The western margin of the Rio Grande Rift in northern New Mexico: An aborted boundary?

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ABSTRACT

The northwestern margin of the Española basin, part of the Rio Grande rift in northern New Mexico, is characterized by a zone >17 km wide of oblique-slip faults that offset upper Paleozoic and Mesozoic strata of the eastern Colorado Plateau from Eocene and younger sedimentary rocks of the rift. Along this margin, a reasonably complete section of pre- and synrift Tertiary sediments is exposed. Combined interpretations of seismic reflection, seismic refraction, gravity, and geologic data acquired along a profile perpendicular to this boundary define the geometry of faulting, possible rotation of sedimentary units, and stratigraphy of rift fill. Vertical separation on the westernmost major fault, assumed to be the bounding fault between the rift and the Colorado Plateau, is <500 m; separation on other faults in the zone is <200 m. Thus the northwestern part of the Española basin ("Abiquiu embayment") is a shallow platform rather than a deep rift basin. The embayment is separated from the main Española basin by the east-northeast–striking Embudo transfer fault, which appears to act as the northern bounding fault of the main basin.

Although Tertiary units are progressively faulted downward toward the axis of the rift, depth to inferred Precambrian crystalline rocks becomes shallower and the stratigraphic thickness of the intervening Paleozoic and Mesozoic units decreases toward the axis. We interpret pinching out of these units toward the east as erosional thinning on the western flanks of the Laramide-age Sangre de Cristo/Brazos geanticline, which underlay much of the present rift basin.

Imprecise age constraints suggest that faulting of the rift margin began 10–7 Ma, but was not active after 7 Ma. Extension was apparently transferred to the Embudo fault zone, which remained active until at least 2.5 Ma and possibly into Quaternary time. The Embudo transfer zone effectively decoupled the Abiquiu embayment from the main Española basin. Thus the boundary at Abiquiu preserves an early stage in the formation of the rift boundary. The shift in activity may have resulted from a change in regional stress field, or from increasing magnitude of strain, or both. The change in locus of extension reflects a narrowing of rift basins through time and an integration of main bounding structures between adjacent basins.

Although we are uncertain whether the Abiquiu region, which uniquely preserves an early stage of deformation, is representative of other areas of continental extension, our results indicate that the initial formation of rift basins may occur as high-angle, planar normal faults distributed over a broad zone. No evidence from seismic data or from rotation of beds exists to indicate that faults become listric with depth, which is compatible with the small amount of extension (3.5%) inferred at this boundary.

INTRODUCTION

Detailed descriptions of the structure of continental rifts are important in evaluating models of their structural and tectonic evolution. Major elements of rift models include half grabens and accommodation zones (Bosworth, 1985; Rosendahl, 1987). Half grabens are structural basins hinged on one side and bounded by major detachment faults (breakaway faults) on their opposite sides. Accommodation zones are regions wherein strain is transferred laterally between oppositely hinged basins. Structures may differ greatly between different parts of a single rift and at different times in the evolution of a rift.

The present work near Abiquiu, northern New Mexico, was undertaken to better characterize a well-exposed boundary of a major continental rift and to document structures associated with the initial stages of crustal extension. Among the uncertainties regarding continental extension are whether rift-bounding structures are listric, whether a single master fault or a broad zone of smaller faults controls basin geometry, and whether low-angle bounding faults initially form with shallow dips or are initiated at high angle and later rotate to shallower dips.

Although we are uncertain about the extent to which the Abiquiu region is representative of other parts of the Rio Grande rift or areas of continental extension, our results suggest that in at least some cases the initial formation of rift basins may occur as numerous high-angle, planar normal faults distributed over a zone 10–20 km wide. No evidence from seismic data or from the geometry of strata exists to indicate that faults are listric at depth, although we cannot rule out this possibility. Planar fault surfaces are

Geological Society of America Bulletin, v. 106, p. 1538–1551, 10 figs., 3 tables, December 1994.

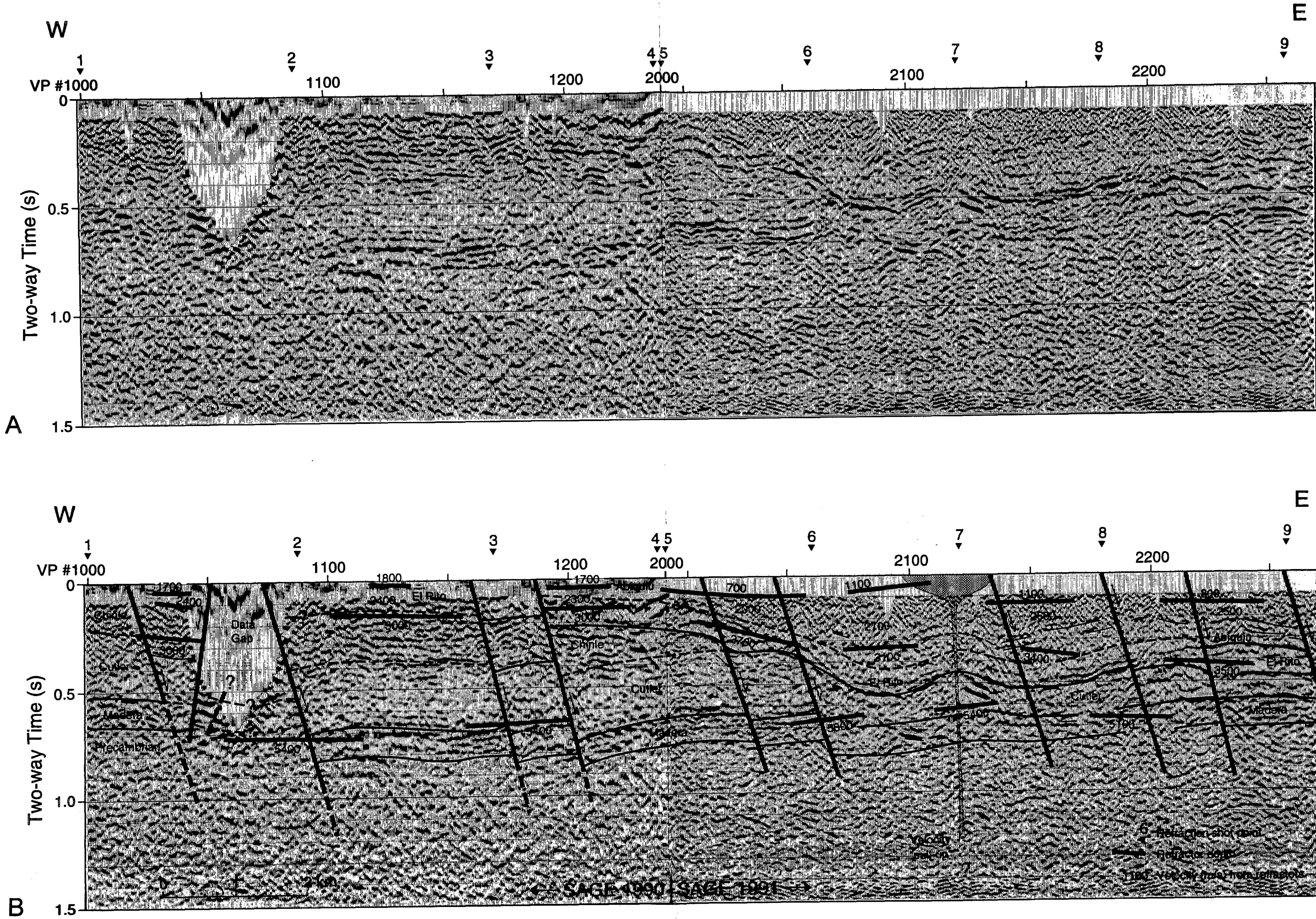

Figure 5. Common mid-point stacked seismic reflection record sections. (A) Uninterpreted section. (B) Interpreted section. Light lines are inferred formation boundaries. Heavy lines are refractor locations; numbers are velocities (m/s) from dipping-layer refraction interpretation.

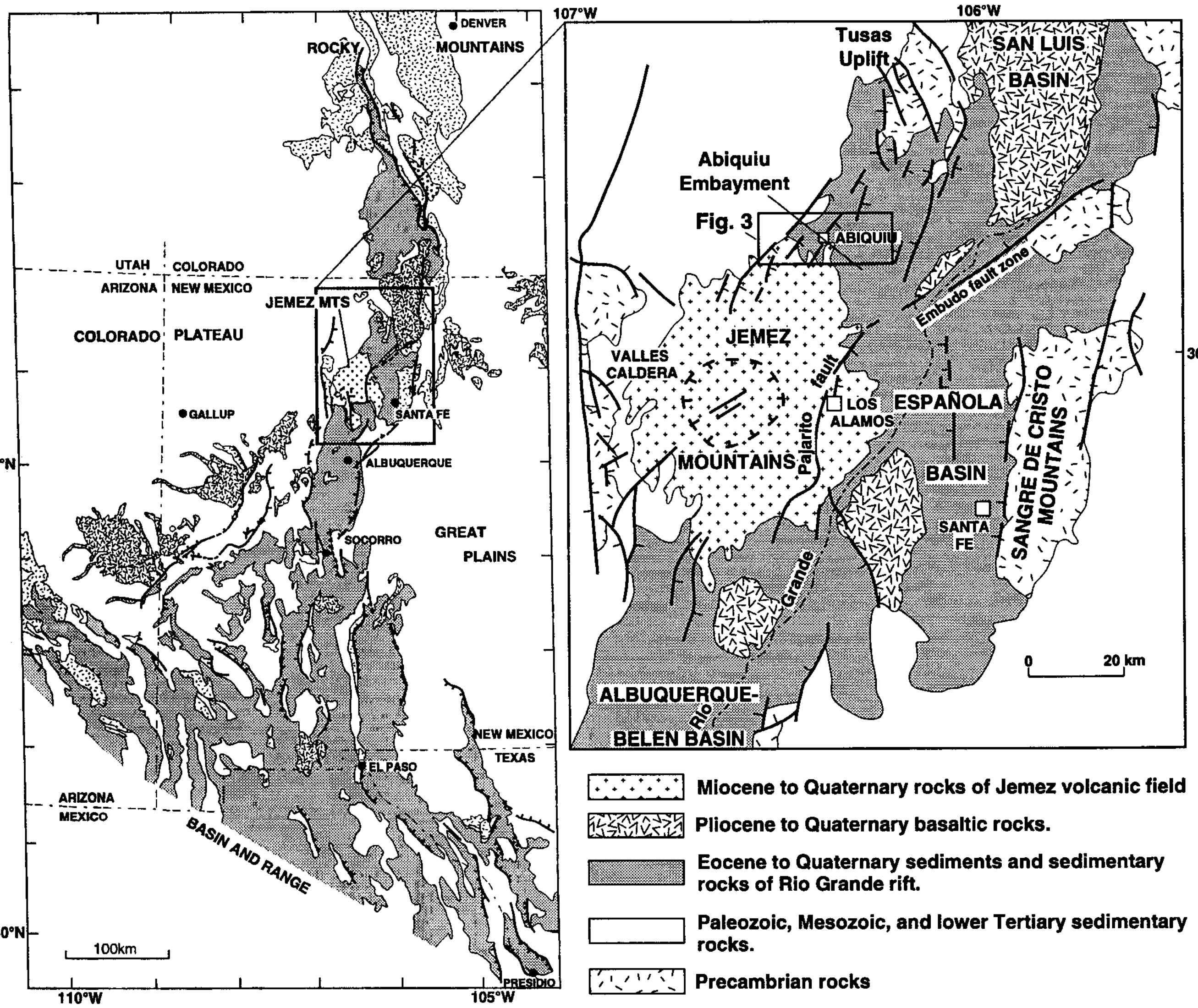

Figure 1. Generalized geologic map of the Española basin (right), showing location within the Rio Grande rift (left). Heavy dashed line on inset shows approximate axis of subsurface basement ridge bounding San Luis basin on south.

