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SUBSURFACE GEOLOGY AND RELATED HYDROLOGIC CONDITIONS, SANTA FE EMBAYMENT AND CONTIGUOUS AREAS, NEW MEXICO

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Abstract—The Santa Fe embayment, a structural element of the Rio Grande rift-related Española basin, is the site of substantial new development, population growth and burgeoning demand on ground-water resources. Within or bounding the Española basin are four major related geohydrologic components with unique structural and stratigraphic attributes. These components are uplifts, deep rift basins, and the northern and southern Santa Fe embayments. Sediments of the Tesuque and Ancha formations are the primary aquifer containing large volumes of fresh ground-water that supply or supplement water use for the region's inhabitants. These syn-rift deposits, part of the Santa Fe Group, are hydraulically connected and generally constitute a superior unconfined aquifer of regional extent, except where they were not deposited on the uplifts and over laccoliths of Oligocene age in the subsurface of the southern embayment. Recent geophysical investigations of the Jemez Mountains and assessments of ancestral Rio Grande deposits in the Española basin suggest that larger volumes of ground-water may be moving through these aquifers from those regions into the Albuquerque basin than previously surmised. In some parts of the southern Santa Fe embayment, substantial increases in demand for ground-water must inevitably be met by alternate sources of water imported from outside of the embayment.

GENERAL GEOLOGY

The Española basin (Fig. 1) occupies a structural low between the Colorado Plateau to the west and the Great Plains to the east. Laramide crustal shortening may have produced a regional topographic welt stretching from the Nacimiento Mountains to the Sangre de Cristo range, but Neogene–Quaternary rifting has structurally inverted this welt forming the current basin. The Galisteo Formation of Eocene age, consisting of alternating beds of mudstone, sandstone, and conglomerate deposited in fluvial channels and floodplains, was deposited in syn-Laramide basins on the flanks of, and possibly within the Española basin. This paper treats the syn-Laramide Galisteo (Hagan) basin as a part of the Española basin. Up to 4700 ft (Lisenbee, 1976) of Galisteo Formation were deposited to localities roughly south and east of Golden. It disconformably or unconformably overlies sediments ranging in age from Mississippian through Cretaceous. On the mountain flanks and in the subsurface of the eastern part of the Santa Fe embayment it was deposited on the eroded surface of Precambrian rocks. It, and later Tertiary deposits, effectively mask the underlying bedrock, making interpretation of the subsurface geology difficult.

A period of volcanism followed Laramide compression during the Oligocene Epoch between 34 and 24 Ma. One of the largest volcanic centers was centered in the San Pedro-Ortiz-Cerrillos-La Cienega region. In the Galisteo basin portion of the Santa Fe embayment as much as 2000 ft of bluish-gray volcaniclastic breccia, conglomerate, mudstone, sandstone, volcanic flows, and water-laid airfall tuffs were deposited (Disbrow and Stoll, 1957). This material, the Espinaso Formation, unconformably overlies the Galisteo Formation in the Cerillos Hills, but the two units are transitional in the Hagan basin to the south (Gorham and Ingersoll, 1979). Large and extensive laccolithic intrusions of igneous material that extend radially outward from the Ortiz-Cerrillos igneous complexes are present in the Galisteo basin-Santa Fe embayment, where they were injected into older sediments. Locally, the laccolithic Cerrillos Hills were responsible for deforming the pre-Oligocene Española basin upward in its center, forming synclines on both sides. The eastern depression became the Santa Fe embayment, and most of the western one foundered during Miocene rifting into a deep northern part of the Albuquerque basin.

