Geological Society of America
Special Paper 291
1994

Tertiary stratigraphy and tectonic development of the Alamosa basin (northern San Luis Basin), Rio Grande rift, south-central Colorado

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ABSTRACT

Analysis of borehole and reflection seismic data from the Alamosa basin (northern San Luis Basin, Rio Grande rift) reveals tectonic development in response to three Tertiary events, each with an associated package of rocks distinguished by mineralogy and petrology. Eocene redbeds of the Blanco Basin Formation (0 to 696 m thick) are micaceous, sandy mudstone and coarse arkosic sandstone units containing lithic pebbles derived from granitic basement rock. They were deposited in a late Laramide basin formed during wrench-fault-related segmentation of the early Laramide San Luis–Brazos uplift. The western half of the younger, rift-related Alamosa basin is superposed over this late Laramide basin. Initiation of Oligocene volcanism is marked by andesitic lava flows and volcaniclastic rocks of the Conejos Formation (0 to 2,300 m thick), also limited in extent to the western half of the Alamosa basin. Ash-flow tuffs (380 to 580 m thick) correlative to 29 to 27 Ma tuffs of the San Juan volcanic field cap the Conejos Formation in the western half of the basin and rest directly on denuded Precambrian basement in the eastern half of the basin. These tuffs exist in deep wells across the Alamosa basin and together represent a basinwide time marker. Extension related to the Rio Grande rift resulted in eastward-tilting of the entire basin area following emplacement of the ash-flow tuffs. Filling the resulting half graben is the upper Oligocene–middle Pleistocene Santa Fe Group (as much as 5.6 km thick) composed of variegated mudstones and coarse lithic sandstones and conglomerates. Lithic fragments in the Santa Fe Group represent two sources: variable-composition volcanic rocks from the San Juan volcanic field to the west (majority) and plutonic-metamorphic-sedimentary, basement-derived rocks from the Sangre de Cristo Range to the east (minority). An angular unconformity within the Santa Fe Group documents strong early tilting due to movement on the Sangre de Cristo fault zone during an early phase of rifting (late Oligocene–early Miocene). The rift-related geometry of the crust beneath the Alamosa basin is that of two east-tilted crustal blocks creating two second-order half grabens within the basin.

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Brister, B. S., and Gries, R. R., 1994, Tertiary stratigraphy and tectonic development of the Alamosa basin (northern San Luis Basin), Rio Grande rift, south-central Colorado, *in* Keller, G. R., and Cather, S. M., eds., Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting: Boulder, Colorado, Geological Society of America Special Paper 291.

INTRODUCTION

The Alamosa basin is a subbasin of the San Luis Basin of south-central Colorado and north-central New Mexico. The San Luis Basin is one of a series of similar features in the Rio Grande rift (Fig. 1), a north-trending intracontinental rift that extends from north of Leadville, Colorado, to El Paso, Texas, and beyond (Chapin, 1971). The San Luis Basin is more than 200 km long from north to south. Its northern physiographic limit is at Poncha Pass, Colorado (Upson, 1939), and its southern limit is near the Embudo constriction in New Mexico (Kelley, 1956). The San Luis Basin is bordered by the San Juan and Tusas Mountains on the west and the Sangre de Cristo Range on the east. At the latitude of Alamosa, Colorado, it is about 70 km across. This paper examines a 5,520 km^2 area in the San Luis Basin, north of the San Luis Hills, termed the "Alamosa basin" by Burroughs (1981). Its stratigraphy, structure, and tectonic history are interpreted from subsurface data, including borehole samples and geophysical surveys.

The Alamosa basin has had a complex history. The region has been recurrently uplifted and down dropped during several tectonic events (Sales, 1983). As a Rio Grande rift basin, the Alamosa basin today takes the form of an asymmetric, first-order half graben with stratigraphic units tilted eastward from their pre-rift orientations (Fig. 2). This half graben is bounded along the Sangre de Cristo Range by the Sangre de Cristo fault zone (Personius and Machette, 1984, p. 87). The basin is divided into a western ("Monte Vista") graben and eastern ("Baca") graben by a basement high termed the "Alamosa horst" (Burroughs, 1981). Both grabens are second-order half grabens, but the Baca graben was the site of the greatest degree of tilting and thickest sedimentary infilling during rifting due to its proximity to the Sangre de Cristo fault zone.

The purpose of this paper is to present an interpretation of

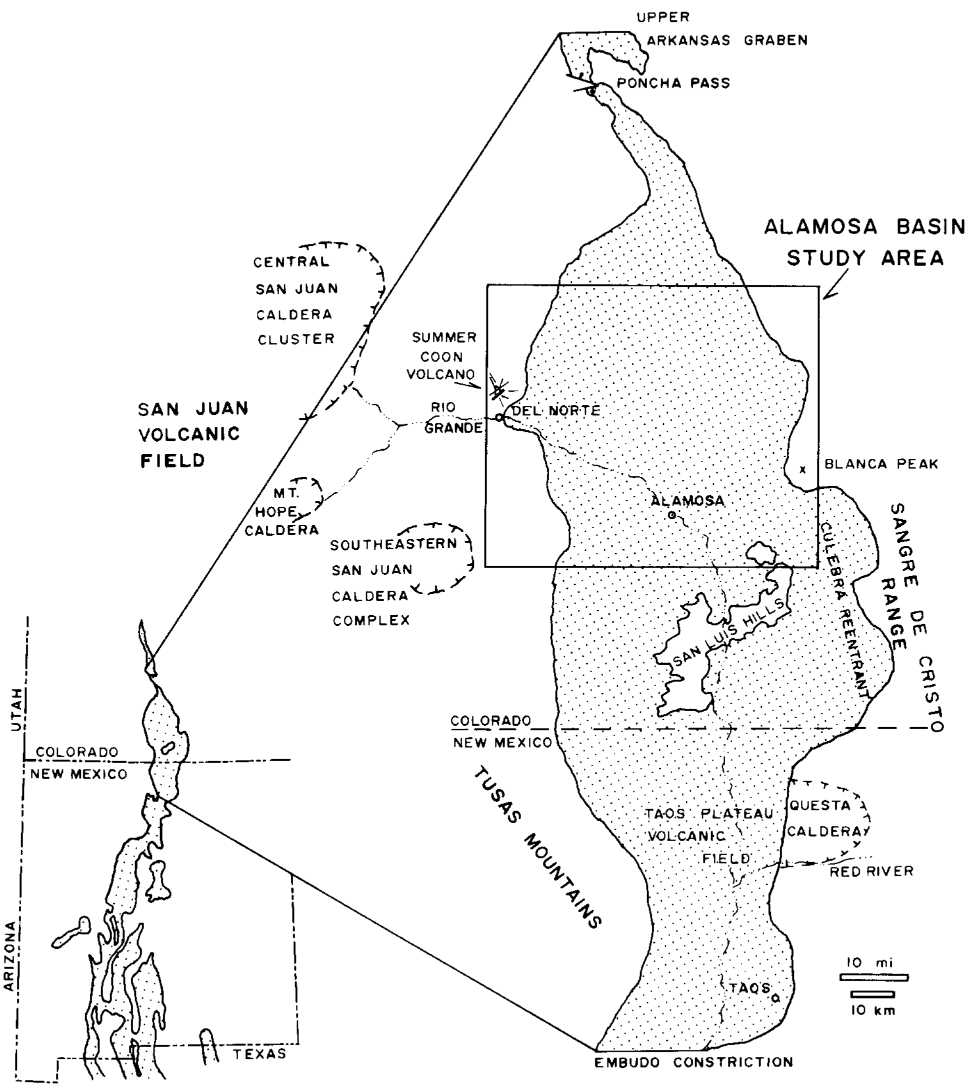

Figure 1. Location map showing Alamosa basin study area, San Luis Basin, Rio Grande rift, and geographic features discussed in text. Stippled pattern denotes rift-basin fill.

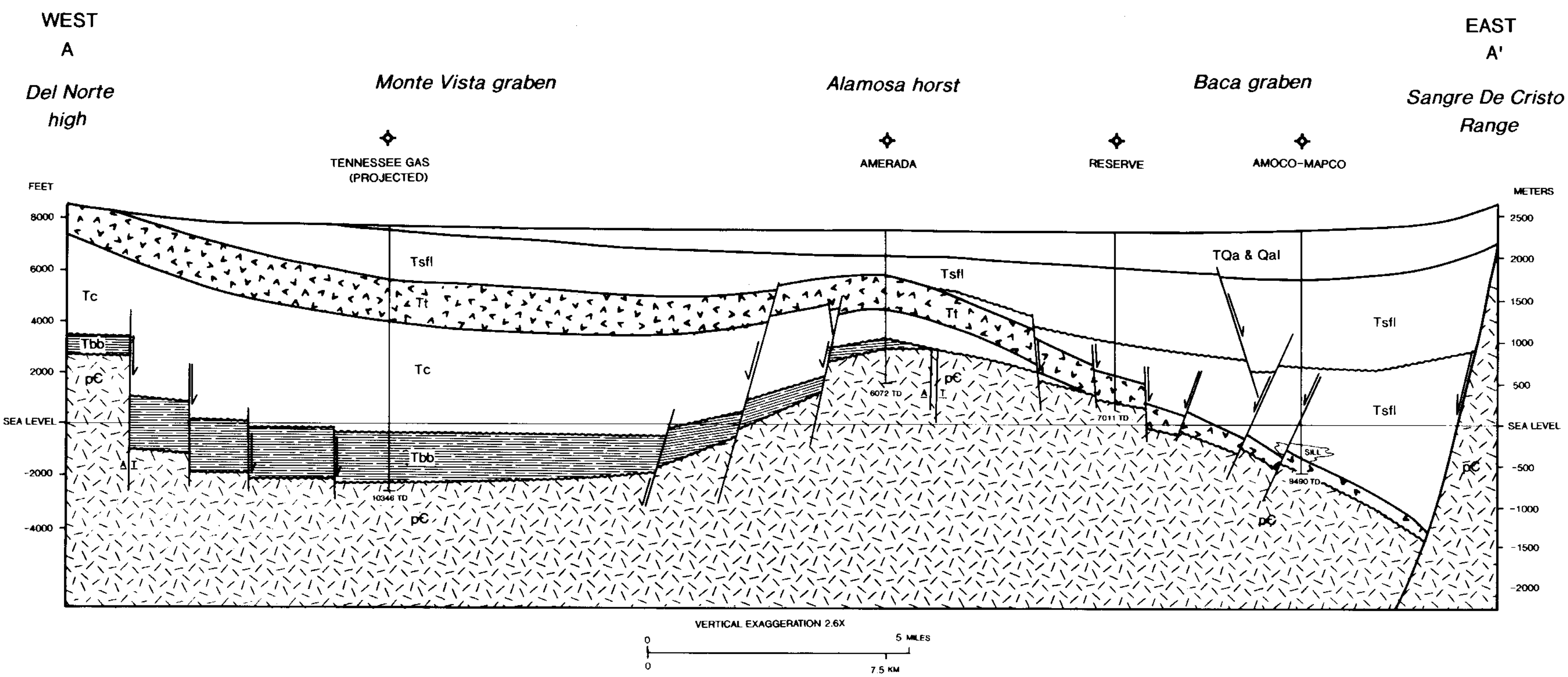

Figure 2. Interpretive cross section A–A′ across the San Luis Basin; location of section indicated in Figure 3. Symbols: TQa and Qal, Alamosa Formation (Plio-Pleistocene) and Quaternary alluvium; Tsfl, lower Santa Fe Group (Mio-Pliocene); Tt, ash-flow tuffs of San Juan volcanic field (Oligocene); Tc, Conejos Formation and equivalents (Oligocene); Tbb, Blanco Basin Formation (Eocene); pЄ, granite-gneiss basement (Precambrian); TD, total depth. Figure modified from Gries and Brister (1989).

