# Geometry and rate of extension across the Pajarito fault zone, Española basin, Rio Grande rift, northern New Mexico

Matthew P. Golombek
Department of Geology and Geography, University of Massachusetts
Amherst, Massachusetts 01003

## ABSTRACT

The central Velarde graben is the active subbasin of the Española basin section of the Rio Grande rift in north-central New Mexico. The Velarde graben is bounded on the west, in the Jemez volcanic field, by the Pajarito fault zone. This fault zone has produced a steep fault scarp about 100 m high where it cuts the 1.1-m.y.-old Tshirege Member of the Bandelier Tuff. Detailed mapping along the north-trending Pajarito fault zone has revealed a fairly simple geometry. In the Tshirege Member, the faults follow numerous vertical joints. Below this member, fault dips are ~60° and not listric at shallow depths. This simple geometry allows calculation of a mean rate of extension of ~0.05 mm/yr across the Pajarito fault zone for the past 1.1 m.y. If extension is not perpendicular to the fault zone, the extension rate could be as great as ~0.07 mm/yr. Lack of transverse tilt of the Velarde graben wedge implies that the extension rate across the eastern margin is about the same as for the western margin. Comparison with a published extension rate for the northern Albuquerque-Belen basin (just to the south of the Jemez Mountains) of 0.3 mm/yr (both sides) since rifting began 26 m.y. ago indicates a slower opening for the Velarde graben during the past 1.1 m.y. If extension is localized along the margins of the Velarde graben with little activity along other fault zones in the Española basin, then both the mean rate of extension and the width of the actively extending region have decreased with time for this section of the Rio Grande rift.

## INTRODUCTION

In New Mexico, the north-northeast–trending Rio Grande rift consists of a series of north-trending en echelon basins that step to the right. Individual basins are fault-bounded valleys with border faults that are commonly poorly exposed or unexposed. In the Española basin (Fig. 1), the eastern border is defined by the contact of the Precambrian rocks of the Sangre de Cristo uplift with the basin fill (Santa Fe Group). No single major border fault is recognized; instead, the contact is both depositional and faulted (Manley, 1979). To the west, the Española basin is bounded by a discontinuous northeast-trending fault zone with down-to-the-east displacements. However, parts of this fault zone are concealed, probably covered by some of the younger Jemez volcanic units, which indicates relative inactivity in the past 1 m.y.

The intrarift Velarde graben (Fig. 1) lies within the Española basin and began forming in early Pliocene time (Manley, 1979). Detectable crustal subsidence and seismicity indicate that the Velarde graben is still active (Reilinger and York, 1979; Jiracek, 1974). The eastern boundary of the Velarde graben has been mapped by Manley (1979) as a series of prominent yet partially obscured north-trending, west-side-down faults that cut the Santa Fe Group at least 20 km to the west of the eastern margin of the Española basin.

The western margin of the Velarde graben is bounded by the prominent Pajarito fault zone, which is the subject of this paper. In the Jemez Mountains, this fault zone cuts the Pleistocene Bandelier Tuff and has produced a down-to-the-east fault scarp (Smith and others, 1970). Kelley (1979) suggested that this fault (which he calls the Los Alamos fault) defines the eastern edge of the Jemez bench, a structural high that marks the up-ramped northern terminus of the Albuquerque-Belen basin. This structural high is capped by the Jemez volcanic field. The Pajarito fault may be a growth fault with as much as 3 km throw at depth; movement along it may be responsible for the gentle westward dips of the Santa Fe Group sediments in the eastern part of the Española basin (Kelley, 1979).

Kelley (1979) and Muehlberger (1979) projected the Pajarito fault zone to the northeast under the Rio Grande flood plain and linked it with the down-to-the-west Embudo fault (Velarde fault of Manley, 1979). They suggested that this fault is involved in the right en echelon offset of the rift. Muehlberger (1979) presented evidence that the Embudo fault, which he suggests is a transform fault, is locally under compression in a northwest-southeast direction. A component of left slip parallel to the Rio Grande rift would produce a counterclockwise rotation of the block bounded to the northwest by the Embudo fault, thereby producing the local compression observed. Moreover, left slip agrees with the general tectonic model of the middle Rio Grande rift proposed by Kelley (1979), in which northward up-ramping structural basins are connected by right en echelon relay faults. In this model, the Jemez bench represents the up-ramped northern terminus of the Albuquerque-Belen basin, and the Pajarito fault zone is the right en echelon relay fault.