compatible with the small amount of extension (3.5%) inferred by us at this boundary.

GEOLOGIC SETTING AND STRATIGRAPHY

The Rio Grande rift extends as a series of interconnected, asymmetrical basins from Leadville, Colorado, to Big Bend, Texas, and Chihuahua, Mexico, a distance of >1000 km (Fig. 1). The northern rift is a distinctive tectonic and physiographic feature separating the Colorado Plateau on the west from the Great Plains, part of the stable North American craton, on the east (Chapin and Seager, 1975; Cordell, 1978; Baldridge and others, 1983, 1984; Olsen and others, 1987). The southern rift is physiographically similar to, and contiguous with, the Basin and Range province in southern New Mexico and northern Mexico.

An early phase of crustal extension occurred during middle Oligocene–early Miocene time. Early extensional basins were generally broader than the present basins, and bounding faults, where recognized, typically dip at low angles (Chapin and Seager, 1975; Seager and others, 1984). Early basins trended northwestward, indicating that rifting occurred in response to northeast-directed extension (Lipman, 1981; Seager and others, 1984; Aldrich and Laughlin, 1984). Evidence for northeast-directed extension during the late Oligocene and early Miocene is also observed in the Basin and Range province of Nevada (Zoback and Thompson, 1978). The preservation of early Tertiary rocks and of early synrift units within rift basins indicates that regional doming did not precede rifting (Chapin, 1979). A later phase of extension occurred during the late Miocene–Holocene giving rise to the modern rift basins (Chapin and Seager, 1975; Baldridge and others, 1980; Seager and others, 1984). The rift boundary at Abiquiu, the subject of this work, became active during the younger phase of rifting.

The Rio Grande rift generally coincides with a north-trending tectonic zone that was intensely deformed during late Paleozoic (ancestral Rocky Mountains) and early Tertiary (Laramide) orogenies (Chapin and Seager, 1975). Although these early periods of deformation clearly influenced rifting, the

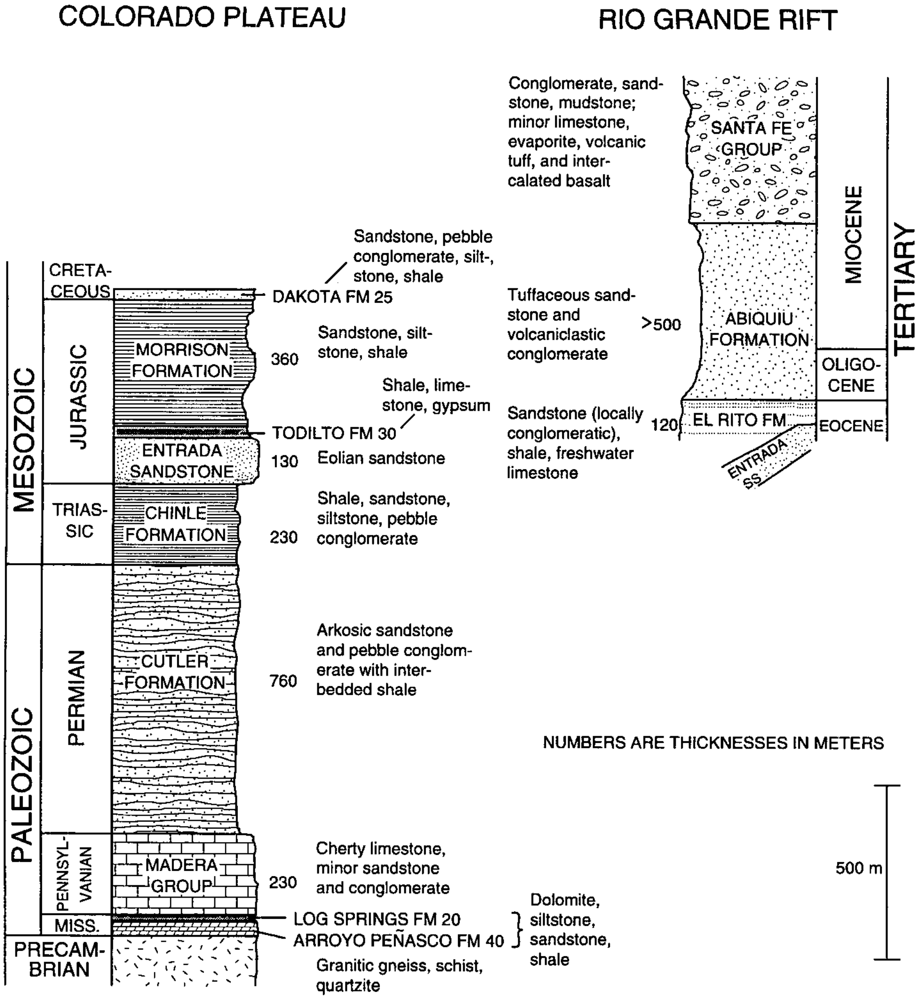

Figure 2. Generalized stratigraphy for rocks of the Colorado Plateau and Rio Grande rift near Abiquiu. Thicknesses are as representative as possible of the Abiquiu area and are probably maxima. Thickness of the Santa Fe Group sediments exceeds 1000 m in the main Española basin (Kelley, 1978; Biehler and others, 1991). Angular unconformity with Entrada Formation (Jurassic) is shown schematically at base of Rio Grande rift section to emphasize lowest stratigraphic unit observed in Abiquiu embayment. References: Armstrong and Mamet (1974), DuChene (1974), Baars (1974), O'Sullivan (1974), Manley (1982), and Ingersoll and others (1990).

effect of earlier structure on individual rift structures is typically ambiguous. In northern New Mexico and southern Colorado, rift basins are partly superimposed upon Laramide uplifts (Baltz, 1978; Kelley, 1978; this work).

The Española basin is transitional between the larger and deeper San Luis and Albuquerque-Belen basins to the north and south, respectively (Kelley, 1978). The northwestern margin of the Española basin near Abiquiu bounds a segment of the basin north of the Jemez volcanic field that is separated from the main Española basin by the northeast-striking Embudo fault zone (Dethier and Manley, 1985; Aldrich, 1986). Because of the semi-isolation of this part of the basin, it is generally referred to as the "Abiquiu embayment" (Kelley, 1979). The Embudo zone transfers extension laterally from the main part of the Española basin to the adjacent San Luis basin. Dungan and others (1984) suggested that the Abiquiu embayment was a western extension of the San Luis basin. However, a northwest-trending, subsurface ridge of Precambrian rocks extends across the rift between Precambrian uplifts on the east and west sides of the rift (Fig. 1), structurally separating the embayment from the San Luis basin (Kelley, 1978; Cordell, 1979; Dungan and others, 1984).

Rocks of the eastern Colorado Plateau and Rio Grande rift in northern New Mexico consist of upper Paleozoic to Cretaceous sandstones, shales, siltstones, and conglomerates (Fig. 2). Tertiary sediments and sedimentary rocks include pre- and synrift units. Continental sandstones and conglomerates of Eocene age (including the El Rito Formation exposed near Abiquiu) were deposited in basins bordering Laramide uplifts and are distributed widely over parts of the Colorado Plateau and Rio Grande rift (Lucas, 1984). The El Rito Formation is dominantly an alluvial fan unit deposited in a shallow, south- to southeast-trending, asymmetrical basin with through-flowing drainage. Composed of quartzite conglomerate and quartzose sandstone facies, the El Rito was derived mainly from the Laramide Brazos–Sangre de Cristo uplift to the north and northeast. Upward-fining deposition suggests that by the end of El Rito time relief in the region was low (Logsdon, 1981). Rocks of Oligocene to middle Miocene age (Abiquiu Formation and Santa Fe Group) were deposited in broad basins, without clear indication of faulted margins (for example, Ingersoll and others, 1990). Outcrops of Abiquiu Formation occur, in part, outside the present rift basins, indicating that early basins were broader. Up to 470 m of Santa Fe Group sediments preserved in the rift basin in and southwest of the Abiquiu area (Manley, 1982) also reflect deposition in a broader basin (including the present eastern margin of the Colorado Plateau) than the present rift basin, but no indication of a faulted margin exists. Late Miocene to Quaternary units (including units of the upper Santa Fe Group; Ingersoll and others, 1990) reflect essentially the present structural geometry of the rift.

DESCRIPTION OF ABIQUIU EMBAYMENT AND RIFT BOUNDARY

The Abiquiu embayment (Fig. 1) is bounded on the west by the Colorado Plateau and on the north by the Tusas uplift (Kelley, 1978). Near these margins, sediments generally dip to the south (at <10°) as well as thicken southward, and they are buried beneath rocks of the Jemez volcanic field south of the study area. Near the main basin, dip directions are more discordant, reflecting basinward transport from other azimuths and local deformation near faults.