the tectonic development of the Alamosa basin based on new insight into the stratigraphy of the basin fill. The physical characteristics of the basin stratigraphy, determined from petrologic analysis of subsurface samples, define lithostratigraphic units that can be correlated using reflection seismic lines. Combining new subsurface stratigraphic and structural information has led to a new interpretation of the timing of episodes of basin development.

PREVIOUS WORK

The classic references on the location and physiographic setting of the basin are Siebenthal (1910b) and Upson (1939). Overviews that discuss the relation of the San Luis Basin to the Rio Grande rift are Chapin (1971, 1979, 1988), Cordell (1978), Hawley (1978), Keller et al. (1984),and Tweto (1979). Ingersoll et al. (1990) present a detailed study of the sedimentation and paleotectonics of the southern San Luis Basin based on outcrop-derived data and regional correlation. Notable geophysical investigations of the northern San Luis Basin are Cordell (1978), Gries (1985a), Keller et al. (1984), and Stoughton (1977).

Huntley (1979) was the first to publish a correlation of stratigraphic units between boreholes suggesting that the basin fill was entirely of Tertiary age. Burroughs (1981) noted that some of the more wide ranging volcanic units of the region could be correlated in borehole geophysical logs.

Reflection seismic lines published by Gries (1985a) were of high quality, but a lack of detailed petrologic data limited interpretation of the various features visible on the lines. Attempts by Gries to resolve this problem utilizing radiometric and palynological dating techniques were unsuccessful. This paper applies the results of a petrologic study of borehole samples to reinterpret seismic data in the basin. Preliminary results were discussed in Gries and Brister (1989).

STRATIGRAPHY

The sequence of lithostratigraphic units in the Alamosa basin varies greatly depending upon location. Regional tectonic events had different effects on the western and eastern halves of the basin, therefore the two halves have significantly different stratigraphic sections. The stratigraphy is illustrated by a west-to-east cross section (Fig. 2, location shown in Fig. 3).

Precambrian basement (p€)

The stratigraphically lowest unit is Precambrian basement. In general, the basement rocks are granitic in composition but have a gneissic texture and have high electrical resistivity (100 to 2,000 ohmms) and densities typical of granitic rocks (greater than 2.6 gm/cc). Cuttings are commonly stained orange by hematite, especially along grain boundaries. This may be a result of weathering when the basement was exposed subaerially during several Phanerozoic orogenic events as will be discussed below.

Basement rocks contain quartz, orthoclase, microcline, perthite, plagioclase, muscovite, biotite, and amphibole. Alignment of micas is common in most samples. Most quartz grains are strained, monocrystalline types that reflect a probable metamorphic origin. Some quartz grains are coarsely polycrystalline with nonsutured boundaries. Although these grains would usually be expected to come from metaquartzites, they may also be found in finer-grained granites and schists (Folk, 1974).

Many metamorphic rock types have been described from exposures in the nearby Sangre de Cristo Range (Johnson, 1969), including granites, gneisses of various compositions, amphibolites, and metasediments. Such variation probably also exists beneath the Alamosa basin, but has not been found by sparse drilling. The top of the Precambrian basement is an unconformable surface of erosion, upon which Tertiary units were deposited.

Blanco Basin Formation (Tbb)

The Blanco Basin Formation (Eocene) consists of nonvolcanic, alluvial redbeds unconformably overlying the Precambrian basement in wells in the western half of the Alamosa basin (Monte Vista graben). Total thickness varies across the basin from 0 to 696 m. The Blanco Basin Formation is composed of sandy, micaceous mudstone and coarse arkosic sandstone and conglomerate.

The mineral composition of the coarser sedimentary rocks is identical to that of the Precambrian basement and indicates that basement rocks were their primary source. Sandstones in some wells also contain a small percentage of sedimentary rock fragments of Paleozoic and/or Mesozoic provenance. Rarely, fine- to medium-grained, frosted, rounded quartz grains exist in the samples, perhaps eroded from Jurassic eolian sandstone formations such as the Junction Creek Formation. In Figure 4, the composition of the Blanco Basin Formation is compared with younger Tertiary sandstones in the basin.

Those units sampled that were interpreted as "sands" from geophysical logs are arkosic, coarse, pebbly sandstones and conglomerate beds containing granitic pebbles. The log characteristics of these bodies are variable, but individual sand bodies tend to be "cylinder shapes" (terminology of Rider, 1986) with lesser bell and funnel shapes. Contacts against surrounding mudstone beds range from abrupt to gradational.

Blanco Basin mudstones are generally reddish brown (Hue 10R, saturation 4 to 6, value 3 to 4) but may vary to red, green, gray, maroon, and purple. A single cutting chip may display mottling of two or more of these colors suggesting that coloration may be dependent upon diagenesis. The mudstones have not yielded fossils or pollen, and thus the exact age of the formation is unknown.

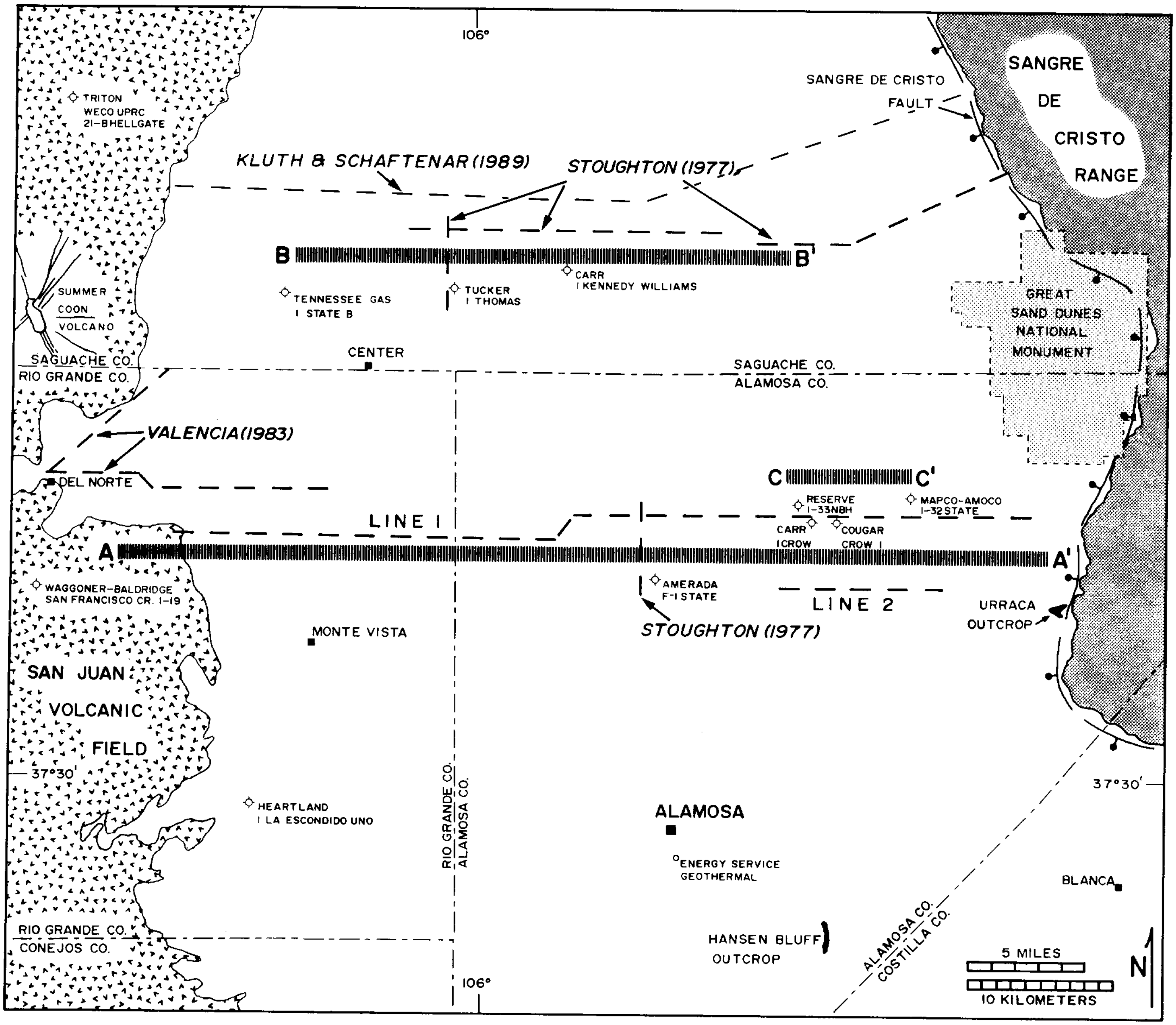

Figure 3. Map of the Alamosa basin study area showing oil and gas drilling, seismic lines illustrated or discussed in this paper, and cross sections A–A′, B–B′, and C–C′.

The formation here termed Blanco Basin Formation in the western part of the Alamosa basin has been considered to be Eocene in age by other workers based on its color, degree of consolidation and cementation, and depositional facies characteristics. Tweto (1979) correlated it with the "Eocene Echo Park Alluvium" (Echo Park Formation of Epis and Chapin, 1974). Covarrubias (1988) termed the formation "Eocene red beds." Baltz (1965) believed the formation to be similar to the Blanco Basin Formation of Larsen and Cross (1956) although he did not specifically assign that name.

