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FOREWORD

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The Rio Grande rift was largely overlooked as a major continental rift until the 1970's. Geologists in the United States were preoccupied with the much larger Basin and Range province and with the southern Rocky Mountains. The pioneering studies of Bryan (1938) and Kelley (1952, 1954, 1956) had appeared in regional publications that were generally not known outside the southwestern United States. During the 1960's, the Rio Grande rift appeared on maps in several regional studies (Eardley, 1962; Hamilton and Myers, 1966; Cook, 1969) and was variously termed the Rio Grande "rift valley system", "rift belt", or "depression". Many geologists regarded the Rio Grande rift as merely a prong of the Basin and Range province. However, the paper by Seager and Morgan in this volume presents evidence that the southern Rio Grande rift differs from the adjacent Basin and Range province in several important aspects.

The surge of modern research on the Rio Grande rift was triggered by two revolutions in the 1960's: 1) the quiet revolution of greatly expanded geologic mapping, especially of volcanic fields, and 2) the noisy revolution of plate tectonics with its focus on fitting major structures into an overall scheme. The series of modern papers began with Lipman's (1969) comparison of the chemical compositions of basalts within the rift versus those on its shoulders. In 1971, I attempted to define the extent of the rift and to outline its characteristic features. Also appearing in 1971 was the epic volume on the stratigraphy of the Santa Fe Group by Galusha and Blick. 1975 was a vintage year for publications on the rift. Lipman and Mehnert described basaltic volcanism and development of the rift, Chapin and Seager the evolution of the rift, Reiter and others the heat flow anomaly associated with the rift, and Decker and Smithson a lithospheric model for the southern rift based on heat flow and gravity data. Woodward and others compiled a tectonic map of the Rio Grande region from the Colorado-New Mexico border to Presidio, Texas. Also published in 1975 was Geological Society of America Memoir 144 Cenozoic History of the Southern Rocky Mountains which documented the major role of uplift and block faulting in shaping the present character of the southern Rocky Mountains. The culmination of papers leading up to the International Symposium was the paper by Cordell (1978) on the regional geophysical setting of the Rio Grande rift ... a paper which caps nearly two decades of geophysical work. I have touched only the highlights here; many significant contributions pertaining to particular areas or features have been made by other researchers.

Another revealing way of measuring the progress of research on the Rio Grande rift is to compare 3 symposia held on the rift during the 1970's, each 4 years apart. The first of these conferences was the Spring Meeting of the New Mexico Geological Society held in April 1970 during which 21 papers on the Rio Grande rift were presented. The abstracts were published in the Society's Twenty-First Annual Guidebook (L. A. Woodward, ed., 1970). The second symposium was a Geological Society of America Penrose Conference convened by Lindrith Cordell and Frank Kottlowski and held in Santa Fe during August 1974. Thirty-five

papers were presented to a group of about 70 scientists from the United States. A volume of papers was not published after this meeting but the Penrose Conference was an important catalyst as evidenced by the number of papers that appeared during the next four years. The third symposium was the International Conference held in October 1978. Approximately 190 scientists attended, 26 of whom represented 13 countries other than the United States. Eighty-seven papers were presented of which 53 were on the Rio Grande rift and involved 86 authors from 28 institutions in 14 states and 2 other countries. These figures tell a story of accelerating research on the Rio Grande rift with involvement of a large number of scientists from many institutions.

The other part of the story is the increase in geophysical and geochemical studies with a greater diversity of research techniques being brought to bear on rift problems. In 1970, 2 of 12 papers were by geophysicists who covered gravity, aeromagnetics, and seismicity. In 1974, 5 of 35 papers were by geophysicists with coverage of gravity, aeromagnetics, heat flow, seismicity, and seismic reflection (a preview of plans by the Consortium for Continental Reflection Profiling). In 1978, 22 of 53 papers on the Rio Grande rift were by geophysicists with coverage of seismicity, seismic reflection profiling, seismic refraction, magma shadowing using microearthquakes, surface wave dispersion, teleseismic delay, magnetotelluric profiling, geomagnetic variation, Bouguer gravity, residual gravity, heat flow, releveling, geodesy, and computer modeling. The increase in geochemical research is also impressive; 10 papers at the International Symposium dealt mainly with chemical and isotopic studies of volcanic rocks along the Rio Grande rift. An additional 6 papers reported the results of geochemical studies on mantle and crustal xenoliths. Attempts were made to model the lithology, temperature gradients, degree of partial melting, magnitude of mantle upwelling, and state of stress in the lithosphere beneath the rift.