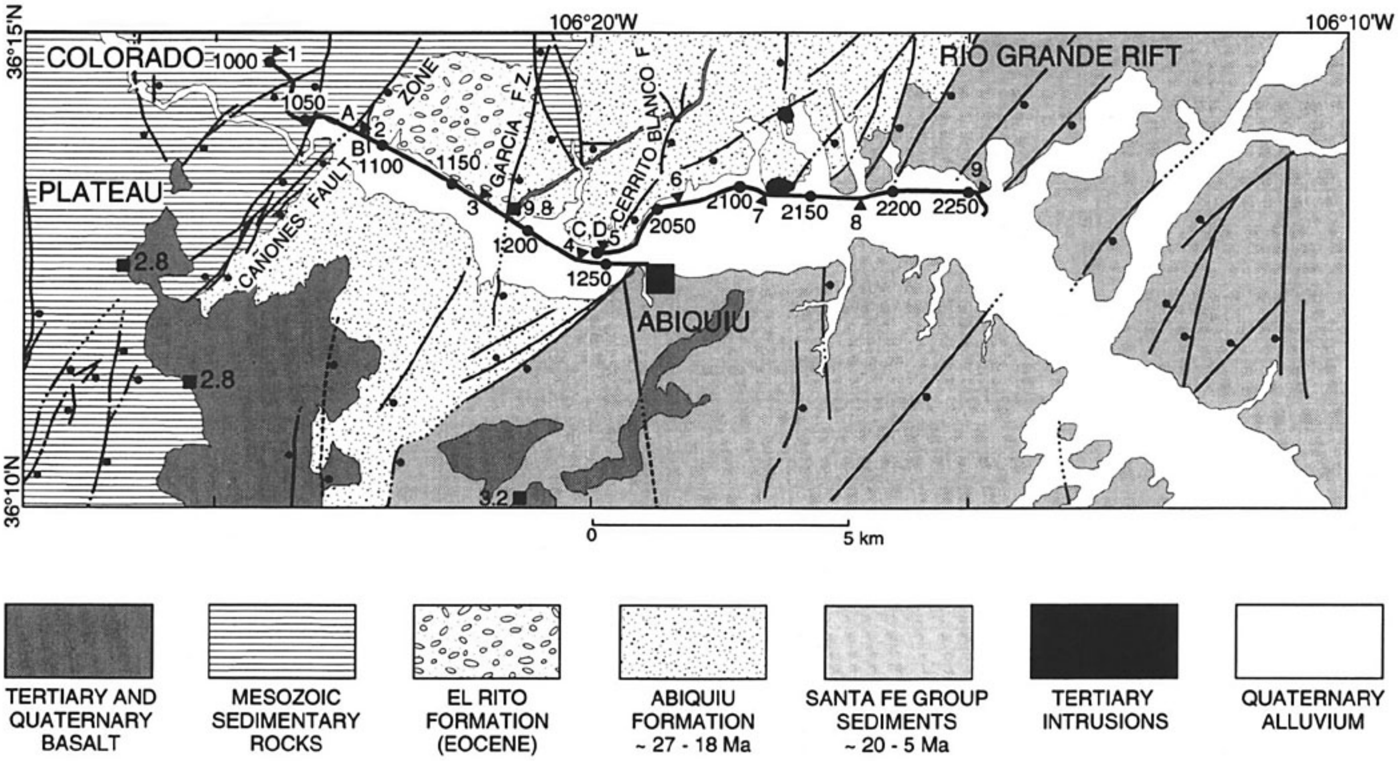

Figure 3. Generalized geologic map of boundary between the Rio Grande rift and Colorado Plateau in the Abiquiu area. Map compiled from Kelley (1978), Manley (1982), and Manley and others (1987). Discrepancies in details among these maps could not, in general, be resolved within the scope of the present work. Locations of SAGE 1990 and 1991 geophysical profiles are shown by heavy lines. Numbers adjacent to the geophysical profiles are Vibroseis point (VP) locations (solid circle at every 50 VPs) and refraction source points (SP, inverted triangles). Small squares are K-Ar dates. Fault names are from Gonzales and Dethier (1991). A–D are locations of photographs shown in Figure 4.

Dip directions in the embayment are also complicated by the presence of large outcrop areas of eolian sandstones (part of the Santa Fe Group). Broad areas of coherent, structurally controlled dip directions (tilt regimes) are not recognized. The embayment is bounded on the east and southeast by volcanic rocks of the San Luis basin, and by the Embudo fault zone. No well data exist for the Española basin; on the adjacent margin of the Colorado Plateau, two wells drilled for hydrocarbon exploration were spudded in Chinle Formation but did not penetrate the Cutler Formation and therefore are not particularly useful for stratigraphic control. Prior to this study, no seismic profiles and only sparse gravity data (Cordell, 1979) were available for subsurface control.

Near Abiquiu the rift boundary is characterized by a 17-km-wide zone of northeast-striking, mainly down-to-the-east oblique-slip faults that offset Paleozoic/Mesozoic rocks of the Colorado Plateau from Eocene and younger sediments and sedimentary rocks of the rift (Fig. 3). The topographic edge of the Plateau is taken as the Cañones fault zone, which juxtaposes Permian and Triassic rocks (Cutler and Chinle Formations, respectively) west of the fault (Fig. 4A) against primarily Eocene and younger rocks to the east. The fault zone consists of several splays, exposing Morrison Formation and Entrada Sandstone within and locally east of the main fault (Manley, 1982). This complexity is not resolvable in our seismic data. East of the Cañones fault zone, Eocene sedimentary rocks angularly truncate Mesozoic rocks (Fig. 4B) in structure inherited from Laramide deformation. Stratigraphic thicknesses indicate a minimum of 120 m of dip-slip offset on this fault in the Abiquiu area (Gonzalez and Dethier, 1991), and up to 670 m at a locality ~18 km southwest (Manley, 1984).

A series of faults east of the Cañones fault zone, including the Garcia and Cerrito Blanco fault zones (Fig. 3), offsets progressively younger units of the rift downward to the east. These faults are prominent, in part, because they juxtapose lithologically distinct units. Along part of its length (Fig. 3), the Garcia fault zone is intruded by a well-exposed basalt dike, which forms a resistant ridge. The Garcia and Cerrito Blanco faults dip 60°–70° to the east (Gonzalez and Dethier, 1991; also, our observations). The plane of the Cerrito Blanco fault, consisting of a gouge zone 1.5–2 m wide, is particularly well exposed (Figs. 4C and 4D). Offset across these and other faults of the boundary zone is dominantly normal slip. Average fault-plane lineations rake 77°–86° and, with the exception of the Garcia fault zone, indicate a slight component of left lateral slip (Gonzalez and Dethier, 1991). The Garcia fault zone has a slight right-slip component of offset. Other faults, which may have comparable or greater offsets, are also present between these prominent faults.

In general, fault offsets seem to increase south of the geophysical line, indicating that the rift basin deepens beneath the Jemez volcanic field (Manley, 1984; Gonzales and Dethier, 1991). Off-line effects complicate the geological interpretation of the seismic and gravity data presented herein.

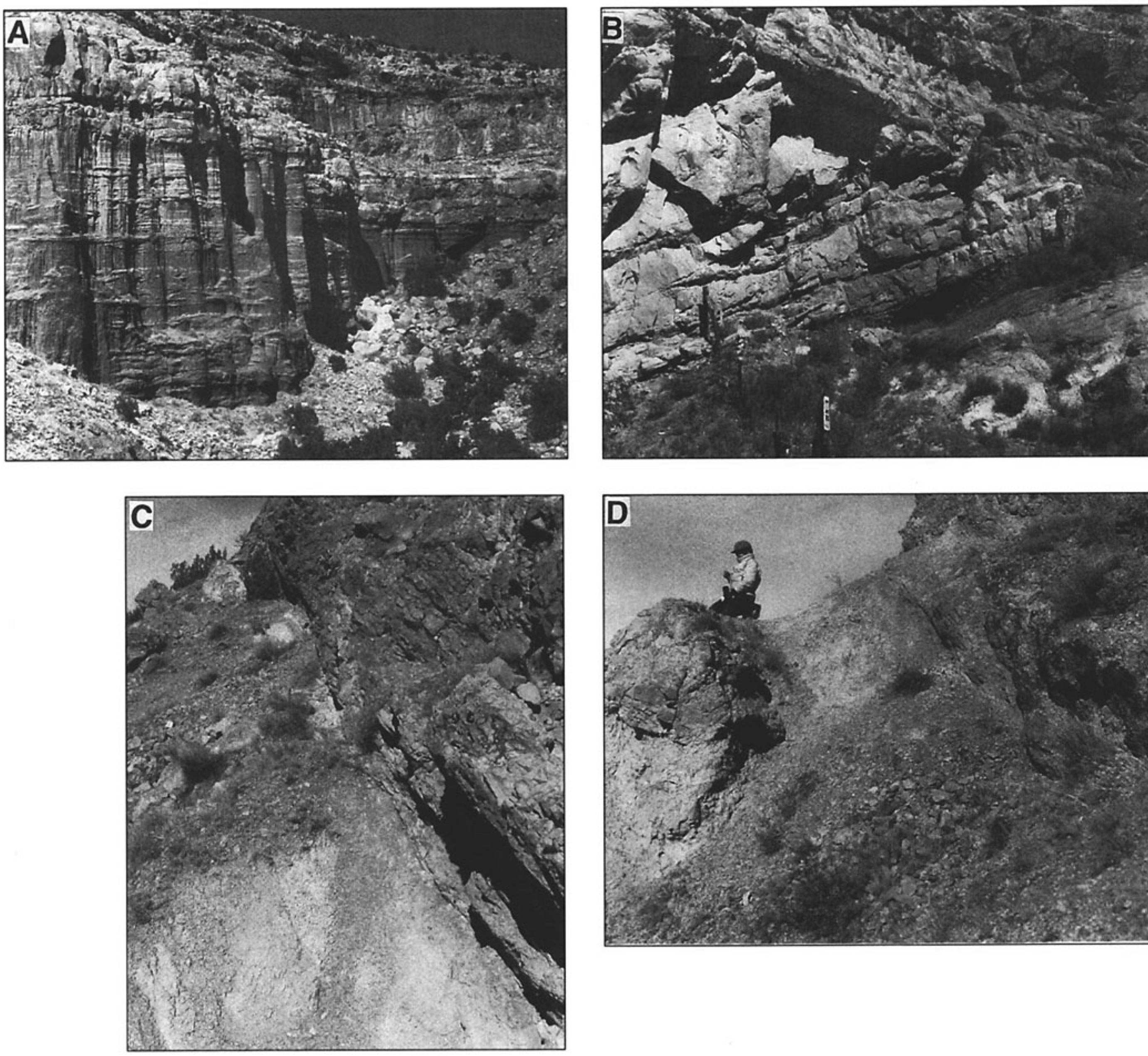

Figure 4. Photographs of rift boundary near Abiquiu (locations shown in Fig. 3). A. Exposure of Cutler and Chinle Formations west of Cañones fault zone. Contact between formations is at base of prominent ledges approximately two-thirds of the distance above base of outcrop. This exposure is the eastern topographic edge of the Colorado Plateau. B. Angular unconformity on eastern side of Cañones fault zone, with El Rito Formation over Entrada Sandstone. Tilting of Mesozoic rocks resulted from Laramide deformation (see text). Note person at right center, for scale. C. The Cerrito Blanco fault offsets rocks of the Santa Fe Group (right) downward against the Oligocene–early Miocene Abiquiu Formation (left). Fault surface dips ~60°E. Rocks of the Santa Fe Group on the downthrown block are more resistant to erosion because of extensive mineralization and cementation (SiO_2, Mn, Fe) of the hanging wall by fluids moving along the fault zone. Slickensides and fracture data suggest that a minor component of left slip has also occurred along this fault. D. The Cerrito Blanco fault is characterized by a gouge zone 1.5–2 m wide. View is toward north.