Huntley (1979) and Burroughs (1981) applied the name Vallejo Formation due to the apparent similarity of these beds to the "fluvial red-beds" described by Upson (1941) in the Culebra reentrant southeast of the study area. However, we believe that the age of the Vallejo Formation at its type locality is Miocene or younger based on regional correlation to units with similar petrologic characteristics. Regardless of the name chosen, both Huntley and Burroughs believed their "Vallejo" beds in the subsurface to be pre-Oligocene.

The best evidence for the identity of the redbeds in the Monte Vista graben comes from recent drilling in the San Juan sag (Gries, 1985b) west of the Alamosa basin. The San Juan sag is separated from the Alamosa basin by the Laramide wrench-fault-related Del Norte high (Gries, 1989; Brister,

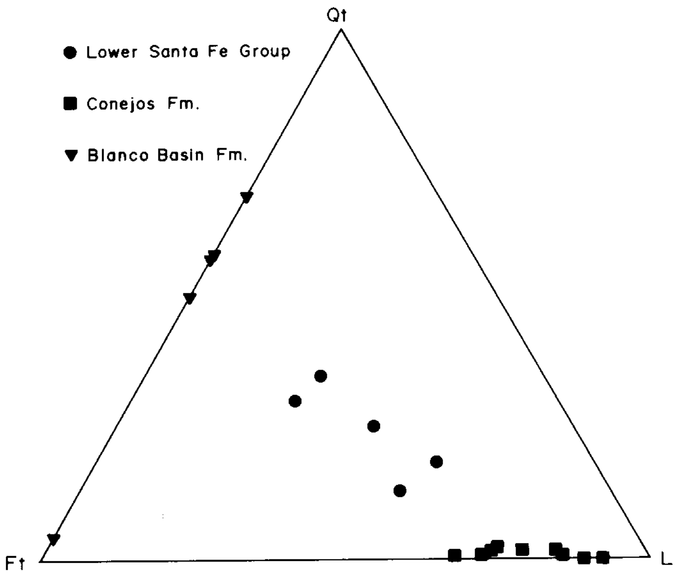

Figure 4. Ternary diagram of sandstone compositions from subsurface units in the Alamosa basin. Qt, total quartz, including polycrystalline grains + quartzite + chert; Ft, total feldspar; L, sedimentary + volcanic + metamorphic lithic grains. Each symbol represents at least 500 points counted in a single sample. See Brister (1990) for data tables and sample locations.

1990). The redbeds of the Monte Vista graben can be correlated in the subsurface across the Del Norte high, into the San Juan sag, and eventually to outcrops some 45 km to the west along the southwestern flank of the San Juan Mountains where they have been assigned the name Blanco Basin Formation (Cross and Larsen, 1935). Their age in the San Juan sag is generally believed to be Eocene because, like the Blanco Basin Formation to the southwest, they are bracketed by unconformable contacts with the Paleocene Animas Formation below and the Oligocene Conejos Formation above. The petrologic characteristics of the redbeds encountered in the Monte Vista graben are similar to those of the Blanco Basin Formation in general and are consistent with the petrologic variability between, and within, Blanco Basin outcrops (Brister, 1992).

The Blanco Basin Formation has been drilled in six of the wells shown in Figure 3. The thickest sections penetrated are 696 m in the Triton/Weco/UPRC 21-B Hellgate well, and 643 m in the Tennessee Gas Transmission 1-State B well. A possible explanation for the great thickness in these wells compared to typical thickness of the formation of about 175 m is that they exist adjacent to a major Laramide basin-bounding fault zone separating the Laramide precursor basin of the Monte Vista graben from the Del Norte high.

Wells drilled west of this fault zone on the Del Norte high contain thinner Blanco Basin Formation. They are the Waggoner-Baldridge San Francisco Creek 1-19 well with 159 m, and the Heartland #1 La Escondido Uno well with only 49 m. The Amerada F-1 State well in the vicinity of the Alamosa horst drilled 115 m, which is the easternmost-known Blanco Basin equivalent rocks. The Tucker #1 Thomas well bottomed in the Blanco Basin Formation, drilling only 34 m as estimated from a description by Powell (1958).

Conejos Formation (Tc)

The Conejos Formation is a series of intermediate-composition volcaniclastic rocks and lava flows (35 to 30 Ma) that were derived from volcanoes active in the San Juan volcanic field from 35 to 30 Ma (Lipman et al., 1970). The Conejos volcanic rocks are high-K, subalkalic, and commonly range from andesite to quartz latite (silicic dacite) in composition (Lipman, 1989). Lithologic units in the formation vary depending upon distance from vents and/or periodic extrusive activity. These include volcanic breccias of both "hot" and "cold" origin and emplacement (these range from mono- to heterolithologic and include, but are not limited to, debris-avalanche and debris-flow deposits), lava flows, autobrecciated flows, stream-laid conglomerate and sandstone, and organic-rich lacustrine claystone. Ash-flow tuffs are rare (Lipman, 1975), but some of the volcaniclastic deposits are tuffaceous, containing relict glass shards and rare reworked welded tuff fragments. The above description applies well to the package of rocks marked Conejos Formation on Figure 2. As seen in Figure 4, Conejos sandstones from wells in the Alamosa basin are lithic rich; this lithic component is generally 100% intermediate-composition volcanic rock fragments.

Only one Conejos vent has been documented in the study area: that of the Summer Coon volcano (Lipman, 1968) located on the western edge of the basin north of the town of Del Norte. Other sources for Conejos deposits in the Alamosa basin are located to the southwest, where vents have been documented in the Platoro, Colorado, area (Lipman, 1975), and possibly the south, from vents in the San Luis Hills (Burroughs, 1971, 1972, 1981; Thompson and Machette, 1989). The vents responsible for the Bonanza Tuff and related andesitic breccias (Steven and Lipman, 1976) comprise a possible northern source for Conejos-equivalent volcaniclastic detritus.

The Conejos units in the Alamosa basin were probably deposited on the distal fringes of vent complexes. In general, those wells along the western side of the Alamosa basin have a high percentage of flows and coarse volcaniclastic rocks, but this percentage decreases eastward in favor of finer-grained deposits. The Conejos Formation also decreases in thickness eastward to a zero edge over the central part of the basin. The thickest section drilled in the study area is 2,300 m in the Triton/WECO/UPRC 21-B Hellgate well, which is situated on the northern flank of the Summer Coon volcano. Most other wells in the western half of the Alamosa basin have penetrated 1.3 to 1.5 km of the Conejos Formation. The easternmost section of the Conejos Formation is in the Amerada F-1 State well, which had only 400 m.

Ash-flow tuffs (Tt)

A package of interbedded ash-flow tuffs and tuffaceous clastic rocks marked Tt on Figure 2 overlies the Conejos Formation. This package is important because it: (1) exists throughout the basin; (2) separates Rio Grande rift-related deposits above it from pre-rift formations below it; (3) has been radiometrically dated (in the San Juan Mountains) and has been demonstrated to represent a short interval of time; and (4) shows distinctive (although nonunique) identifiable characteristics on borehole geophysical logs and reflection seismic lines. These characteristics used in conjunction with petrologic examination have allowed the utilization of the package as a time marker in the stratigraphic sequence (Brister, 1990).

The ash-flow tuffs in this sequence are part of a series of volcanic rocks, 26 to 30 m.y. old (Steven and Lipman, 1976), which originated in the eastern San Juan volcanic field. Only the most voluminous flows made their way to the Alamosa basin area. The key to their identity are outcrops in the eastern foothills of the San Juan Mountains where the tuffs dip at angles of less than 10° into the basin. The 29.5 to 28.4 Ma Treasure Mountain Tuff (Lipman and Steven, 1970; Lipman, 1989), erupted from the southeastern San Juan caldera complex, and the 28.4-Ma Masonic Park Tuff (Lipman et al., 1970; Steven et al., 1974; Lipman, 1989), erupted from the Mount Hope caldera, contributed the majority of the material to the tuff package in the southern part of the Alamosa basin. Likewise, the 27.75-Ma Fish Canyon and 27.35-Ma Carpenter Ridge tuffs (Olson et al., 1968; Lipman, 1989) from the central caldera cluster dominate the tuff sequence to the north.

Figure 5 is a cross section constructed from borehole geophysical logs drawn such that the datum is the top of the tuff package. In each well shown, there are no lava flows or welded tuffs above this horizon. The figure illustrates which units have been positively identified as ash-flow tuffs using criteria outlined above. Tentative correlations have been drawn between the logs based primarily on log response rather than petrographic criteria. Resistivity curve profiles for the tuff units may mimic welding profiles. It is assumed that any given ash-flow tuff has similar log response between two wells over a relatively short distance, thus pattern recognition of log curves was helpful in correlation.

It can be observed that the westernmost (which are also the northernmost) wells generally have thin Masonic Park Tuff and Treasure Mountain Tuff compared to those wells farther south and east. These wells are near the distal edge of the

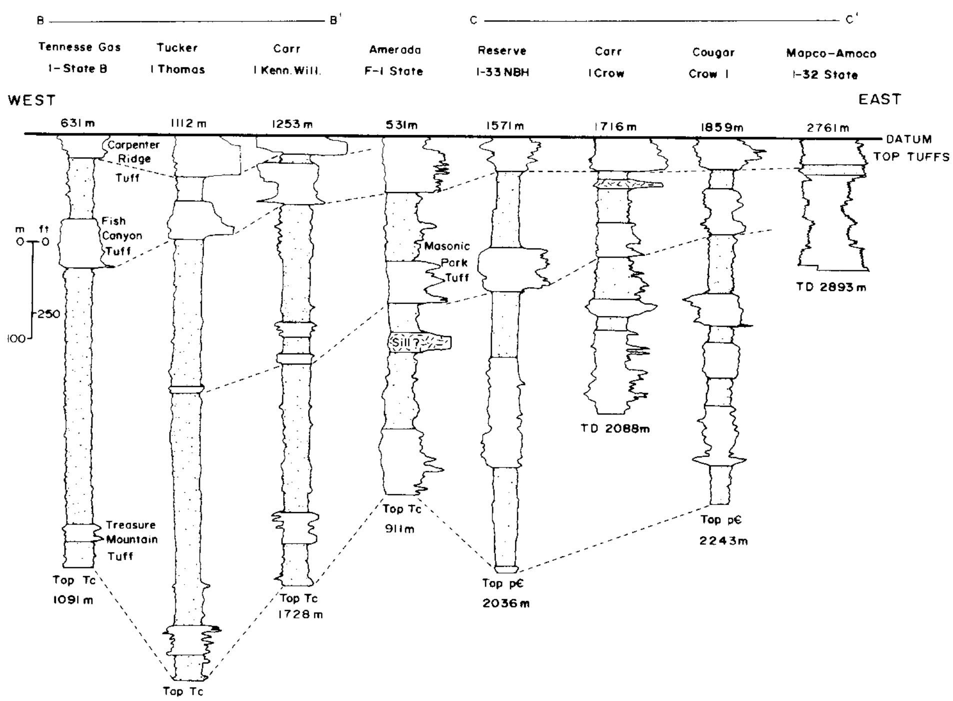

Figure 5. Well-log comparison of Oligocene ash-flow-tuff package in Alamosa basin illustrating tentative correlations; drillholes indicated are on Figure 3. Log curves are spontaneous potential (left) and resistivity (right); exception is Mapco-Amoco 1-32 State well (gamma ray on left; density on right). Datum is top of the ash-flow tuffs/base of Santa Fe Group (depth of datum listed above heavy line). Unit underlying tuffs and depth of contact indicated at bottom. A similar package of tuffs to that in the Amerada F-1 State well is present in the Energy Service #1 Alamosa Geothermal well but electric logs are not available. Stippled areas are unwelded tuffs and tuffaceous sediments; unstippled areas are welded units.