Rifting began in the early Miocene, about 20–24 Ma, inaugurating a number of substantive geologic events. Rift flanks including the Sandia, Sangre de Cristo, and Manzano Mountains were uplifted (Kelley and Duncan, 1984; Baltz, 1978; Galusha and Blick, 1971). Faulting and segmenting of the basins between many of these uplifts commenced, collectively defining the Rio Grande rift. As rifting continued the pre-Miocene rocks were faulted, tilted and eroded as the syn-rift basins filled with eolian and fluvial deposits of the Santa Fe Group. Based on evidence from deep wells and geophysical data, Santa Fe Group sediments filled the rift valley adjacent to the Sangre de Cristo Mountains north and west of Santa Fe with up to 5000 ft of clastic material. These sediments are the partly consolidated Tesuque Formation (or its time equivalent) that, depending upon the area, overlies rocks ranging in age from Precambrian to Oligocene in the Santa Fe embayment and throughout the Rio Grande rift. Gravity data (Keller and Cordell, 1983) imply as much as two times this thickness accumulated in the deeper rift troughs under the present course of the Rio Grande.

Events of the last several millions of years include continued fault movement, eruptive episodes in the Jemez Mountains and Cerros del Rio region east of the Rio Grande, continued erosion of uplifted regions and the integration of the Rio Grande as a south-flowing axial drainage. Up to 300 ft of piedmont-slope gravels, sands, and silts containing mostly Precambrian clasts were deposited in the Santa Fe embayment south of the Santa Fe River. These alluvial floodplain and fan deposits of the Pliocene Ancha Formation rest on an erosional surface that bevels the tilted and moderately faulted beds of Tesuque and pre-Tesuque rocks.

The southern Sangre de Cristos and eastern margin of the Galisteo basin-Santa Fe embayment were not profoundly affected by rift extension taking place to the north and west, and they are structurally comparatively uncomplicated. It is unlikely that there are major rift bounding faults along the western boundary of the Sange de Cristo uplift.

Many investigators have described structural and stratigraphic components within the study area (Fig. 1). Especially germane is work by Kelley (1978, 1979) that explains the surface geology of the Española basin, extrapolates subsurface conditions and describes in detail the Tertiary sediments that fill the basin. Baltz (1978) and Manley (1979) contributed excellent resumes of structure and stratigraphy in this region. Other data that contributed to interpreting the complex subsurface geology include: (1) a regional Bouger gravity map by Keller and Cordell (1983); (2) a composite residual total intensity aeromagnetic map by Cordell (1983); (3) an isostatic residual gravity anomalies map by Heywood (1992); (4) the results of several years' investigations by a Los Alamos National Laboratories sponsored field training program for student geophysicists (Summer of Applied Geophysical Experience/SAGE); (5) information obtained by a reflection seismic program conducted by an oil company in the 1970s; and (6) several deep oil tests, including the Yates Petroleum No. 3 La Mesa Unit in sec. 13, T15N, R8E, Yates Petroleum No. 2 La Mesa Unit in sec. 24, T17N, R8E, John Gianardi No. 1 CKZ in sec. 22, T15N, R8E, and Trans Ocean No. 1 McKee in sec. 4, T13N, R9E.