GEOPHYSICAL DATA

Seismic

Reflection and refraction seismic data were acquired along a 16-km-long line (Fig. 3) by participants of the Summer of Applied Geophysical Experience (SAGE) program of the Institute of Geophysics and Planetary Physics (IGPP) at Los Alamos National Laboratory (Jiracek and others, 1991; Baldridge and Jiracek, 1992) and the Arco Oil and Gas Company's seismic crew using Vibroseis[1] techniques. The western

[1]Vibroseis is a registered trademark of the Continental Oil Company.

TABLE 1. SEISMIC RECORDING PARAMETERS

1990 data	
Source:	3 Vibroseis trucks
Sweeps	10 s, sum of 10 sweeps, 15 s records, 8–58 Hz nonlinear sweep (3 db/oct)
Recording:	
Recorder	Gus 1000 system
Channels	200, split spread, gap = 4
Group interval	33.5 m (110 ft)
Source interval	33.5 m (110 ft), between groups
Geophone array	12 geophones (10 Hz) over 67 m
Refraction records:	
Source locations	SP 1 at VP 1000.5, SP 2 at VP 1087.5, SP 3 at 1168.5, SP 4 at 1240.5
Channels	272 at 33.5 m (110 ft) interval
Sweeps	20 s, sum of 10 sweeps, 35 s record, 6–32 Hz linear sweep
1991 data	
Source:	2 Vibroseis trucks
Sweeps	12 s, sum of 12 sweeps, 15 s record, 6–96 Hz nonlinear sweep (0.2 db/Hz)
Recording:	
Recorder	Gus 1000 system
Channels	108, split spread, gap = 4
Group interval	33.5 m (110 ft)
Source interval	33.5 m (110 ft), between groups
Geophone array	12 geophones (10 Hz) over 67 m
Refraction records:	
Source locations	SP 5 at VP 2000.5, SP 6 at VP 2060.5, SP 7 at 2120.5, SP 8 at 2180.5, SP 9 at 2255.5
Channels	268 at 33.5 m (110 ft) interval
Sweeps	12 s, sum of 12 sweeps, 18 s record, 6–56 Hz linear sweep

TABLE 2. SEISMIC REFLECTION PROCESSING SEQUENCE

1. Cross-correlation with pilot sweep
2. 3-trace mix (1991 data only)
3. CMP sort
4. 60 Hz notch filter (1991 data only)
5. Spiking deconvolution
6. Bandpass filter 15-20-70-80 Hz
7. AGC
8. Semblance velocity analysis
9. NMO correction, 25% stretch mute
10. CMP stack, offsets = 61 m to 1220 m
11. 5-trace mix
12. Bandpass filter 5-10-50-60 Hz
13. Display, 500 ms AGC

AGC = Automatic gain control.
CMP = Common mid-point.
NMO = Normal moveout.

and eastern halves of the line were acquired during the 1990 and 1991 field seasons, respectively, and the two data sets were merged into a single profile and processed by SAGE participants (Fig. 5[2]). Examples of the raw and processed reflection data are displayed in the shot-gather shown in Figures 6A and 6B. Recording parameters are presented in Table 1, and the seismic reflection processing sequence in Table 2. Data were not migrated, in part because only low dips were observed in this section. The locations of reflectors with low dips would not significantly change. Also, diffracted energy at faults was not a problem. A disadvantage of migration processing is that it may create additional noise.

Seismic reflection and refraction data were interpreted using a simultaneous traveltime inversion procedure to derive a velocity model that optimally fits the observed data. The model includes lateral and vertical velocity variations and the configuration of reflecting interfaces, which incorporate fault offsets. The simultaneous inversion technique (Wang, 1993) uses ray-trace calculations to derive traveltimes for a starting model, which is iteratively adjusted until a satisfactory fit between observed and theoretical traveltimes for both reflected (vertical incidence common mid-point [CMP] data) and refracted (wide-angle) arrivals is achieved. The traveltime fit for the final model is displayed in Figure 7A. Raypath coverage for the final model is illustrated in Figure 7B by representative raypaths for reflected and refracted phases. Figure 7C shows the interpreted seismic velocity model, including inferred stratigraphic units and faults that were delineated by the seismic data and the derived compressional wave velocities.

Near the western end of the line, two major "groups" of reflectors were imaged at 0.2–0.3 s and 0.7–0.8 s (Fig. 5A). Each group of reflectors appears to compose a separate stratigraphic interval. The upper group of reflectors becomes deeper toward the eastern end of the line, whereas the lower group becomes slightly shallower to the east. Hence the vertical distance between these two groups of reflectors decreases toward the eastern end of the line, where they closely approach each other.

Refraction data (Fig. 6C) provide good constraints on P-wave interval velocities (Fig. 7). In addition, a good correlation exists between refracting and reflecting boundaries (Fig. 5B). Despite having velocities from the refraction data, seismic time sections were not depth-converted because of the possibility of distortion. Instead, we converted depth-related data to time and plotted them on the seismic section (Fig. 5B).

Gravity

Gravity data (Fig. 8A) were obtained along the same profile as the seismic survey, using locations surveyed for the seismic source (Vibroseis points [VP]) (Fig. 3). Details of data collection and reduction procedures are given in Biehler and others (1991). The regional anomaly across this profile is gently concave upward, with about 6 mgal of variation. The anomaly is due to deeper and three-dimensional sources that are not related to the shallow structure imaged in this work; hence it is not interpreted here.

INTERPRETATION AND RESULTS

Nature of Rift Boundary

A prominent group of reflectors at 0.7–0.8 s near the western end of the profile is laterally continuous across the entire profile, becoming shallower (to ~0.6 s) near the eastern end. We infer that these reflectors correspond to the Pennsylvanian section, principally Madera Group, based on the lithologic character and thicknesses of units exposed on the Plateau and on the relatively high velocity (about 5.2 km/s) derived from the refraction modeling for this layer. The Madera Group consists mainly of cherty limestone, sandstone, and conglomerate (DuChene, 1974); in contrast, the overlying Cutler Formation is mainly sandstone and conglomerate with interbedded shale (Baars, 1974; Manley, 1982). Thus it is likely that the Madera Group has a substantially higher velocity than the Cutler Formation, yielding a large acoustic impedance contrast at the boundary between them. The estimated thicknesses of these units (Fig. 2) suggest that the Madera Group occurs ~800 m below the surface at the western end of the profile. This depth is in reasonable agreement with the observed time to the reflectors, assuming a velocity for the Cutler and Chinle Formations of 2.4–3.0 km/s (Fig. 5C). The upper surface of the Precambrian is not a distinct, separate reflector, because its acoustic impedance is not much different from that of the Madera Group. In general, the Precambrian basement does not seem to have coherent reflectors within it.

A second group of reflectors, which extends from the surface to ~0.4 s near the western end of the line, may correspond to the El Rito Formation and to the underlying Mesozoic section (especially, Chinle Formation and Entrada Sandstone). Exposures of Entrada east of the Cañones fault zone indicate that Chinle is present in the shallow subsurface. The uppermost reflectors are assumed to correspond to the El Rito Formation, which is expected to have a velocity contrast with the overlying Abiquiu Formation. Because the El Rito Formation is not very thick (~120 m, Fig. 2), much of the

[2]Loose insert: Figure 5 is on a separate sheet accompanying this issue.