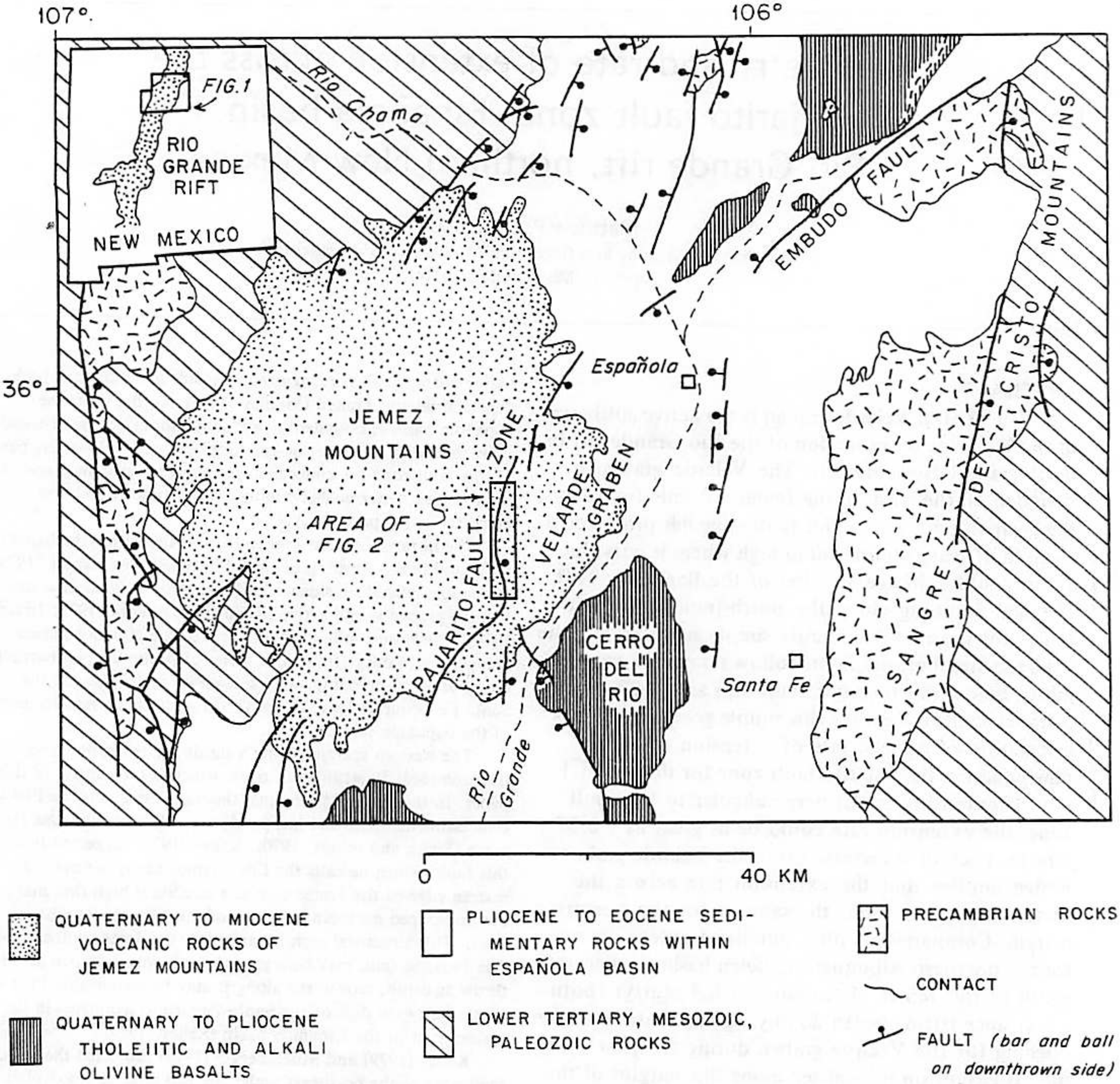

**Figure 1. Generalized geologic map of the Española basin, Rio Grande rift, north-central New Mexico (modified from Manley, 1979).**