Masonic Park and Treasure Mountain tuffs that were erupted from the Mount Hope and southeastern caldera complex (see Fig. 1). The nearby Summer Coon volcano of Conejos age was probably topographically high enough to stand in the way of the ash flows, creating a shadow. For the same reasons, wells to the southeast generally lack a recognizable section of Carpenter Ridge Tuff.

Prior to this study, it was believed that the upper Oligocene San Juan tuffs pinch out in the Monte Vista graben (Tweto, 1979) or over the Alamosa horst (Burroughs, 1981). The explanation for such pinching out was that the Alamosa horst prevented tuffs from reaching the eastern half of the basin. Figure 5 shows that if a topographically high area existed, it provided no impediment to ash flows moving across it. In fact, it is likely that the ash flows may have reached eastward beyond the present-day Sangre de Cristo Range (Burroughs, 1981; Scott, 1975). Also, there is no apparent thinning of ash-flow tuffs in wells (Amerada F-1 State, and Energy Service Geothermal) over the horst area. There is, however, overall thinning of the intertuff clastic deposits eastward in the wells, suggesting increasing distance from the major source of these sediments and/or a positive paleotopographic gradient to the east. The effect of this sedimentation was to blanket and subdue existing topography. The top of the tuffs in the subsurface is an east-dipping surface today, due to postemplacement tilting.

Santa Fe Group (Tsfl and Ta)

The Santa Fe Group includes all pre–middle Pleistocene sediments above the upper Oligocene tuffs. It can be roughly divided into two units, upper and lower Santa Fe Group, based upon lithologic criteria. The lower Santa Fe Group is ubiquitous in the subsurface of the basin and represents large-scale sedimentary response to half-graben development from late Oligocene to Pliocene. The upper Santa Fe Group, named the Alamosa Formation, represents lacustrine and fluvial sedimentation ranging in age from Pliocene to middle Pleistocene. Cross section B′–C′ (Fig. 6), summarized from well data, illustrates the stratigraphy of the Santa Fe Group in the Alamosa basin.

Lower Santa Fe Group. The lower Santa Fe Group in the Alamosa basin has been called the Santa Fe Formation (Siebenthal, 1910b; Powell, 1958). However, Spiegel and Baldwin (1963) began the modern usage of "Santa Fe" as a group term "that includes all the synrift basin fill, both volcanic and sedimentary, ranging in age from late Oligocene to Quaternary, but excluding deposits that postdate entrenchment of the Rio Grande in middle Pleistocene time" (Chapin, 1988, p. 169). Burroughs (1981) has suggested that the lower Santa Fe Group may be divided into formations based on composition and provenance. No attempt has been made in this study to subdivide the lower Santa Fe Group because of lack of sufficient subsurface data. The age of lower Santa Fe Group sediments in the Alamosa basin is poorly constrained, but ranges from about 26 Ma to about 4.5 Ma. The older age is approximately the end of ash-flow volcanism in the eastern San Juan Mountains (Steven et al., 1967; Lipman, 1989). The younger age marks the beginning of tholeiitic basalt volcanism and construction of the Taos Plateau volcanic field that blocked surface drainage in the southern San Luis Basin (Lipman and Mehnert, 1979) and was responsible for the widespread fluviolacustrine system of the Alamosa Formation.

Grain size and composition of the lower Santa Fe Group vary depending primarily upon proximity to sources and character of dispersal systems. Well samples from the study area are of claystone, sandstone, and conglomerate. The claystone and sandy mudstone in the lower Santa Fe Group are compact but soft, nonfissile, and micaceous. They deepen in color with increasing depth in the basin, but are everywhere variegated. Typical colors include tan, pink, buff, orange, brick red, light olive, and light gray to black. Most of these colors are indicative of an oxidizing environment of deposition. A coal seam was penetrated in fine-grained units in the Mapco-Amoco #1-32 State well at 1,774 m depth. There are no known bedded evaporites in the sequence, but scattered selenite crystals can be found in the cuttings.

The lowermost Santa Fe beds have been reported to be early Tertiary in age on the basis of pollen analyses (Huntley, 1976; Gries, 1985a). However, the pollen assemblages are sparse, not indicative of any specific Tertiary age, and contain a few specimens of probable Eocene age that may have been reworked. Lithologic and stratigraphic criteria discussed above provide strong evidence that these sediments postdate upper Oligocene ash-flow tuff volcanism. A rhyolite sill(?) in the Mapco-Amoco 1-32 State well at the base of the Santa Fe Group but above the Oligocene ash-flow tuff package has yielded a whole-rock K-Ar age of 22.2 Ma (R. Gries, unpublished data).

Some generalized observations of Santa Fe Group sandstones from the basin indicate that Precambrian detritus tends to increase in abundance eastward in the basin towards the Sangre de Cristo Range. All sandstones examined are lithic-rich with a majority of these fragments being of volcanic origin. Sandstone samples from the deepest part of the Baca graben are tuffaceous, but contain significant amounts of Precambrian material. On a ternary diagram (Fig. 4), these sandstones span the range in composition between samples of the Blanco Basin Formation and the Conejos Formation.

The lower Santa Fe Group sediments indicate provenance from two primary sources. The San Juan volcanic field to the west and northwest provided an influx of intermediate-composition volcanic debris including ash-flow-tuff clasts. Such deposits of late Oligocene–Pliocene age derived from the San Juan Mountains are usually referred to as the Los Pinos Formation (Butler, 1946, 1971; Manley, 1981), which Chapin (1988) has included in the Santa Fe Group. Interbedded volcanic flows are rare in the Santa Fe Group of the Alamosa basin; however, Hinsdale basalts ranging in age from 25.7 to

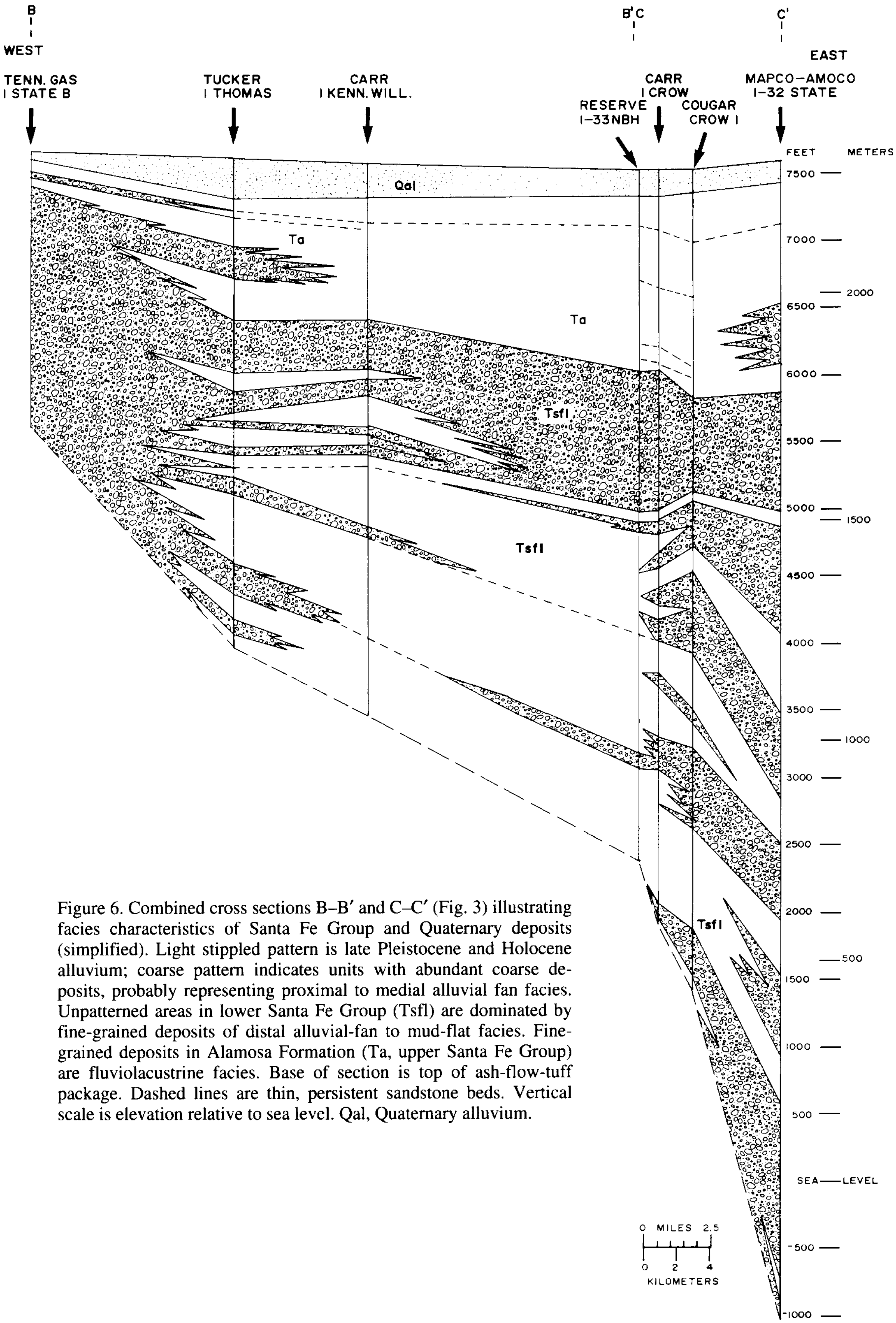

Figure 6. Combined cross sections B–B′ and C–C′ (Fig. 3) illustrating facies characteristics of Santa Fe Group and Quaternary deposits (simplified). Light stippled pattern is late Pleistocene and Holocene alluvium; coarse pattern indicates units with abundant coarse deposits, probably representing proximal to medial alluvial fan facies. Unpatterned areas in lower Santa Fe Group (Tsfl) are dominated by fine-grained deposits of distal alluvial-fan to mud-flat facies. Fine-grained deposits in Alamosa Formation (Ta, upper Santa Fe Group) are fluviolacustrine facies. Base of section is top of ash-flow-tuff package. Dashed lines are thin, persistent sandstone beds. Vertical scale is elevation relative to sea level. Qal, Quaternary alluvium.