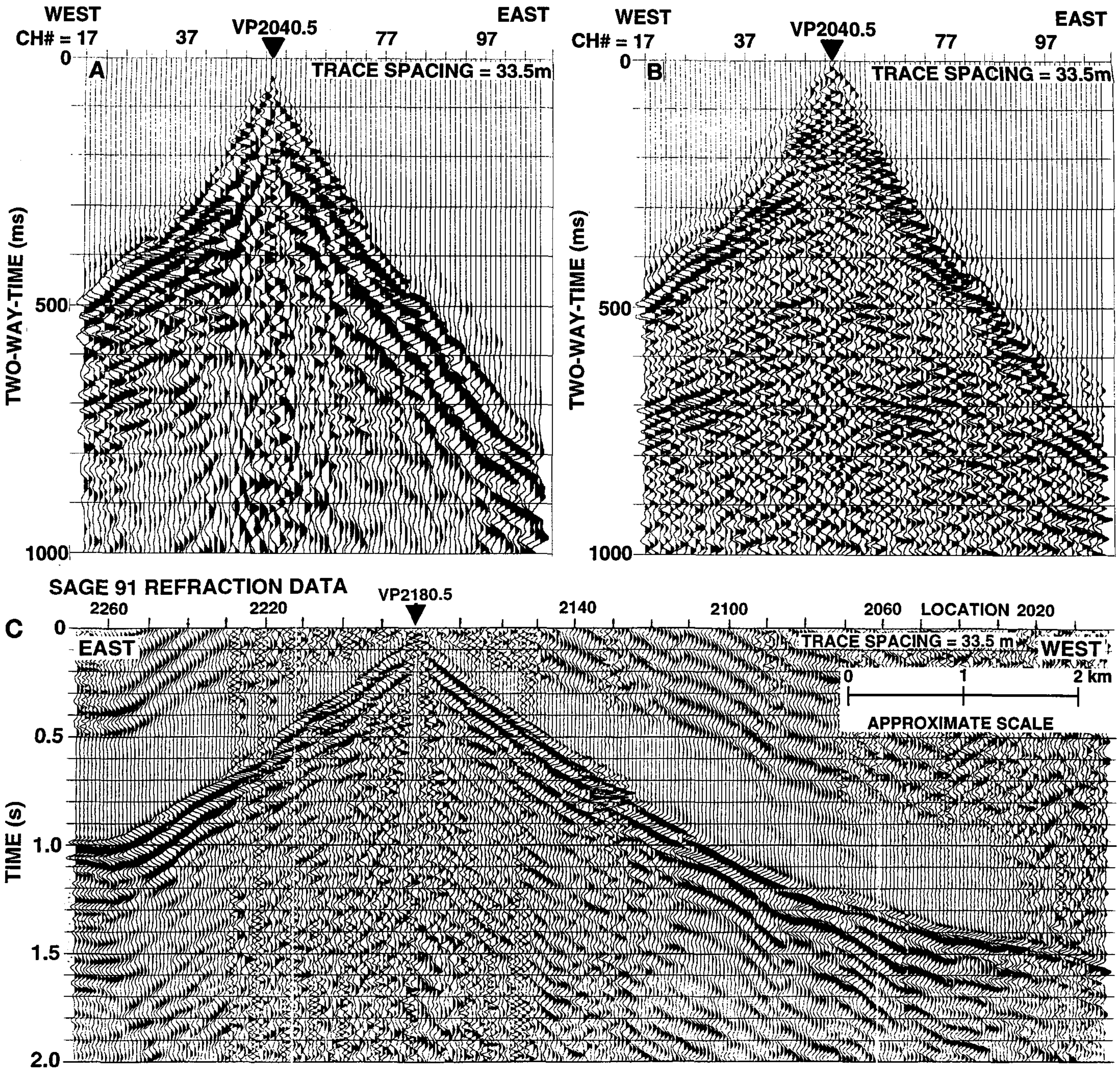

Figure 6. Examples of seismic data from SAGE 1991. VP locations (Fig. 3) are shown at the top of the record sections. A. Unprocessed reflection shot gather from VP 2040.5. B. Processed (spiking deconvolution and band pass filter) reflection shot gather from VP 2040.5. Prominent reflection at 650–750 ms two-way traveltime corresponds to Madera Formation. C. Refraction (long offset) record section from SP 8 (VP 2180.5, Fig. 3).

series of cyclic reflections must correspond to the underlying Chinle Formation. In the seismic interpretation (Fig. 5B), we have somewhat arbitrarily designated the base of the reflectors as the contact between the Chinle Formation and the underlying Cutler Formation. This seismic definition of the boundary may not correspond exactly to the lithologic definition. However, the aggregate thickness of the stratigraphic interval between the upper and lower packages of reflectors, assuming a velocity of ~3000 m/s, is ~900 m, which is in very close agreement with the combined thickness of Chinle and Cutler (990 m) estimated from surface exposures (Fig. 2).

Near the middle of the profile, corresponding approximately to the Cerrito Blanco fault, this group of reflectors thins and deepens eastward and closely approaches the lower group of reflectors. The

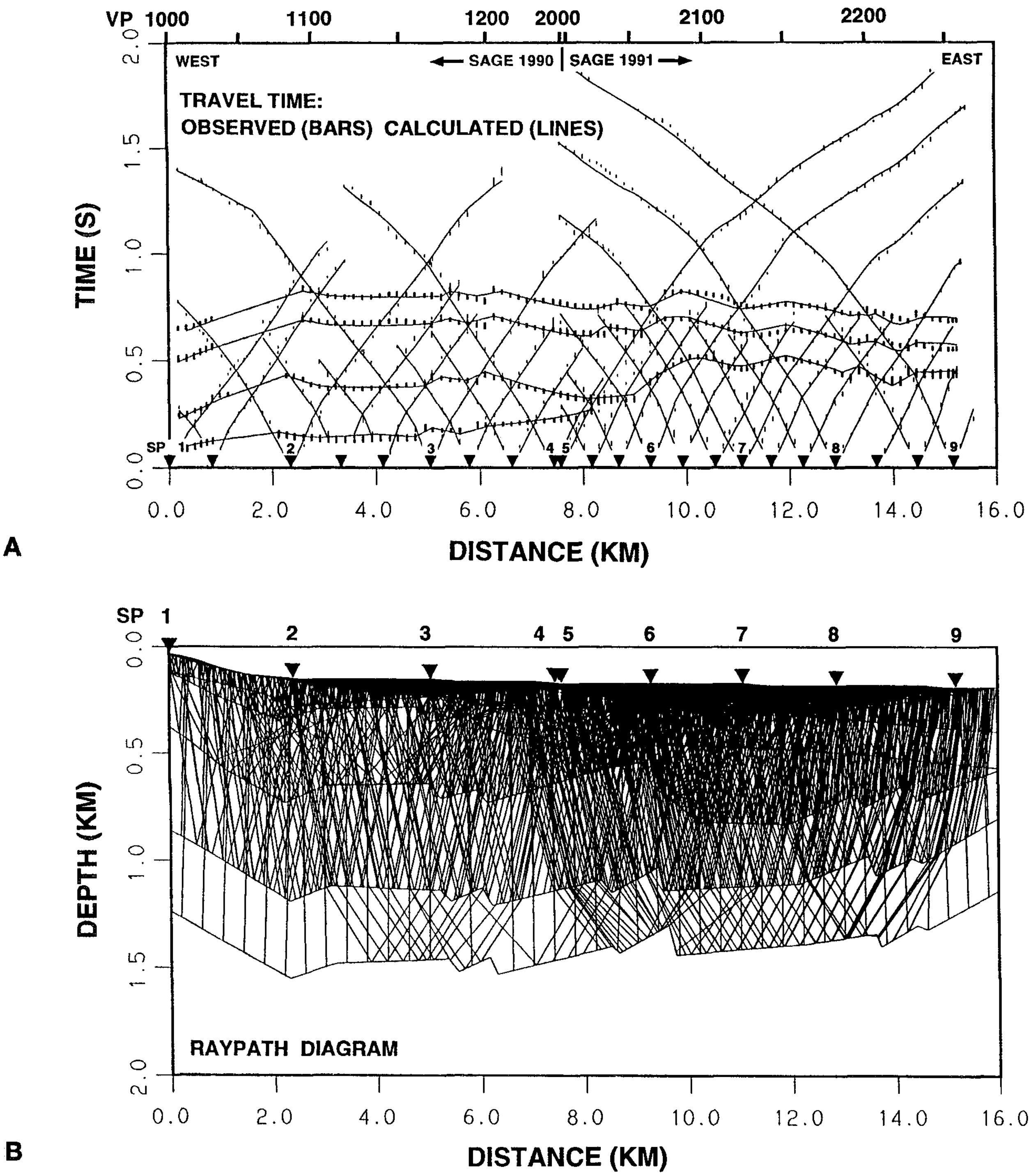

Figure 7. Simultaneous inversion of SAGE 1990–1991 reflection and first arrival refraction data. A. Observed (vertical bars equal two standard deviations of estimated picking error) and calculated (lines) traveltimes. Triangles are shot locations. B. Raypath diagram, showing representative reflection and refraction raypaths and interface configuration. Depth is relative to 2 km elevation datum.

eastward thinning of this group of reflectors and of the section between the upper and lower groups of reflectors strongly suggests that the uppermost Paleozoic (Cutler Formation) and Mesozoic (Chinle Formation) section thins dramatically toward the eastern end of the profile. We infer that thinning was accomplished by erosion prior to, or in, early Eocene time. This interpretation implies that the Eocene El Rito Formation was deposited over an older, deformed terrain that was beveled by erosion and is supported by the angular contact between the Entrada Sandstone and overlying El Rito Formation observed east of the Cañones fault zone (Fig. 4B). An erosional unconformity with eastward thinning of underlying units would explain the apparent absence of units strat-

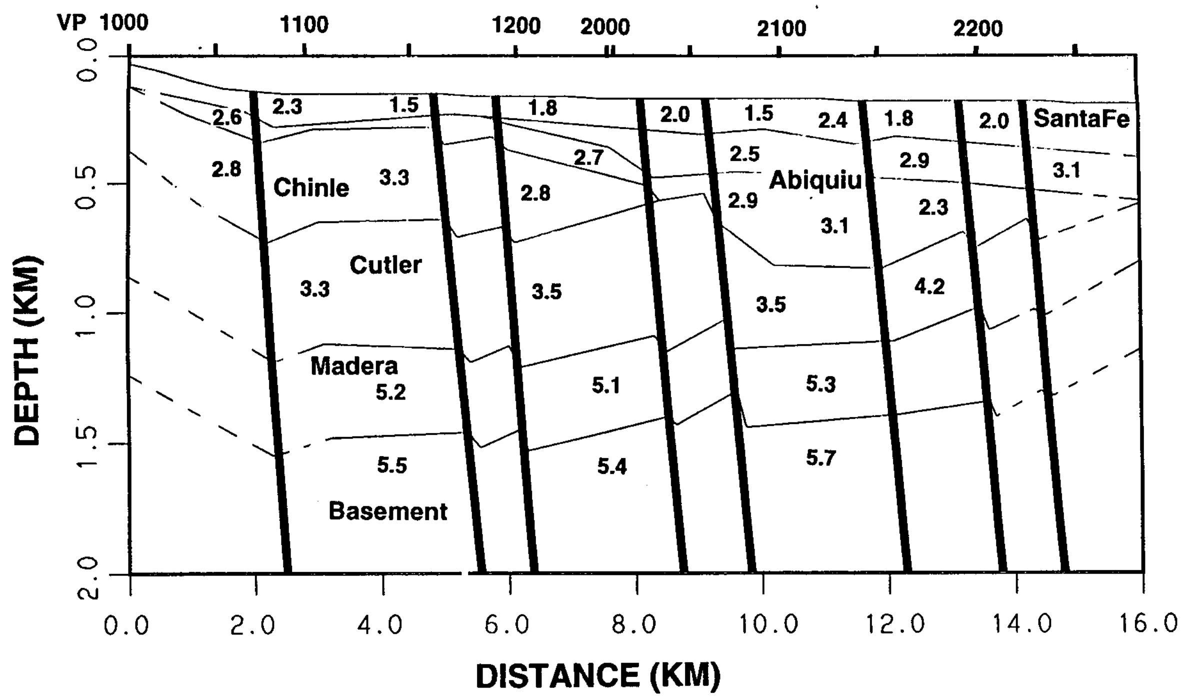

Figure 7. (*Continued*). C. Derived velocity model and geological interpretation. Dashed interfaces are poorly constrained due to limited raypath coverage. Depth is relative to 2 km elevation datum. Numbers are velocities in kilometers per second. Vertical exaggeration is approximately 4:1.

igraphically higher than Entrada along our profile, despite the presence of Todilto, Morrison, and Dakota 3 km to the southwest.