In general, in order to determine the rate of extension across a fault or group of faults, the geometry, kinematics, and timing of movement must be known or approximated. Woodward (1977) was able to do this for the Albuquerque-Belen basin where he calculated the rate of extension to have been 0.3 mm/yr since rifting began 26 m.y. ago. In this paper I analyze the Pajarito fault zone where it cuts the broad, gently eastward-dipping surface of the Pajarito Plateau that is underlain by the 1.1-m.y.-old Tshirege Member of the Bandelier Tuff (Doell and others, 1968). This ash-flow unit provides a time line to which data on the geometry and kinematics of the Pajarito fault zone are added to derive a rate of extension.

## GEOLOGIC MAP AND STRUCTURAL DATA

A detailed geologic map of part of the Pajarito fault zone is shown in Figure 2. Noted on the map are approximate stratigraphic displacements, strike and dip of bedding, stations where brittle fracture features were measured, and mapped geologic units. Data that help constrain fault geometry and amount of possible extension are briefly described below.

Typical offset of the Bandelier Tuff by major faults is expressed as a steep fault scarp. Even though the major faults are covered by talus and alluvium, most movement is east-side-down. West-side-down faults occur in only a few places and always with minor displacements (~10 m). Nevertheless,

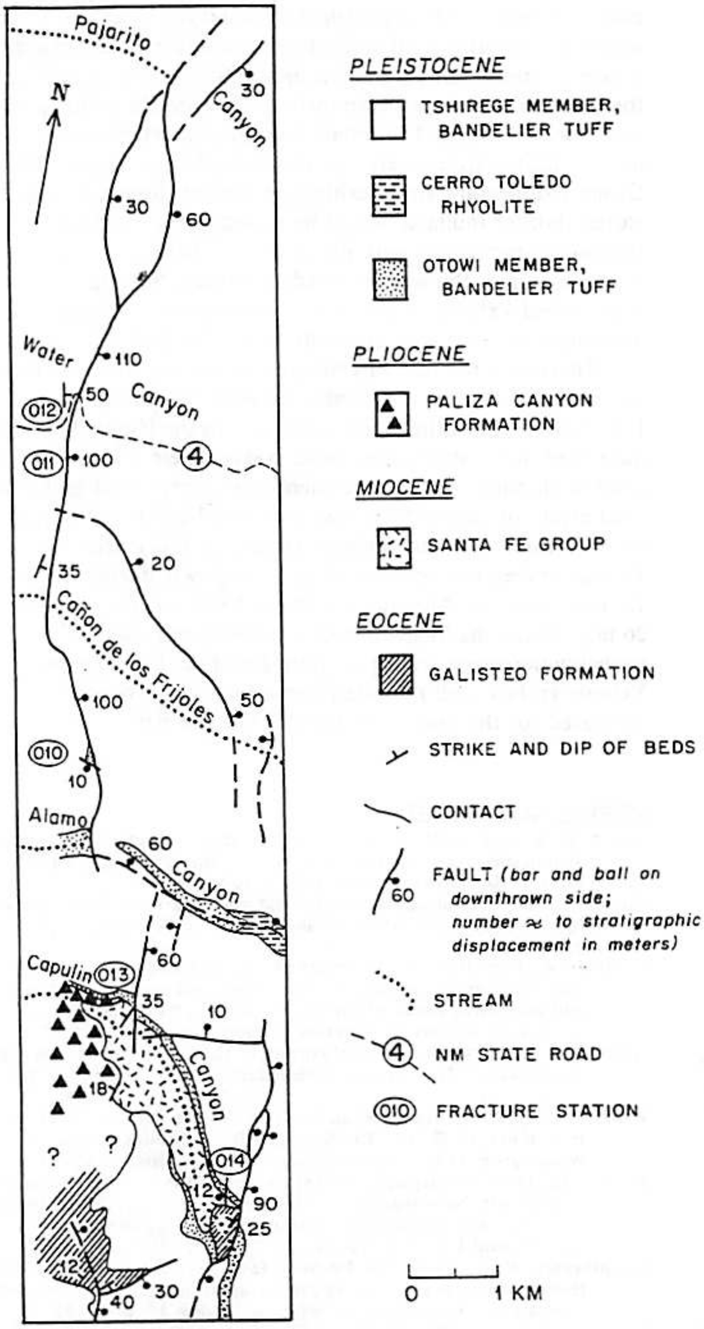

**Figure 2. Geologic strip map of part of the Pajarito fault zone.**

exposure of one of these minor faults illustrates the probable geometry of normal faults in the map area. This fault, located on the north side of Capulin Canyon (station 014, Fig. 2), dips to the west at ~70° and drops the Pleistocene Otowi Member of the Bandelier Tuff against the Miocene Santa Fe Group. The well-bedded Gauje Pumice Bed of the Otowi Member exhibits normal drag but is not rotated toward the fault as would be required if the fault flattened with depth. The fault appears to follow vertical joints in the overlying Tshirege Member.

Slickensides were observed at only two localities (stations 010 and 013), along minor west- and northwest-striking faults. These minor faults are immediately adjacent to major north-striking faults but do not show large displacements. Attitudes of fault planes and movement directions for these minor faults show a predominance of steeply dipping normal faults with pure dip-slip motion; this indicates local extension in north-south and northeast-southwest directions, approximately parallel to the Rio Grande rift.