In 8 years of intensive research the Rio Grande rift has evolved from a largely unknown structure to one of the best documented continental rifts in the world. Research will not slacken with publication of this volume. The next few years will bring important new discoveries and concepts in an endeavor which has become a fine example of interdisciplinary research.

This volume contains a special collection of papers selected from those presented at the International Symposium on the Rio Grande rift held at Santa Fe, New Mexico, in October 1978. The Symposium was sponsored by Working Group 4 of the Inter-Union Commission on Geodynamics and 9 other organizations with Los Alamos Scientific Laboratory as host. Emphasis of the program was on tectonics and magmatism of the Rio Grande rift. Two previous publications have resulted from the meeting: 1) a Program and Abstracts volume published as report LA-7487-C of the Los Alamos Scientific Laboratory, and 2) a Guidebook to the Rio Grande Rift in New Mexico and Colorado compiled by J. W. Hawley and published as Circular 163 of the New Mexico Bureau of Mines and Mineral Resources.

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EVOLUTION OF THE RIO GRANDE RIFT — A SUMMARY

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The purpose of this summary is to provide a concise overview of the Rio Grande rift. For details and other interpretations see the individual papers in this volume, regional syntheses by Chapin and Seager (1975) and Cordell (1978), and Guidebook to the Rio Grande Rift in New Mexico and Colorado compiled by Hawley (1978).

Rifting began between 32 and 27 m.y. ago when regional extension reactivated the southern Rocky Mountains, a major north-trending zone of weakness that had developed during late Paleozoic and late Cretaceous-early Tertiary orogenies. By 26 m.y. ago, the crust along the developing rift had sagged sufficiently to form broad, shallow basins in which mafic flows and volcanic ash beds were intercalated with alluvial fill. Preservation within rift basins of complete pre-rift volcanic sections and early-rift volcanic-alluvial sections eliminates regional doming as an early rift process. As the rift opened, it broke en echelon across a series of northeast- and west-northwest-trending flaws which appear as lineaments in the basement terrane of the southern Rocky Mountains. Basins forming on opposite sides of lineaments tended to develop opposing symmetries -- hinged on the west versus hinged on the east. Consequently, those portions of lineaments connecting the ends of staggered basins were subjected to a scissors-like torque in the brittle near-surface rocks and to a transverse shear at depth. Near-surface strain along these transverse structures has been relieved mainly by a complex intermeshing of normal faults of opposing sense rather than by strike-slip faulting. The deeply penetrating transverse structures have tended to leak magmas and to be zones of high heat flow and geothermal activity. See Chapin et al. (1978) for a map showing major lineaments transected by the Rio Grande rift and for geological and geophysical documentation of a transverse shear zone at Socorro.

The main portion of the Rio Grande rift can be divided into three segments, each with its own structural style and history but with a common thread of major events and timing. The northern segment, Leadville to Alamosa (Figure 1), began to open about 27 m.y. ago and is characterized by: a north-northwest trend paralleling the late Paleozoic and Laramide structural grain; a near absence of synrift volcanism in the axial basins; and a shift in extension away from the axial grabens into a broad belt along the east shoulder of the rift (Tweto, this volume). The axial graben system tapers northward and pinches out about 20 km north of Leadville. Extension continues northward to near the Wyoming border as a broad zone of block faulting (Tweto, this volume).

The central segment, Alamosa to Socorro (Figure 1), is characterized by a north-northeast-trending series of en echelon basins separated by complex transverse structures. This segment traverses an area of northeast-trending basement lineaments and crosses 1.4-1.8 b.y.-old Precambrian rocks (Hedge et al., 1968) in the north and 1.3-1.5 b.y.-old Precambrian rocks (White, 1978) in the south. Except near Taos,

UTAH
KANSAS
OKLA.
TEXAS
ARIZONA
TEXAS
EP
MEXICO
0
100
200 Kilometers

early-rift magmatism was relatively sparse within this segment, but late-rift bimodal volcanism was voluminous. The Jemez lineament and the Taos Plateau have been especially active during the past 5 m.y.

The southern segment, Socorro to El Paso (Figure 1), has undergone the most extension as evidenced by the widening of the rift near Socorro into a north-trending series of parallel basins and ranges with a total width about 2.5 times that of the large single basins to the north. The rift also bifurcates near Socorro with a weaker arm (the San Augustin rift) extending southwestward along the Morenci lineament into Arizona. Between the San Augustin arm and the southern segment of the main rift is a triangular area about 80 km on a side which has undergone moderate to extreme (> 50 percent) crustal attenuation and voluminous early-rift and late-rift magmatism. "Domino-style" normal faulting (Chamberlin, 1978) and 30 to 60° of rotation of early Miocene and older strata is common within this triangle, wherever intrarift horsts expose the floor of an early rift basin. A similar structural style is present in the Rincon-Radium Springs area north of Las Cruces. The Socorro triangle is bisected by a northeast-trending transverse shear zone across which the sense of rotation of strata and normal faulting changes 180°. A large, present-day, sill-like magma body at mid-crustal depths of 12 km (Rinehart et al., this volume) ends against this transverse structure and is apparently leaking magmas along it to form shallow reservoirs.