Modeling of the gravity data was performed in a forward sense only, with iterative, trial-and-error adjustment of boundaries as required to fit the data (Fig. 8B). Gravity calculations were performed using polygonal prisms of infinite strike length, with density either constant or a linear function of depth (Murthy and Rao, 1974). Densities (in kg/m^3) were estimated from seismic P-wave interval velocities (which could be associated with particular stratigraphic units; Fig. 7) from the relationship $\rho(v) = 310 \times v^{0.25}$ (Gardner and others, 1974), where v is in meters per second. This relationship works well for clastic sediments in the Española basin area (Biehler and others, 1991). Values for physical properties and assumed stratigraphic thicknesses used in the gravity modeling are presented in Table 3. The model was adjusted to fit the observations to within about 0.5 mgal (1.4 mgal maximum error).

The model was constrained by thicknesses of formations and locations of major faults (Figs. 2 and 3). The inferred configuration of units in Eocene time was the starting point for the gravity model. The El Rito Formation was assumed to be horizontal and constant in thickness. Based on seismic observations (Figs. 5 and 7), the Cutler Formation was assumed to thin by 40% near the eastern half of the profile, and the Chinle to pinch out near the middle of the profile. Offsets on faults were then adjusted to provide a best fit to the observed gravity. For purposes of modeling, faults were assumed to dip 60° eastward, in accordance with limited surface observations (see above).

Good qualitative agreement is achieved with the short wavelength, low amplitude anomalies associated with the normal faults. West of the Garcia fault (and especially west of the Cañones fault) gravity coverage is inadequate to resolve uncertainties in the model, which, based on surface geology (Fig. 3), are most likely due to three-dimensional effects. Some disagreement between seismic and gravity models is apparent at the western end of the profile (Figs. 7 and 8), where limited ray coverage significantly reduces resolution of the velocity model (due to trade-off between velocities and depth to interfaces). We prefer the interpretation implied by the gravity data for this section.

The eastern end of the profile requires substantial normal faulting, with a total vertical separation of ~0.3 km over the three eastern faults. However, because these faults are near the end of our seismic profile, they are not well observed in the seismic records. Constraints imposed by the gravity data imply a westward dip of ~3° on the Mesozoic contacts during the Eocene. A small, shallow body of high-density material (2350 kg/m^3) is required near the eastern end of the profile. We infer that this body corresponds to the basaltic tuff ring exposed at the surface (Fig. 3). This same feature results in a high velocity zone and traveltime anomaly (velocity "pull-up") in the seismic reflection section (near VP 2120, Fig. 5). In the middle part of the section, seismic and gravity models are in good agreement, de-

TABLE 3. PHYSICAL PROPERTIES AND STRATIGRAPHIC THICKNESSES USED IN GRAVITY MODEL

Unit	Velocity (m/s)	Density* (kg/m^3)	Thickness† (m)
Precambrian	5800	2700	N.D.§
Madera Group	5400	2650	280
Cutler Formation	3500	2380	600
Chinle Formation	3000	2290	300
El Rito Formation	2500	2190–2320	150
Abiquiu Formation	2000	2070–2235	<400
Santa Fe Group	1200	1820	<200

*Determined from seismic interpretation.
†From gravity interpretation.
§No data.

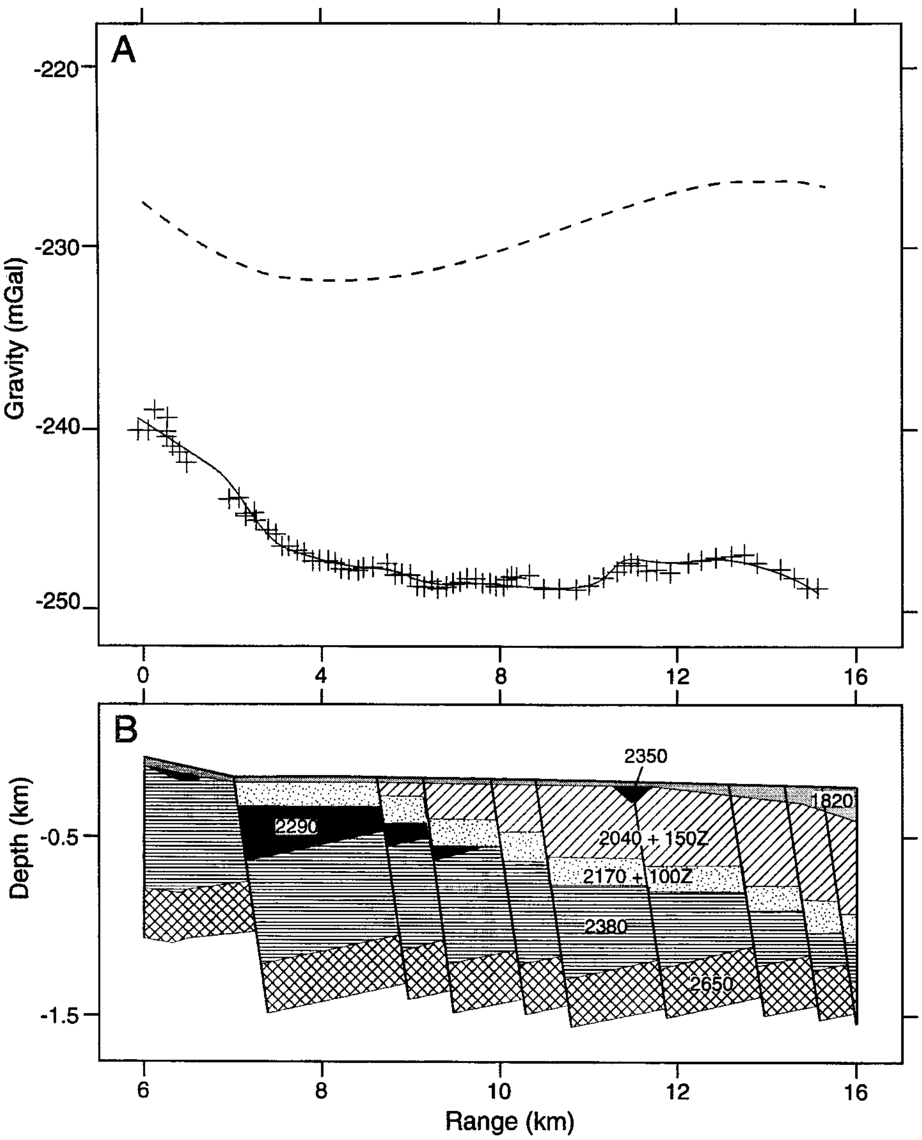

Figure 8. A. Observed, regional, and calculated gravity along Abiquiu profile (Fig. 3). The regional gravity (dashed line) is represented by a polynomial of degree 3, fitted to the difference between the observed Bouguer anomaly (+ symbols) and gravity calculated from the density cross section in B. The sum of the calculated and regional anomalies is the solid line in A. B. Gravity model based on geologic and seismic constraints (see text). Density is in kilograms per cubic meter. Depth is relative to 2 km elevation datum; Z is in kilometers. Vertical exaggeration is approximately 4:1.

spite the fact that the final interpretations were independently derived.

The resulting gravity model (Fig. 8C) is a two-dimensional representation of structure in an area with some significant three-dimensional structure. Lack of off-line gravity coverage defined by seismic data and the presence of adjacent geologic complexity (for example, the Jemez volcanic field to the south) prevent construction of a full three-dimensional model. Despite these limitations, the two-dimensional model is a reasonable fit to both the geologic and seismic data and appears to yield a satisfactory representation of the overall structure.

Our integrated geologic model is shown in Figure 9A. Both seismic and gravity data suggest that the Cañones fault zone, separating exposures of Paleozoic/Mesozoic sedimentary rocks of the Plateau from Tertiary rocks of the rift, has <500 m of vertical separation where it is crossed by our profile. Vertical offsets across all other faults appear to be <100–200 m. Thus the Paleozoic/Mesozoic section is present at shallow depths, overlain by only a thin Tertiary section. Finally, the apparent rotation of Paleozoic and Mesozoic formations, which is not mirrored by the Eocene El Rito Formation, is the result of pre-Eocene westward dip on the western flank of an inferred Laramide uplift, rather than of rotation about a horizontal axis parallel to fault planes. Thus, our study provides no evidence that basin-bounding faults are listric at depth. Yet, because the amount of extension is small (3.5%, see below) and hence any expected rollover of strata is minor, faults could still be listric and not detected in this study.

Implications for Laramide Structure

The western margin of the Laramide (early Tertiary) Sangre de Cristo/Brazos geanticline was known from previous studies to underlie the Española basin (for example, Baltz, 1978). This interpretation was based, in part, on two related observations. First, the Eocene section angularly overlies Mesozoic and older units in outcrop. For example, the angular unconformity between Entrada Sandstone and El Rito Formation near Abiquiu (Fig. 4B) indicates that significant post-Jurassic deformation was present prior to deposition of the El Rito Formation. Moreover, the high dip of the Entrada in outcrop suggests that small-scale structures exist at depth in the pre-Eocene units that could not be resolved by our geophysical surveys. Rotating the El Rito back to a presumed originally horizontal position results in a strike of N36°E and dip of 36°NW, indicating that the axis of deformation is oblique to the geophysical line.