## GEOMETRY

The Tshirege Member of the Bandelier Tuff is characterized by numerous vertical joints interpreted by Bailey and Smith (1978) as columnar joints. Thus, an upward-propagating fault would probably follow these pre-existing fractures in the Tshirege Member. Movement along vertical fractures would cause a very steep fault scarp. This fault geometry in the Tshirege Member is supported by (1) the steep fault scarps along the Pajarito fault zone, (2) the expected response to tensile stress of pervasively fractured rock under low confining pressure, (3) observations at station 014 discussed earlier, and (4) the report by Woodward and DuChene (1975) that the Sierrita fault (at the southern edge of the Jemez Mountains) is vertical where it cuts the Bandelier Tuff.

The dip of individual faults below the Tshirege Member of the Bandelier Tuff where the rocks do not have columnar joints is less certain. Nevertheless, 60° fault dips are in keeping with the Anderson hypothesis, mechanical scale model studies, and experimental fracture work (Fig. 3). It is possible that individual fault dips vary as much as ±10° from 60°; however, fault dips beyond these limits are mechanically unsound. Finally, an average dip of ~60° is also in agreement with observations at station 014 discussed earlier and with gravity models across master faults of the Rio Grande rift by Cordell (1979).

Faults below the Tshirege Member probably do not shallow appreciably with depth but maintain ~60° dips. The following arguments support this interpretation: (1) There is no evidence for rotation of the downthrown block toward the fault as would be expected for listric faults. (2) Faults that shallow with depth require readjustments in the downthrown block, which would result in antithetic west-side-down faults that are rare along the Pajarito fault zone. (3) The lack of tilt of the graben floors formed by the minor west-side-down faults (Fig. 2) does not allow interpretation of these features as antithetic faults like those described by Woodward and DuChene (1975) for the listric Sierrita fault. (4) The shallow eastward dip of the Pajarito Plateau, even in places where the fault splits, is essentially undisturbed across the fault zone. (5) A detailed gravity profile across the major Hubble Springs fault, which marks the eastern boundary of the Albuquerque-Belen basin near Belen, indicates no flattening of faults above a depth of 3 km (Cordell, 1979). If fault dips do decrease with depth, this decrease must occur at sufficient depth not to affect the rocks on the surface and thus will not affect the ensuing calculations.