26.4 Ma are interbedded with these sediments in the San Luis Hills along the southern border of the basin (Thompson and Machette, 1989). In the San Juan volcanic field the Hinsdale basalts range in age from 26 to 5 Ma (Lipman, 1975, 1969; Steven et al., 1974).

The second source of sediment was the rising Sangre de Cristo Range to the east, which was a source of detritus from Precambrian granitic and metamorphic rocks and Paleozoic limestones and clastic rocks. The Sangre de Cristo Range was at least partially covered by volcanic rocks in the late Oligocene and thus was also a source for some volcanic material.

Another possible source of sediment that has been suggested is stream flow from the Upper Arkansas graben into the Alamosa basin (Hanna and Harmon, 1989). A possible connection between the San Luis Basin and Upper Arkansas graben has been postulated due to the presence of the Mio-Pliocene Dry Union Formation (Tweto, 1961) in a narrow graben north of Poncha Pass, Colorado (Van Alstine, 1968, 1970; Knepper and Marrs, 1971, Taylor, 1975). However, neither surface mapping nor gravity surveys indicate significant Dry Union/Santa Fe deposits at Poncha Pass, but instead, demonstrate that a topographic and/or structural barrier existed in the area during the Miocene and Pliocene (Knepper, 1976).

Rare outcrops of the lower Santa Fe Group exist along the basin margins. In one location along the Sangre de Cristo fault zone, a fault slice of lower Santa Fe Group is exposed at the surface (marked "Urraca outcrop" on Fig. 3; see Gries and Vandersluis, 1989, p. 35). This deposit contains interbedded fluvial conglomerates and pebbly sandstones with beds less than a meter thick. Pebble imbrications suggest a south-southwest stream-flow direction that paralleled the Sangre de Cristo fault zone at this location. Current indicators show that the braided stream was draining parallel to the axis of the paleobasin. The rocks are well indurated and reddish brown, probably due to postdepositional cementation and oxidation. Such reddening of Santa Fe Group sediments has been reported elsewhere in the Rio Grande rift by Chapin and Lindley (1986) and has already been noted above for nearby deep-basin well samples. Composition of the pebbles in the outcrop reflect two provenances. Pebbles from the Sangre de Cristo Range include Precambrian granitic and metamorphic rocks and minor amounts of Paleozoic arkose, graywacke, siltstone, shale, limestone, and chert. Pebbles derived from the San Juan volcanic field include volcanic rocks of intermediate composition and minor flow-banded rhyolite and ash-flow tuff.

Alamosa Formation. The Alamosa Formation (Siebenthal, 1910a) is a fluviolacustrine formation deposited conformably upon the uppermost beds of the lower Santa Fe Group in the Alamosa basin. The depositional environment of the Alamosa Formation was dominated by reducing conditions (Huntley, 1979) as demonstrated by the predominance of gray, black, and green claystones. Well samples contain fossil debris including ostracods, bones, peat and wood fragments, and mollusc shell fragments. Organic material taints water from some wells and is a source of methane, the discovery of which has helped stimulate intermittent oil and gas wildcat drilling in the basin (Gries, 1985a). Toward the top of the section are persistent, poorly cemented sandstone horizons that can be correlated over broad areas of the basin. These mark the beginning of a return to drier and/or higher energy conditions in the basin. These beds have been extensively drilled in the basin because they are fresh-water bearing and artesian. They are the primary source of ground water for agriculture in the San Luis Valley.

Rogers (1984) sampled some 20 m of surface outcrop of the Alamosa Formation at Hansen's Bluff near the town of Alamosa (Fig. 3) and found the beds to be Pleistocene (0.6 to 0.9 Ma). The outcrop contains volcanic ash, various fish, bird, and mammalian bones, and fresh-water mollusc shells. The great thickness of underlying Alamosa deposits (the formation ranges up to 550 m thick) suggests that the formation is as old as Pliocene. The Hansen's Bluff deposits are overlain by Quaternary alluvium and probably predate the capture of drainage in the Alamosa basin by the Rio Grande in middle to late Pleistocene.

INTERPRETATION OF SEISMIC DATA

Seismic characteristics

Figure 7 is a synthetic seismogram from the Tennessee Gas 1-B State well, which contains all the stratigraphic units in the basin. The strongest reflections at about 0.6 seconds (two-way travel time) mark the late Oligocene welded ash-flow tuffs and the base of the Santa Fe Group. This strong reflection package was interpreted in every seismic line examined in the Alamosa basin. Because the top of the tuffs is the transition between pre-rift and syn-rift deposits, any faults that offset these reflections are a result of the rifting events. Faults that offset units below these reflections, but not the reflections themselves, are pre-rift in origin. Thus, this reflection package is important for deciphering the tectonic history of the basin.

Another strong reflection on Figure 7 exists at about 1.25 seconds. This is a local reflection associated with a 75-m-thick lava flow within the Conejos Formation. Such reflections in the Conejos are generally not far ranging. A weak double reflection exists at about 1.95 seconds and marks the top of the Precambrian basement.

An interpreted seismic line across the Alamosa basin (Fig. 8) illustrates the seismic characteristics of the lithostratigraphic units present. The top of the late Oligocene tuffs is the strong reflection that is not visibly faulted in the western half of the basin, but is faulted and tilted down to considerable depth in the Baca graben to the east. Well control helps to distinguish this reflection from internal reflections of the Santa Fe Group in the deeper parts of the Baca graben.

Below the strong tuff reflections, the Conejos and Blanco Basin Formations contain reflections that vary from strong and

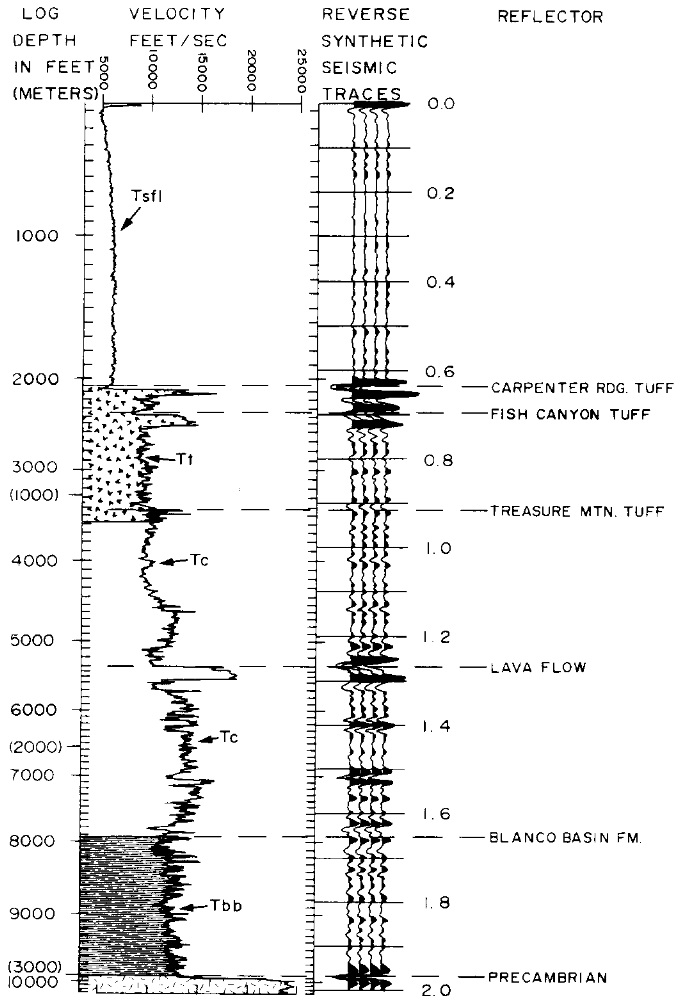

Figure 7. Synthetic seismogram from the Tennessee Gas Transmission 1 State B well in the Monte Vista graben. For other synthetic seismograms in the area, see Gries (1985a).

continuous, to weak and discontinuous. In some cases a weak reflection exists at the contact between the two formations; however, well control is generally necessary to correctly identify the contact. The Conejos–Blanco Basin package of reflections thins eastward to zero over the central high of the Alamosa basin.