Rifting began about 5 m.y. earlier (32 m.y.) in the southern segment of the Rio Grande rift. The change to bimodal volcanism occurred near the beginning of ash-flow magmatism in the Datil-Mogollon field (Elston and Bornhorst, this volume) instead of at the end as in the San Juan field (Lipman et al., 1978). Large volumes of basaltic-andesite lavas with high initial Sr^{87}/Sr^{86} ratios (0.7055-0.7090, Stinnett and Stueber, 1976) are interbedded with high-silica ash-flow sheets dated at 32 to 26 m.y. in age. Basaltic andesite volcanism continued to about 20 m.y. and was followed by a lull in magmatism between about 20 and 13 m.y. ago. A similar hiatus occurred throughout the Intermountain West but was shorter in the Basin and Range province(s) (20-17 m.y., McKee et al., 1970). Following the middle Miocene lull, bimodal magmatism changed to a basalt-rhyolite suite with low initial Sr^{87}/Sr^{86} ratios (basalt, 0.7034-0.7051; rhyolite, 0.7048-0.7070). Everson and Silver (this volume) report highly radiogenic rock leads similar to those of oceanic islands in Pliocene and Pleistocene basalts of the southern segment and suggest a deep mantle upwelling. The structural characteristics of the southern segment and its magmatic evolution support their conclusion. In contrast, magma source regions in the central and northern segments remained in the lithosphere throughout rifting as evidenced by the lack of systematic chemical changes between early-rift and late-rift rocks (Lipman et al., 1978; Baldridge, this volume; Williams and Murthy, 1978; Dungan et al., 1978). The more silicic pre-rift and early-rift rocks of the southern

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Fig. 1. Shaded relief map of the Rio Grande rift. L = Leadville, Al = Alamosa, SJ = San Juan volcanic field, T = Taos, J = Jemez volcanic field, A = Albuquerque, S = Socorro, SA = San Augustin rift, DM = Datil-Mogollon volcanic field, LC = Las Cruces, EP = El Paso. Modified from cover of New Mexico Bureau of Mines and Mineral Resources Circular 161, 1978.

segment and their higher initial Sr^{87}/Sr^{86} ratios probably reflect differences in age and composition of the Precambrian lithosphere between the two areas.

Volcanism along the Rio Grande rift increased slowly after the middle Miocene lull (20-13 m.y.) with activity concentrated initially in the Socorro triangle and the Jemez Mountains where the rift transects major northeast-trending lineaments. The southern Rocky Mountains and adjacent areas were strongly uplifted between about 7 and 4 m.y. ago. Total uplift since middle Miocene has been about 1100 m (Axelrod and Bailey, 1976), much of which probably occurred during this brief interval. The uplift is probably due to mantle upwelling like that documented for the Great Basin and adjacent areas by Eaton et al. (in press). Block faulting accompanying epeirogenic uplift disrupted the early broad basins of the Rio Grande rift and formed the modern topography, with narrower, more sharply defined basins. Preliminary calculations based on deflection of lineaments indicate a total extension across the Rio Grande rift of 100-150%. These figures are an order of magnitude larger than previous estimates, but they are consistent with the quantities of basaltic magma that must be injected into the crust to maintain the heat flow anomaly (A. Lachenbruch, 1978, oral commun.) and to explain the residual positive gravity anomaly along the rift axis (Decker and Smithson, 1975; Cordell, 1978).

Increased runoff from newly elevated alpine regions integrated the drainage to form the ancestral Rio Grande prior to 4 m.y. ago. Widespread geomorphic surfaces, graded to the ancestral Rio Grande and its tributaries, became mantled with basalt flows following sharp acceleration of basaltic volcanism about 5 m.y. ago. Lowering of base levels following capture of the Rio Grande at El Paso during middle Pleistocene time (Kottlowski, 1958) resulted in dissection of basins along the Rio Grande drainage and isolation of basalt-capped mesas. Epeirogenic uplift has continued since 4 m.y. ago but at a reduced rate. Rifting continues today as evidenced by abundant fault scarps cutting Pleistocene deposits, high heat flow, modern elevation changes, modern magma bodies, and geophysical evidence for anomalous crust and upper mantle beneath the rift.

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