## RATE OF EXTENSION

The amount of extension since deposition of the 1.1-m.y.-old Tshirege Member can be calculated from the geometry of the fault shown in Figure 3. The extension $x$ can be calculated from $x = s/\tan\theta$, where $s$ is the scarp height and $\theta$ is the dip of the fault beneath the Tshirege Member. Values of $s = 100$ m and $\theta = 60°$ yield an extension of 58 m. Thus, the average rate of extension across the Pajarito fault zone for the past 1.1 m.y. is ~0.05 mm/yr. The greatest source of error in this calculation lies in the fault dip chosen; nevertheless, a variation in the fault dip of ±10° yields similar extension rates of ~0.03 and ~0.08 mm/yr.

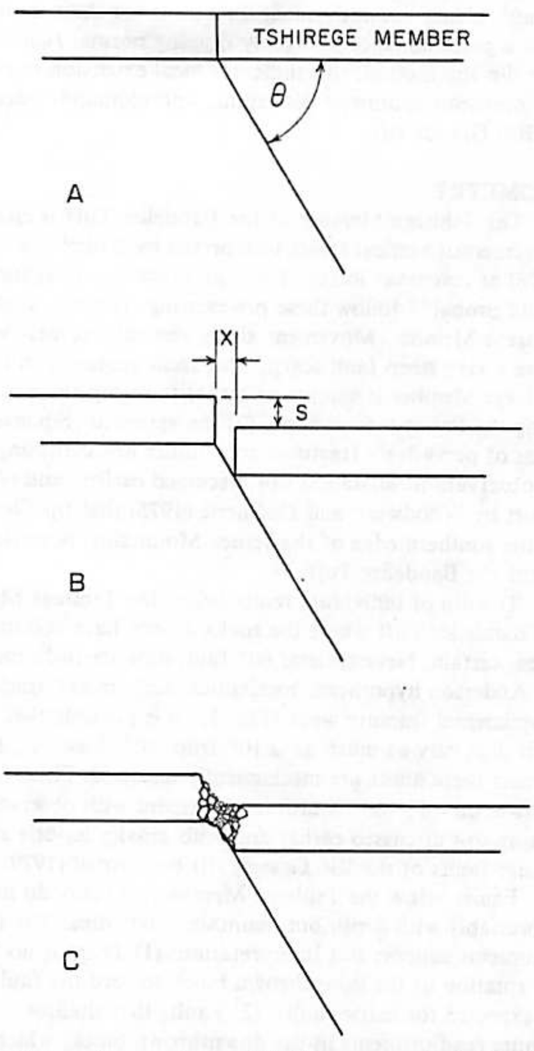

**Figure 3. Near-surface mechanics of faulting across a typical fault of the Pajarito fault zone. (a) Major fault propagates upward at angle $\theta$ to the base of the Tshirege Member of the Bandelier Tuff. (b) Extension $x$ produces a scarp of height $s$, $x = s/\tan\theta$. (c) Mass wasting, erosion, or rotatation of upthrown tuff into the fault fills the void.**

This extension is a minimum because the calculation assumes that extension is perpendicular to the fault zone, approximately east-west. Minor slickensided faults at stations 010 and 013 indicate local extension in north-south and northeast-southwest directions. This extension may be the result of some component of left slip along the rift, as suggested by Muehlberger (1979) and Kelley (1979). Muehlberger (1979) stated that left slip would cause a counterclockwise rotation of the block bounded to the northwest by the Embudo fault and to the west by the Pajarito fault zone. This rotation could result in extension across the Pajarito fault zone in the directions indicated by these minor slickensided faults. Woodward (1977) calculated an extension rate of 0.3 mm/yr across the *entire* northern section of the Albuquerque-Belen basin for the past 26 m.y. If extension is in a northwest-southeast direction, as suggested by Woodward (1977), the rate of extension across the Pajarito fault zone during the past 1.1 m.y. is still only ~0.07 mm/yr for fault dips of 60°. This is one-half of the long-term extension rate (0.15 mm/yr per side) calculated by Woodward (1977) just to the south of the Jemez Mountains.