Second, successively younger Mesozoic units pinch out to the north along the northwestern margin of the Española basin (Fig. 10). The El Rito Formation, which was deposited in a sedimentary basin between the Sangre de Cristo/Brazos uplift and the Nacimiento uplift to the west, is a prominent post-Laramide, prerift datum. Southwest of Abiquiu (Fig. 10), the El Rito Formation overlies Cretaceous rocks. Directly west of Abiquiu, along the seismic profile, El Rito Formation overlies rocks of Jurassic age (Fig. 4B). A few kilometers to the north, El Rito overlies Triassic rocks. North of Abiquiu, El Rito directly overlies crystalline rocks of Precambrian age, with no intervening Paleozoic or Mesozoic section (Manley, 1984; Manley and others, 1987). Thus the El Rito Formation overlies an erosional surface that cuts down-section

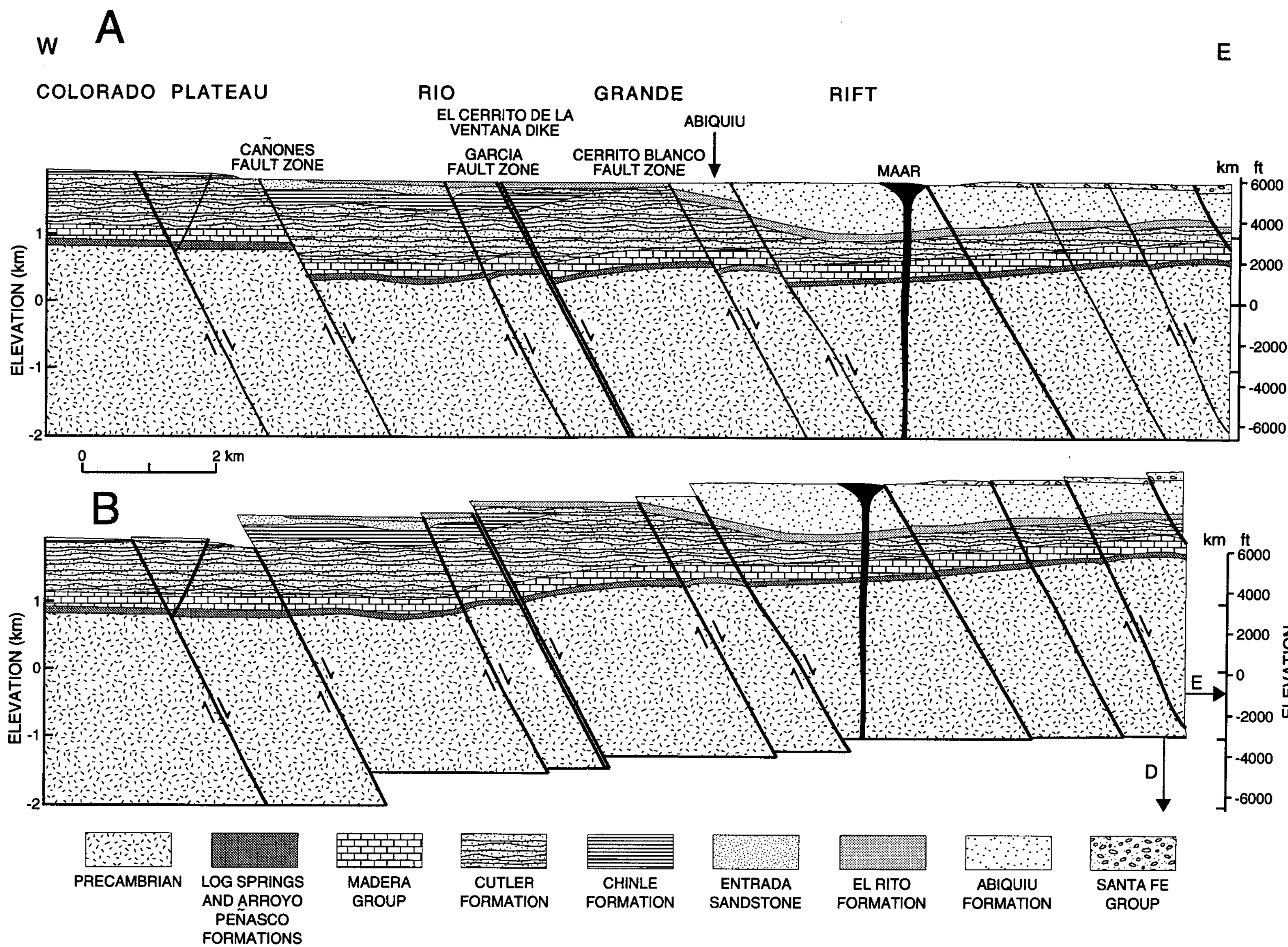

Figure 9. A. Interpretive geologic cross section of western margin of Rio Grande rift at Abiquiu. B. Restored cross section, derived by reversing offsets on faults to restore Madera Group to smooth surface. This restoration assumes that all offset is dip slip, which is only approximately true. Misfit of El Rito Formation is a measure of error resulting from above assumption and other offline effects (see text). Cross section approximately corresponds to Eocene time. E represents the amount of horizontal extension (~1.1 km) and D represents the vertical displacement (~0.6 km) that have occurred over the length of the section due to (post-Eocene) rifting.

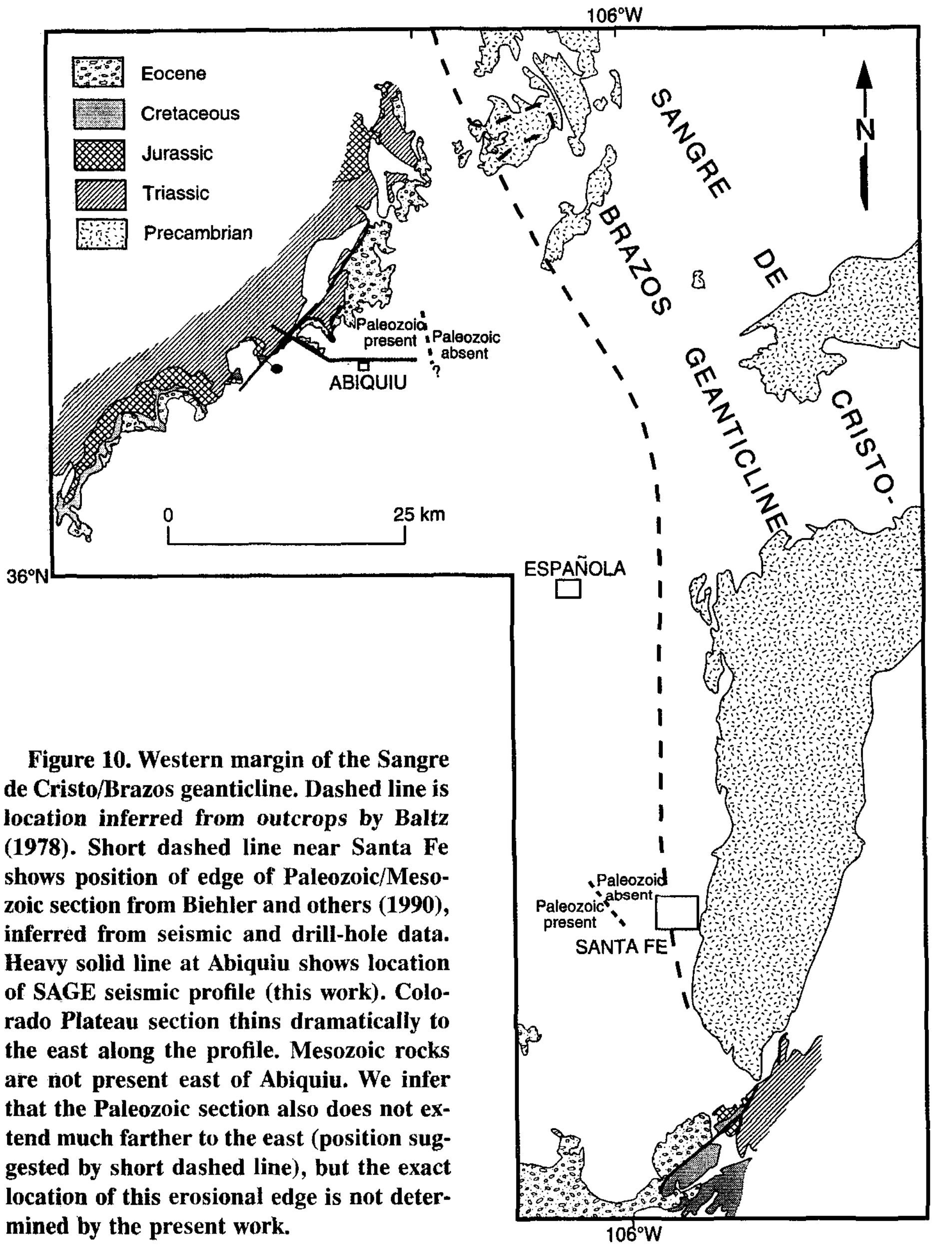

Figure 10. Western margin of the Sangre de Cristo/Brazos geanticline. Dashed line is location inferred from outcrops by Baltz (1978). Short dashed line near Santa Fe shows position of edge of Paleozoic/Mesozoic section from Biehler and others (1990), inferred from seismic and drill-hole data. Heavy solid line at Abiquiu shows location of SAGE seismic profile (this work). Colorado Plateau section thins dramatically to the east along the profile. Mesozoic rocks are not present east of Abiquiu. We infer that the Paleozoic section also does not extend much farther to the east (position suggested by short dashed line), but the exact location of this erosional edge is not determined by the present work.

to the northeast. The exact location of the western boundary of the Sangre de Cristo/Brazos uplift lies beneath the Española basin and cannot be determined from surface exposures.

These relationships are compatible with an inferred erosional thinning of the section beneath the Eocene along the Abiquiu seismic line, which we interpret to represent an erosional unconformity cutting out Paleozoic/Mesozoic rocks on the western flank of the Laramide uplift. In previous SAGE work, we also observed pinching out of the Mesozoic section against the Precambrian in the subsurface west of Santa Fe in the southern Española basin (Fig. 10). This relationship was also interpreted as an erosional unconformity on the flanks of the Sangre de Cristo/Brazos geanticline (Biehler and others, 1991). The western margin of the uplift lies near the center of the Española basin, westward of the position inferred by Baltz (1978). Thus the thinning to the east of Paleozoic/Mesozoic strata observed in the profiles at Santa Fe and at Abiquiu provides tighter controls on the edge of the Laramide Sangre de Cristo/Brazos uplift. Reconstruction of the pre-Eocene configuration of this boundary, made by restoring vertical offset on faults, suggests that, prior to rifting, ~1 km of relief existed on the upper surface of the Precambrian over the length of our profile (Fig. 9B).

