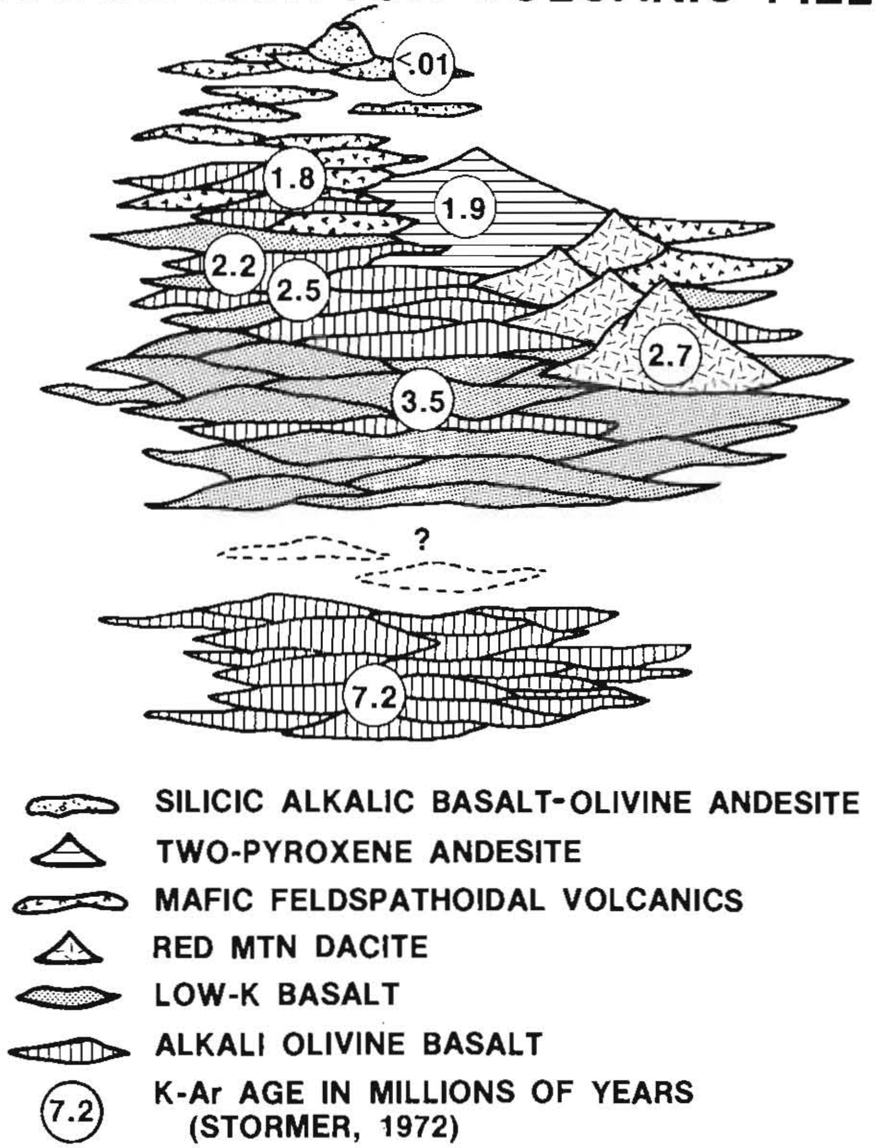

Figure 1.- Schematic representation of the stratigraphic relationships in the Raton-Clayton volcanic field.

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