The extension across the eastern margin of the Velarde graben is unknown. However, the following arguments imply an extension rate that is approximately equal to the extension rate across the Pajarito fault zone. If extension across the eastern border of the Velarde graben is appreciably less than that across the Pajarito fault zone, asymmetric westward tilt of the graben wedge would occur. The broad Pajarito Plateau shows no sign of such tilting. Conversely, the gently westward-dipping Santa Fe Group sedimentary strata exhibit no sign of tilting into the eastern border faults as would be expected if these faults shallowed appreciably with depth or if extension were greater than that across the western border. Finally, the relatively undisturbed Velarde graben wedge necessitates that only minor movement has occurred on faults within the graben.

Therefore, the rate of extension across the Velarde graben for the past 1.1 m.y. is probably between 0.1 and 0.15 mm/yr. It is possible that other fault zones within the Española basin have been active during this time. Nevertheless, the absence of other fault zones within prominent fault scarps implies that the total extension across them has been small compared to the Pajarito fault zone and Velarde graben. If this is true, the Velarde graben has been opening more slowly during the past 1.1 m.y. than the Albuquerque-Belen basin has for the past 26 m.y. Thus, the locus of major tectonic extension has probably narrowed from the entire Española basin to the Velarde graben, and the rate of extension has probably decreased for this section of the Rio Grande rift.

## REFERENCES CITED

Bailey, R. A., and Smith, R. L., 1978, Volcanic geology of the Jemez Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 184–196.

Cordell, L., 1979, Sedimentary facies and gravity anomaly across master faults of the Rio Grande rift in New Mexico: Geology, v. 7, p. 201–205.

Doell, R. R., Dalrymple, G. B., Smith, R. L., and Bailey, R. A., 1968, Paleomagnetism, potassium-argon ages, and geology of rhyolites and associated rocks of the Valles caldera, New Mexico: Geological Society of America Memoir 116, p. 211–248.

Jiracek, G. R., 1974, Geophysical studies in the Jemez Mountains region, New Mexico: New Mexico Geological Society Guidebook 25, p. 137–144.

Kelley, V. C., 1979, Tectonics, middle Rio Grande rift, New Mexico, *in* Riecker, R. E., ed., Rio Grande rift: Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 57–70.

Manley, K., 1979, Stratigraphy and structure of the Española basin, Rio Grande rift, New Mexico, *in* Riecker, R. E., ed., Rio Grande rift: Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 71–86.

Muehlberger, W. R., 1979, The Embudo fault between Pilar and Arroyo Hondo, New Mexico: An active intracontinental transform fault: New Mexico Geological Society Guidebook 30, p. 77–82.

Reilinger, R. E., and York, J. E., 1979, Relative crustal subsidence from leveling data in a seismically active part of the Rio Grande rift, New Mexico: Geology, v. 7, p. 139–143.

Smith, R. L., Bailey, R. A., and Ross, C. S., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-571, scale 1:125,000.

Woodward, L. A., 1977, Rate of crustal extension across the Rio Grande rift near Albuquerque, New Mexico: Geology, v. 5, p. 269–272.

Woodward, L. A., and DuChene, H. R., 1975, Geometry of Sierrita fault and its bearing on tectonic development of the Rio Grande rift, New Mexico: Geology, v. 3, p. 114–116.

## ACKNOWLEDGMENTS

Reviewed by K. Manley and L. A. Woodward. Supported by National Aeronautics and Space Administration Grant NGR-22-010-076 from the Planetary Geology Program Office. Thanks to G. E. McGill and A. G. Goldstein for critically reading the manuscript. V. DelloRusso assisted in the field work.

MANUSCRIPT RECEIVED MAY 22, 1980
MANUSCRIPT ACCEPTED OCTOBER 27, 1980