DISCUSSION AND CONCLUSIONS

The rift boundary at Abiquiu consists of a zone of faults distributed over a distance of at least 17 km. Vertical offsets on individual faults, including the bounding Cañones fault zone, do not exceed 500 m, and the total vertical offset across the 17-km-wide zone is ~1.1 km (Fig. 9). Thus the Abiquiu embayment is a shallow platform rather than a well-defined deep rift basin, at least at the latitude of our seismic profile. The fact that pre- and early-rift sedimentary rocks were never deeply buried beneath younger rift fill explains the good exposures of lower and middle Tertiary sedimentary rocks. The small amount of offset on faults and the lack of rotation of fault blocks indicate that overall extension of this zone is minor (~0.6 km, or 3.5%, determined from Fig. 9).

Two related questions arise from our work: First, how and when did this boundary develop, and second, why is extension and offset relatively minor here, when offset is so much greater in parts of the Española basin farther south (Biehler and others, 1991)? We suggest that the rift boundary at Abiquiu is an *incipient boundary that ceased to develop.*

Age of Rift Boundary at Abiquiu

Constraints on the timing of the development of the rift boundary at Abiquiu are as follows:

(1) Basaltic dikes are oriented parallel to, and in places intrude, faults of the boundary zone. The Cerrito de la Ventana dike, the southernmost part of which intrudes the Garcia fault zone, is dated at 9.8 ± 0.4 Ma (Bachman and Mehnert, 1978). Also, Window Rock dike, part of the Rio del Oso dike swarm (Galusha and Blick, 1971) 12 km to the southeast, is 9.7 ± 0.3 Ma (Baldridge and others, 1980). No slickensides are reported in these dikes, nor other indicators of synkinematic intrusion; thus faulting could significantly precede intrusion. Nevertheless, because of the close spatial association of dikes (and of temporally and compositionally related early Jemez basalt flows) with faults over a >25-km-wide zone of the Abiquiu embay-

ment, we prefer the interpretation that intrusion of the dikes was approximately contemporaneous with, or closely followed, extension throughout the embayment.

This conclusion is at variance with that of Gonzalez and Dethier (1991), who inferred the presence of a single geomorphic surface (T4) preserved beneath western and eastern flows of El Alto basalt (3.2–2.8 Ma, Fig. 2). Their inference was based on the presence of gravels, interpreted as axial stream gravels from the ancestral Rio Chama, on the T4 surface. They thus concluded that the T4 surface was offset by the Garcia and Cerrito Blanco fault zones. However, identification of these gravels is based on only poor exposures. We think it is more likely that the age of the Garcia fault, at least, is best indicated by the age of the intruded dike and that flows of El Alto basalt were erupted at different elevations on a terrane already faulted.

(2) A late Miocene geomorphic surface, capped by flows of the Lobato Formation (Cerro Pedernal, 7.8 Ma; Mesa Escoba, 7.9 Ma; Polvadera Mesa, 7.8 Ma) in the northern Jemez volcanic field, is offset across splays of the Cañones fault zone (Manley, 1982; Gonzalez and Dethier, 1991). Younger flows (El Alto Formation, ca. 2.8 Ma) cover faults of this same zone without structural offset (Manley, 1982). Thus major development of the boundary of the Colorado Plateau occurred at 7.8–2.8 Ma.

(3) A fault scarp offsetting flows of Lobato basalt (10.1 ± 0.3 to 9.6 ± 0.3 Ma) in the northern Jemez volcanic field appears to be covered by a flow dated at 9.9 ± 0.5 Ma (W. S. Baldridge and D. T. Vaniman, unpub. data). Therefore, faulting was essentially contemporaneous with volcanism at ca. 10 Ma.

Thus although unambiguous temporal constraints (for example, dated basalt flows) on observable fault offsets yield only broad constraints (ca. 10.1 to >2.8 Ma), it seems likely that the dikes and major basaltic magmatism in the northern Jemez volcanic field were coeval with the main extensional phase affecting the rift boundary. This association of volcanism and faulting is supported by the fact that the Garcia fault zone is intruded by a dike. The youngest Lobato volcanism is ca. 7.8 Ma (Manley, 1982). Therefore, we conclude that the rift boundary at Abiquiu was actively extending from ca. 10 Ma to slightly <8 Ma but has been essentially inactive since, except for minor late Pleistocene faulting (Gonzalez and Dethier, 1991). Needless to say, better constraints are required to more closely define the timing of tectonic activity at this boundary.

Moreover, no evidence, either from the magmatic or the sedimentary record, exists to suggest that extension along this boundary occurred earlier than ca. 10 Ma. For example, except locally near magmatic centers, "early rift" sedimentary rocks in the Abiquiu area (including the Abiquiu Formation) broadly consist of volcaniclastic aprons spread over the pre-existing topography, with no evidence of syndepositional faulting (Ingersoll and others, 1990). Exposures of Santa Fe Group sediments along the Cañones fault zone southwest of Abiquiu (Manley, 1982) indicate deposition in a broad basin without evidence for a faulted margin. Therefore, we see no evidence in this area for development of fault-bounded rift basins prior to the late Miocene (ca. 10 Ma).

Age of Embudo Fault Zone

The major fault bounding the main Española basin on the north may be the Embudo fault zone, 20 km southeast of Abiquiu (Dungan and others, 1984). The relative sense of horizontal displacement seems to be right slip on the western part of the zone (Aldrich, 1986) and left slip on the eastern part (Dungan and others, 1984). Change in the sense of slip is accommodated by extension of the crustal block south of the fault zone (Aldrich, 1986). Along with strike-slip offset, stratigraphic evidence argues for a significant (at least several hundred meters) but unknown amount of down-to-the-south offset (Dethier and Manley, 1985; Aldrich, 1986; Aldrich and Dethier, 1990). Activity on the Embudo fault zone may in part be coeval with that of the Abiquiu margin but apparently continued more recently. Aldrich and Dethier (1990) suggested that the Embudo fault may have been active as early as 10 Ma and that its dominant offset was dip slip. Right-lateral strike slip offset along the eastern part of the zone commenced after deposition of the youngest sediments of the Santa Fe Group (Chamita Formation), ca. 6–4.5 Ma (Manley, 1979) but did not affect upper Puyé sediments, younger than ca. 2.5 Ma (Dethier and Manley, 1985; Aldrich, 1986; Aldrich and Dethier, 1990). Dungan and others (1984) suggested that offset on the Embudo continued into the Quaternary, based in part on geomorphic evidence.

Shift of Fault Activity?

On the basis of the age relations summarized above, we suggest that rifting commenced at the margin of the Abiquiu embayment in the late Miocene, ca. 10 Ma. However, extension and fault offset may have essentially ceased after 7–8 Ma, and extension transferred to the Embudo fault zone. This idea is compatible with greater offsets (hence extension) to the east in the Española and Taos basins. The Embudo zone remained active until at least 2.5 Ma and possibly into the Quaternary. The Embudo transfer zone effectively decoupled the Abiquiu embayment from the main Española basin. In addition, the shift in activity may reflect a narrowing of rift basins through time (Manley, 1984) and an integration of the major basin-bounding structures between the San Luis and the main Española basins. The shift closely correlates in time with a major reorientation of the direction of regional extension from north-northeast to west-northwest (Zoback and others, 1981; Aldrich and others, 1986) that occurred over a broad region of the western United States ca. 10 Ma. The change in locus of activity may have occurred in response to the change in the regional stress field, or simply to the magnitude of local extension as the rift basins continued to develop.

Sediment dispersal patterns do not definitively document the shift in extension from the boundary west of Abiquiu to the main Española basin, because these patterns dominantly reflect major changes in source areas rather than the detailed structure of the basin. From late Oligocene through middle Miocene, sedimentation in the Abiquiu area reflected the growth of several partially overlapping volcaniclastic aprons to the north and northeast of the Española basin (Ingersoll and others, 1990). Between 10 and 5 Ma, sedimentation throughout the basin was dominated by uplift of the Sangre de Cristo range, hence sediments were also derived mainly from the east side of the basin. Because the earlier volcanic source areas were largely eroded away, those sediments that were deposited in the Abiquiu embayment area were derived from the east, and portions of the area underwent erosion. The Rio Grande became established as a throughgoing drainage 3–5 Ma (Manley, 1979), dominating sediment transport throughout the basin about the time that activity shifted from the margin at Abiquiu to the Embudo fault zone.

In conclusion, the boundary at Abiquiu preserves an early stage in the formation of the late Miocene–Holocene rift boundary, indicating that extension occurred over a broad (>17 km wide) zone with no single master fault. Faulting was high angle (60°–70°), with no evidence that fault planes are listric or merge with a detachment fault at depth. Our work suggests an evolution in the structural development of the northwestern margin of the Española basin, as well as an ongoing integration of structures as rift basins became narrower with continued extension. These results may be typical of the initial stages of formation of other extensional basins.

ACKNOWLEDGMENTS

We gratefully acknowledge the Arco Oil and Gas Company for donating the services of the Field Acquisition Survey Team (FAST), which conducted the seismic survey on which this work is based. We especially thank S. Raeuchle, R. Withers, and others at Arco who made this collaboration possible. We express our appreciation to the members of the FAST crew—L. Hix, L. Forgey, G. Clark, R. Dart, W. Davis, and J. Johnson—and to their contractors for their skillful and professional execution of the field work and their great patience with the students and faculty of SAGE. We thank J. Darnall and M. Verhoeks of Arco, who aided with lectures, data processing, and interpretation. We thank R. Bridges and T. Kneale of Advance Geophysical Corporation for loan of Micromax computer systems.

We express our sincere appreciation to C. F. Keller of the IGPP for his unflagging support and encouragement of the SAGE program. We also acknowledge the efforts of J. Tallent of the U.S. Army Corps of Engineers, P. Garcia and E. Duda of Rio Arriba County, and F. Martinez of the New Mexico Highway and Transportation Department for their assistance with permits and logistics. We have benefited from informal discussions with K. Manley and from reviews of this manuscript by K. Carter, R. Raynolds, T. A. Cross, and an anonymous reviewer.

Finally, and perhaps most important, we appreciate the diligence of the students of SAGE 1990 and 1991 and have profited from our interactions with them. Coauthors K. Eckhardt, D. Evans, and C. Schultz are former SAGE students.

This work was supported by IGPP, the Los Alamos National Laboratory, the Research Experiences for Undergraduates Program of the National Science Foundation, and the Industrial Affiliates Program of SAGE.

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Manuscript Received by the Society September 9, 1993
Revised Manuscript Received April 19, 1994
Manuscript Accepted April 21, 1994

Printed in U.S.A.