Above the strong tuff reflections is a complex series of reflections corresponding to the Santa Fe Group. The Alamosa Formation is distinguished by low-amplitude, weak reflections typical of unconsolidated fine-grained lithologies. The transition to the lower Santa Fe Group is marked by a change to higher amplitude, more continuous reflections characteristic of interbedded coarse and fine clastic lithologies. The lower Santa Fe Group is characterized by two seismic packages, illustrated on Figure 9. The upper package is relatively flat lying and unfaulted, and traceable to some extent across the basin. The lowermost package dips moderately to the east, is

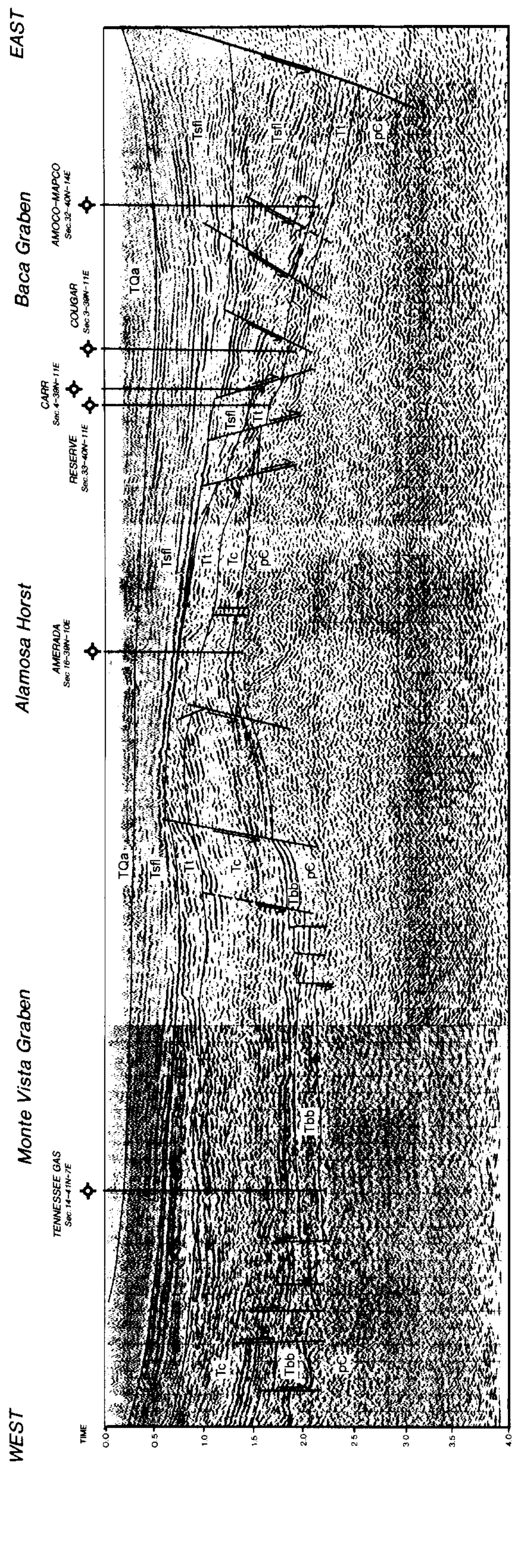

Figure 8. Seismic line 1, crosses the Alamosa basin from west to east (modified from Gries, 1985a; Gries and Brister, 1989). See Figure 3 for location and Figure 2 for abbreviations. Vertical scale in two-way travel time; see Figure 2 for approximate depth conversion.

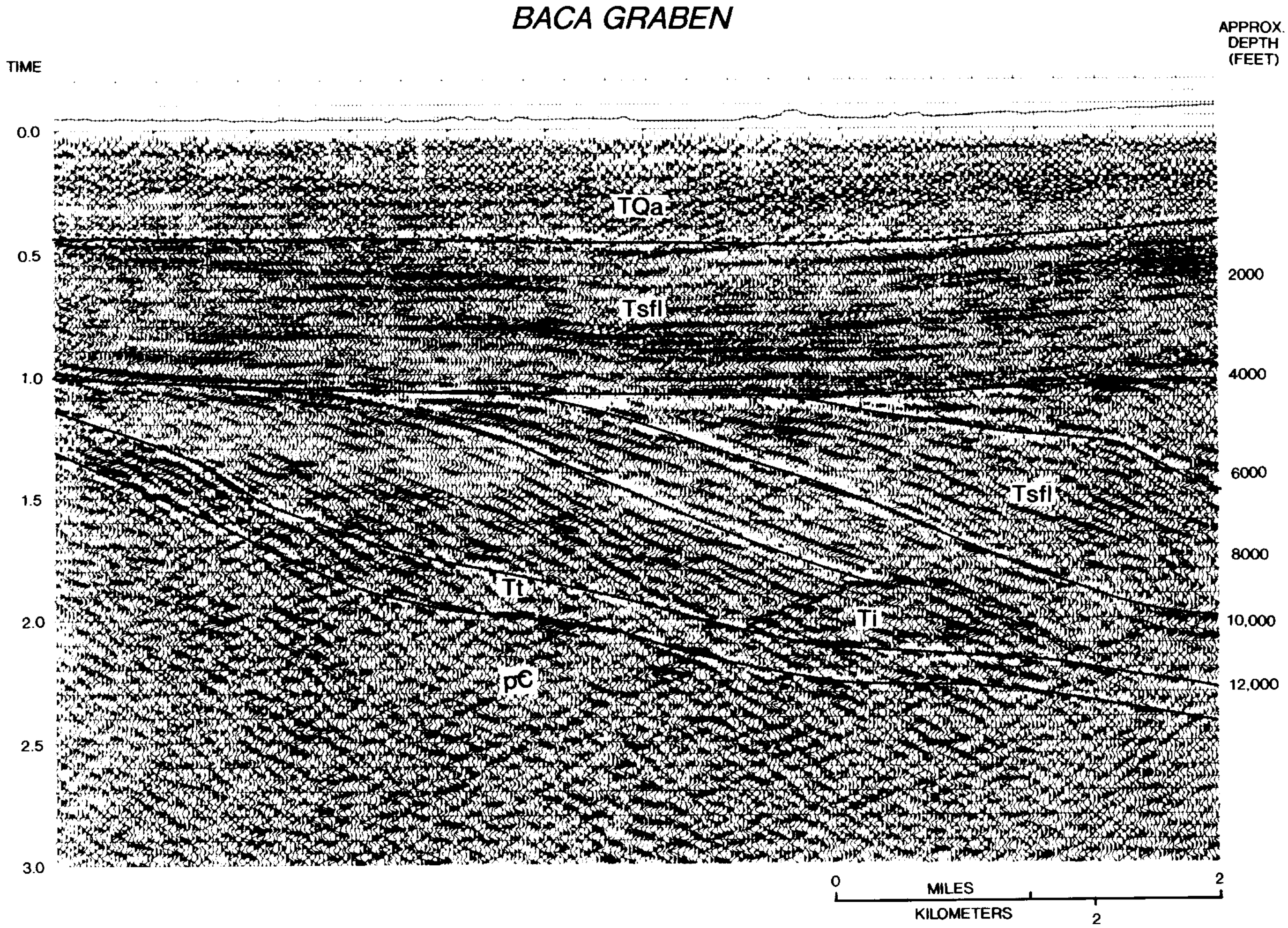

Figure 9. Seismic line 2, showing angular unconformity within the lower Santa Fe Group (after Gries, 1985a; Gries and Brister, 1989). See Figure 3 for location and Figure 2 for abbreviations. Ti, rhyolite intrusion.

highly faulted, and appears limited in extent to the Baca graben. The intervening angular unconformity within the lower Santa Fe Group can be seen on a number of seismic lines from the southern part of the Baca graben, and has some obvious implications for its early tectonic development. Although an increase in bed dip in the Baca graben is suggested in Figure 6 starting at about 1,400 m elevation, there is not an abrupt change in sample composition to mark this boundary. The mudstones and claystones common to the lower Santa Fe Group do not seem to radically change color across this boundary, although they do become reddened towards the base of the lower package.

Isochron maps

The presence of a recognizable, ubiquitous horizon that essentially separates pre-rift and syn-rift rock units in the Alamosa basin has great implications for reconstructing its tectonic history. The top and base of these intervals are readily identified on the 350+ km of seismic lines in the basin. The top of the rift-related interval is simply a horizontal datum at 0 seconds. The base of the rift interval and the top of the pre-rift interval is the uppermost strong reflection of the tuff package. The base of the pre-rift Tertiary interval is the Precambrian double reflection.

Isochron maps made for these intervals from published and unpublished seismic lines are Figures 10 and 11. Published seismic lines used in constructing the isochron maps are indicated on Figure 3. The maps are not intended to show detailed depth and structure of the basin; rather, they illustrate general trends of "thickening" or increasing of the two-way time intervals in the grabens and "thinning" or decreasing of the intervals across the central basement high. No depth conversion is offered because of the scarcity of well control. Faults or fault zones that offset reflections within the intervals are indicated by dashed lines. These maps compare favorably with gravity studies conducted in the area (e.g., Keller et al., 1984).

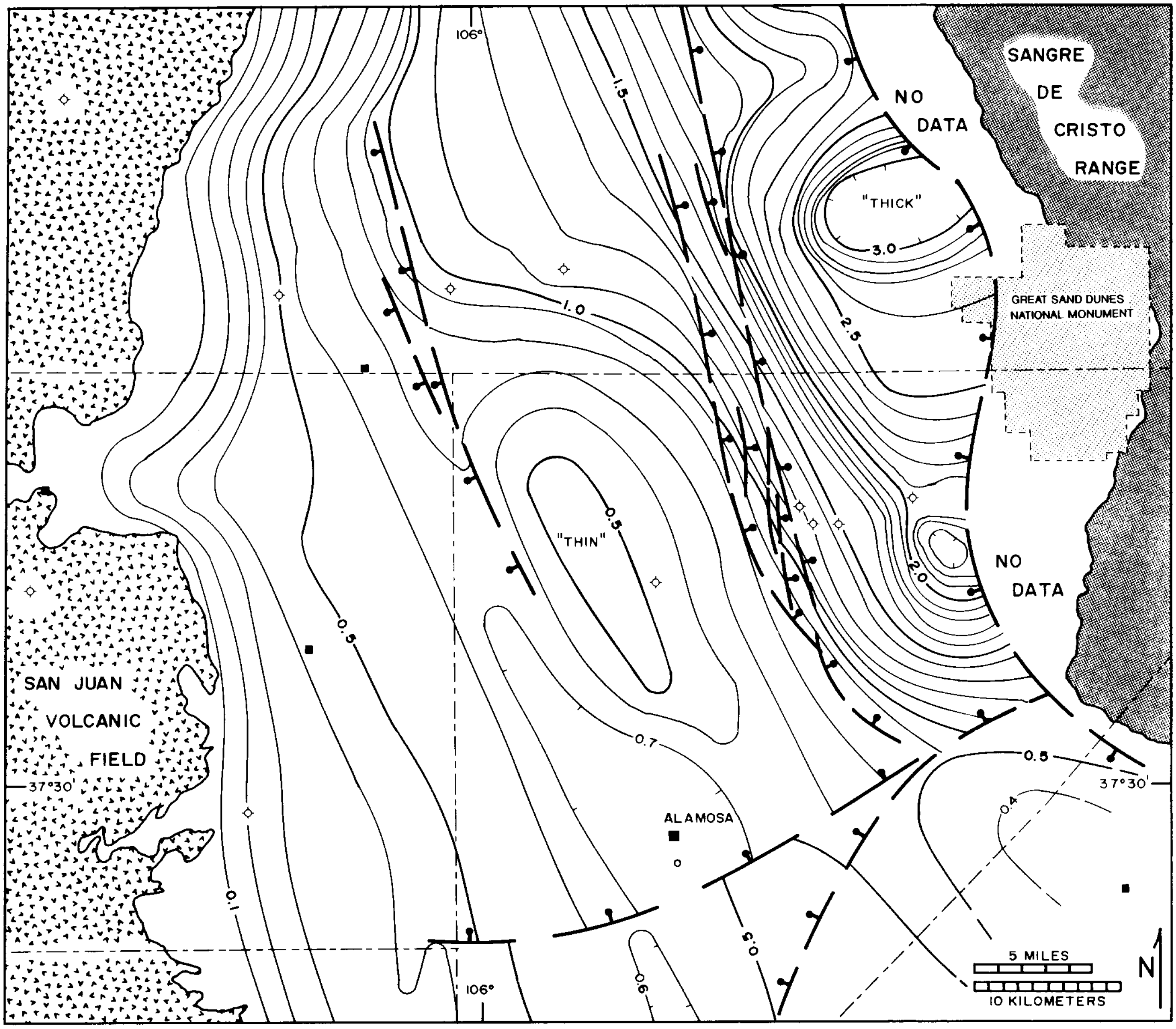

Figure 10. Isochron map: contoured two-way travel time interval between surface datum and top of Oligocene ash-flow tuff reflections. Fault zones depicted have demonstrated syn-rift displacement. Contour interval 0.1 seconds.

Rift-basin geometry

The rift-related architecture of the Alamosa basin is essentially that of a first-order, east-tilted half graben (Figs. 8, 9, 10). All pre-rift lithostratigraphic units have been tilted eastward; however, tilting within the Baca graben is more pronounced than in the Monte Vista graben. The western hinge of the first-order rift graben exists within the San Juan volcanic field, west of the depositional basin (Lipman, 1975; Phillips, 1985). The western edge of the depositional basin is where volcanic units of the San Juan volcanic field dip into the basin beneath the Santa Fe Group. Faulting along this margin is minor but has a distinctive style (Lipman, 1969). Faults generally have only a few meters or tens of meters of normal displacement and fault planes dip steeply to the west. However, due to the eastward dip of the beds, the net displacement of the volcanic rocks over the region is downward to the east.

The eastern boundary of the basin is the Sangre de Cristo fault zone. In plan view, it is concave towards the basin adjacent to the Great Sand Dunes National Monument. Farther south, the fault zone is convex toward the basin, forming the distinct promontory of the Blanca Peak massif. Based strictly on well control, the thickness of graben fill adjacent to the fault zone is at least 3 km. A seismic line by Stoughton (1977)

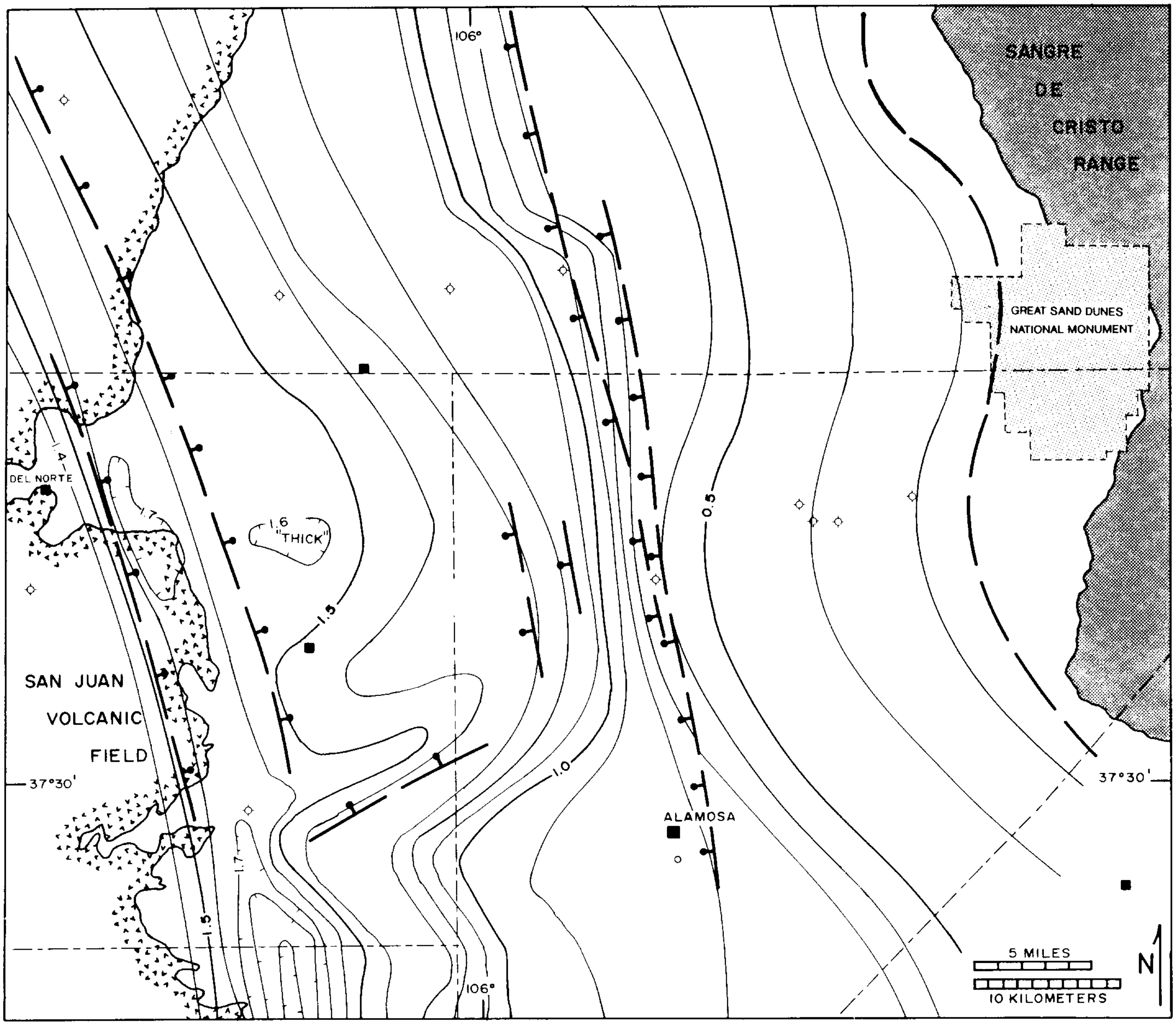

Figure 11. Isochron map: contoured two-way travel time interval between top of Oligocene ash-flow-tuff reflections and top of Precambrian reflections. Fault zones depicted have demonstrated pre-rift displacement. Contour interval 0.1 seconds.

indicates that the greatest thickness of fill exists in the Baca graben adjacent to the Sangre de Cristo fault zone near the Great Sand Dunes National Monument. A reasonable estimation of the depth of the basin at this locality is about 5.6 km. When the difference in elevation between the valley floor and the top of the Sangre de Cristo Range immediately adjacent to the dunes area (about 2 km) is added, the total vertical displacement of basement at the Sangre de Cristo fault zone is about 7.6 km. Basement relief has been estimated from gravity studies to be 7 km (Davis and Keller, 1978), approximately the estimate from seismic data in this paper. The fault plane dips steeply (>45°) to the west and remains steeply dipping to the depths of resolution on seismic lines.

The southern boundary of the Alamosa basin is a probable accommodation zone between the Alamosa basin and the San Luis Hills, an intrabasin horst block that brings Oligocene volcanic rocks to the surface. The Baca graben is truncated at this zone, accounting for the great increase in isochron gradient at that location in Figure 10. South of this zone, the eastern graben is deflected some 20 km eastward to form the Culebra reentrant (Fig. 1).

The Alamosa basin is divided into the two second-order half grabens by the central basement high, the Alamosa horst, which is not symmetrical. This north-trending feature is marked by high gravity and conspicuous thinning of syn-rift sediments. The eastern side of the "horst" is marked by a combination of strong eastward tilt of the basement and normal faults. The Alamosa horst is essentially the uptilted western edge of the east-tilted basement-cored crustal block flooring the Baca graben. The western margin of the "horst" is a hinge zone marked by monoclinal folding and less pronounced normal faulting of the ash-flow-tuff package (Figs. 2 and 8).

The high-gravity gradient on the western side of the Alamosa horst (e.g., Keller et al., 1984) is not the result of major rift-related block faulting as suggested by Tweto (1979) because faults along its western edge (Fig. 10) show relatively minor displacement of syn-rift units. Instead, the gravity gradient is attributable to pre-rift structural relief that developed along the eastern margin of the Paleogene precursor basin of the Monte Vista graben.

The syn-rift seismic interval over the horst area is "thinnest" west of the Amerada F-1 State well, but "thickens" northward along the trend of the horst. The basement high is not prominent on seismic lines in the northern part of the basin in the vicinity of the Carr #1 Kennedy Williams well (Stoughton, 1977). The positive gravity anomaly on Bouguer and residual gravity anomaly maps of Keller et al. (1984), thought to be a northern extension of the Alamosa horst, probably represents dense basement rock in this area. The only manifestation of the Alamosa horst in this location as seen in Figure 10 is a flattening of the east-sloping surface on top of the ash-flow-tuff package. Along the northern border of the study area, the Monte Vista graben and Alamosa horst essentially merge into an east-sloping bench, whereas the Baca graben continues to be a deep, narrow trough extending into the northernmost part of the San Luis Basin.

Pre-rift basin

Figure 11, the contoured two-way time interval between the top of the upper Oligocene tuffs and the top of the Precambrian, supports the observation that the area of the present Monte Vista graben was a depositional basin during the Paleogene. This basin was bounded on the east by a north-trending fault zone, paralleling a basement shoulder. This fault zone does not coincide exactly with the modern western margin of the Alamosa horst, but as mentioned above, is probably in part responsible for the steep gravity gradient between the present Monte Vista graben and the Alamosa horst.

The faults bounding the basin on the west, at about the longitude of Del Norte, are north-northwest trending. These faults created the structural relief that distinguishes the Del Norte high. Both the Blanco Basin and Conejos Formations appear to thicken eastward across this fault zone, indicating that it was active during their deposition. This fault zone was also active during rifting, but with an opposite sense of displacement. The Paleogene basin appears to end southward at about the latitude of Alamosa. Its northern extent is probably in the vicinity of the town of Saguache, Colorado.

DISCUSSION: TECTONIC DEVELOPMENT

Pre-Tertiary tectonic setting

No post-Precambrian, pre-Eocene, strata exist in the boreholes studied. During the early and middle Paleozoic, the San Luis Basin region was part of a broad highland that lay to the south of the east-west–trending central Colorado sag of Eardley (1951, Plates 3, 4). Unfortunately, little evidence of the uplift or of deposition along its flanks has survived later tectonic events (Ross and Tweto, 1980). Parts of this highland were reactivated in Pennsylvanian to Permian time as the Uncompahgre–San Luis highland (Tweto, 1980), apparently bounded on the east by reactivated Precambrian structures (Sutherland, 1972; De Voto, 1980). This uplift was responsible for the coarse synorogenic deposits of the Sangre de Cristo Formation exposed in the Sangre de Cristo Range east of the Alamosa basin (De Voto, 1980). Denudation of the uplift continued until the Jurassic, when Middle to Late Jurassic nonmarine deposits lapped onto the old highland, eventually inundating it (Berman et al., 1980). Cretaceous nonmarine and marine strata were deposited over the area (Haun and Weimer, 1960) until onset of Laramide tectonism in latest Cretaceous time.

Laramide history

The Laramide orogenic event, extending from late Campanian into Eocene time, was a period of uplift and erosion in a broad region including the San Luis Basin–Sangre de Cristo Range area and the Brazos uplift (Tweto, 1975), collectively referred to here as the San Luis–Brazos uplift. Two pulses of uplift are recorded in the synorogenic sedimentary deposits of the San Juan sag and San Juan Basin. The first pulse, marked by the Animas Formation (Upper Cretaceous–Paleocene), initiated uplift of the region and stripping of post-Precambrian strata from the San Luis–Brazos uplift. The Animas Formation contains volcanic detritus recording nearby Laramide volcanic activity, but it becomes increasingly arkosic upwards in its section, indicating that the uplift was being unroofed to expose its Precambrian core (Brister and Chapin, 1994). The known fault style of the eastern part of the uplift was that of west-dipping reverse faults that flatten at depth (Lindsey et al., 1983) and low-angle thrust faults (Schavran, 1984). The Del Norte high is probably a remnant of the western flank of the uplift.

An angular unconformity between the Animas and the Blanco Basin Formations indicates that a second pulse of tectonic activity began in late Paleocene, extending into the Eocene (Cather and Chapin, 1990). North-northeast translation of the Colorado Plateau during late Laramide time resulted in wrenching in a north-south zone along the axis of the Southern

Rocky Mountains in New Mexico and Colorado (Chapin and Cather, 1981; Chapin, 1983) and north-south compression within uplifts in Wyoming (Gries, 1983, 1990). This episode involved reactivation of the western margin of the San Luis–Brazos uplift due to development of a wrench-fault system, creation of a basin over the western half of the former uplift, and rejuvenation of sedimentation westward into the San Juan sag–San Juan Basin areas (Brister and Chapin, 1994).

The Blanco Basin Formation depocenter, which was probably wrench-fault related (Brister and Chapin, 1994), formed within the western part of San Luis–Brazos uplift. This basin is classified as an Echo Park–type basin (terminology of Chapin and Cather, 1981) or as an axial basin (Dickinson et al., 1988). The Eocene basin was approximately 20 to 25 km wide and at least 60 km long in a north-northwest trend with its thickest preserved deposits existing along the fault system on the west side. It may have had an open drainage connection to the San Juan sag to the west.

The effect of 30+ m.y. of Laramide uplift and erosion of the San Luis–Brazos uplift was to subdue the mountain chain and fill the adjacent basins, resulting in the development of a wide-ranging, low-relief, geomorphic surface in the region (Steven, 1975), referred to as the late Eocene erosion surface of Epis and Chapin (1975). This surface is now buried deeply beneath Oligocene volcanic strata; it was developed on the Blanco Basin Formation in the western half of the basin and the eroded Precambrian basement in the eastern half. An unconformity marks the late Eocene erosion surface between the top of the Blanco Basin Formation and volcaniclastic rocks of the basal Conejos Formation. There is only minor angularity visible between the two formations on seismic lines. Most drill cuttings from the lowermost Conejos Formation contain minor amounts of basement detritus, either removed from remnant high areas or reworked from Blanco Basin sediments. Oligocene stream channels eroded into the Eocene surface in Colorado have been described by Epis et al. (1980).

Oligocene volcanism

The Oligocene was a time of widespread andesitic volcanism in a north-trending band along the axis of the Southern Rocky Mountains. This period of volcanism has been attributed to rising magmas in a continental-arc tectonic setting during a change from a flat-dipping to a steep-dipping subduction zone along the western North American margin (Lipman, 1983a). During this event, several kilometers of volcanic rocks were deposited in the San Juan volcanic field. As illustrated in Figures 2 and 8, the faults bounding the Paleogene basin in the western half of the Alamosa basin were reactivated during Conejos deposition.

By 29 Ma, a period of extension had begun in southern Colorado, marked by north-northeast–trending dikes in the San Luis Hills mapped by Bartlett (1984) and dated by Burroughs (1972). Volcanism accompanying this early period of extension was primarily associated with caldera formation in the San Juan volcanic field and emplacement of regional ash-flow sheets, such as those deposited across the Alamosa basin. This early extension preceded development of rift-related half grabens.

Neogene rifting

Indicators of the beginning of the Rio Grande rift event have been discussed in some detail by Chapin (1971, 1979, 1988). Initiation of rifting in the Alamosa basin is fairly well constrained by the stratigraphy of its western margin. Structures directly associated with rifting were not active until after emplacement of the uppermost Oligocene ash-flow tuff (Carpenter Ridge Tuff, 27.35 Ma, Lipman, 1989). Several lines of evidence support this conclusion. First, there is no evidence that the pre-27-Ma ash-flow sheets ponded in areas soon to become grabens. Secondly, sediments deposited between the ash-flow sheets thin eastward, indicating that the Baca graben had not yet begun to form. Where these sediments are thickest is in an area of structural sagging along the western edge of the present Monte Vista graben. There is no evidence that sagging in that vicinity continued after initiation of rifting. Also, where faults cut the Oligocene tuffs, they cut across the entire package. As seen on reflection seismic lines, the lower tuffs in the package are not more highly faulted than upper tuffs. This indicates that the entire tuff package was emplaced prior to significant local rift faulting.

The rift event began at about 27 Ma. This conclusion is supported by several observations. At about this time, the composition of regional volcanism changed from dacitic to basaltic. The Hinsdale basalts (as old as 26.8 Ma) lie atop the ash-flow tuffs of the San Juan volcanic field in angular unconformity (Lipman and Mehnert, 1975; Lipman, 1975, 1976). Following emplacement of the basalts, the eastern edge of the San Juan volcanic field was uplifted, tilted eastward, and deeply eroded. Other dated evidence for initiation of rifting is the 26.5-Ma Amalia Tuff (Lipman et al., 1986; Lipman, 1988) interbedded with the Los Pinos Formation in the Tusas Mountains along the west side of the southern San Luis Basin (Lipman, 1983b; Manley, 1981).

During early rifting the eastern half of the Alamosa basin was progressively tilted eastward along the Sangre de Cristo Range. The Sangre de Cristo fault zone was probably controlled by the thrust root zones of the Laramide San Luis uplift (Sales, 1983). Seismic lines and cross sections illustrate episodic faulting on the basin-bounding faults during the rift event. This is demonstrated in angular relationships within the lower Santa Fe Group and the cyclic pattern of alternating coarse and fine deposition. Streams flowing from the San Juan volcanic field carrying a coarse volcanic load emptied into the Alamosa basin, developing alluvial fans at their mouths, perhaps much like the modern alluvial fan constructed where the Rio Grande enters the San Luis Basin at the town of Del

Norte. A broad piedmont extended as a veneer eastwards across the western half of the basin towards the eastern (Baca) narrow graben.

The Sangre de Cristo Range also supplied material to the basin. Shorter, steeper alluvial fans were constructed along the eastern margin of the Baca graben. Rift half grabens such as the Baca graben tend to develop axial drainage systems that closely parallel the faulted margin of the graben due to increased subsidence along the margin (Leeder and Gawthorpe, 1987; Mack and Seager, 1990). The sediment load from alluvial fans is redistributed within such axial stream systems. This probably accounts for the mix of Precambrian and volcanic detritus in the lower Santa Fe Group of the Baca graben. The fault-slice of lower Santa Fe Group cropping out on the western edge of Blanca Peak (Urraca outcrop, Fig. 3) contains current indicators suggesting stream deposition parallel to the basin margin. Recent fission-track dating of apatite in Precambrian rocks making up Blanca Peak indicate rapid uplift of the Blanca massif between 28 and 18 Ma (Kelley, 1990). This probably coincided with rapid subsidence and eastward tilting of the Baca half graben.

The angular unconformity visible in Figure 9 is evidence for a change in fault activity and degree of tilting of the Baca graben. Sediments above this unconformity are only gently tilted, and not as intensely faulted as the lowermost package of Santa Fe rocks. The basin-spanning coarse units above the lower Santa Fe Group (Fig. 6) represents response of drainage systems to this period of truncation of previously deposited sediments. By about 4.5 Ma, the through drainage from the northern to southern parts of the San Luis Basin was impeded by the intervening Servilleta flood basalts of the Taos Plateau. Internal drainage created conditions for fluviolacustrine sedimentation common to the Alamosa Formation (Rogers et al., 1992).

Elsewhere in the rift at this time, basins were being integrated into the ancestral Rio Grande. By middle Pleistocene time, integration of the upper Rio Grande drainage system with the lower Rio Grande system (Gulf of Mexico terminus) in the Trans-Pecos Texas region below El Paso, caused lowering of base levels, dissection of basins, and stranding of geomorphic surfaces (Gile et al., 1981). The Rio Grande integrated basins as far north as Red River of New Mexico (Wells et al., 1987). The Servilleta basalts north of the Red River and the San Luis Hills horst served as a hydrologic divide until middle to late Pleistocene when the Rio Grande was able to erode a gorge through these barriers. This event occurred after 0.69 Ma, the youngest documented age of the Alamosa Formation (Rogers et al., 1985), but before 0.3 Ma (Wells et al., 1987).

ACKNOWLEDGMENTS

This paper resulted from a dissertation by the senior author at the New Mexico Institute of Mining and Technology, which was directed by Charles Chapin and funded by the New Mexico Bureau of Mines and Mineral Resources. The authors wish to thank Charles Chapin and Chuck Kluth for their critical reviews. We also thank Steve Cather, Matthew Golombek, John Hawley, Raymond Ingersoll, and Peter Lipman for suggestions that improved the manuscript. Amarex Inc. and Reserve Oil provided seismic data and Randy Ray contributed the synthetic seismogram.

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Manuscript Accepted by the Society October 13, 1993