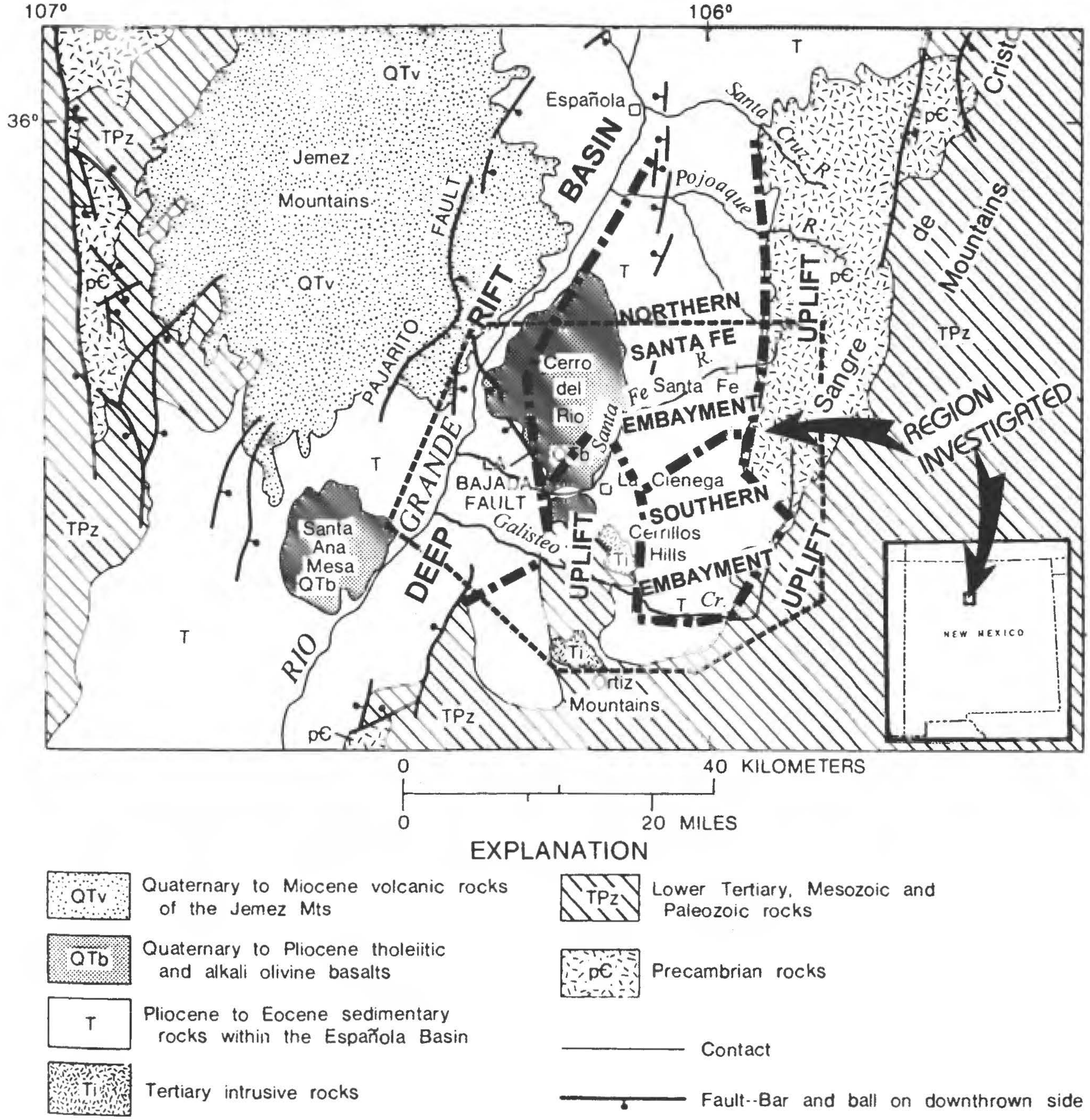

FIGURE 1. Index map and generalized geology of the Santa Fe embayment. Modified from Manley (1979). Thick dashed lines denote Española subbasin boundaries.

STRUCTURE

Santa Fe embayment

The Bouger gravity map by Keller and Cordell (1983), when overlain on the Rio Grande tectonics map of Kelley (1979), clearly indicates that the Galisteo basin-Santa Fe embayment element of the Española basin is structurally related to the Estancia basin south of it more than to any segment north of it. Rather than being a Rio Grande rift block, the Española basin south of Santa Fe is a relatively undeformed northerly extension of the Estancia basin syncline, with a structural saddle and the Cañoncito-Tijeras fault separating the two depressions.

Pre-Tertiary sedimentary bedrock exposures in the Galisteo basin-Santa Fe embayment are severely limited by Tertiary cover north of the Cañoncito-Tijeras fault. They are restricted to a narrow band of outcrops about 2.5 mi long, just north of Galisteo Creek where Cretaceous, Jurassic, Triassic, Permian and Pennsylvanian rocks are exposed southwest and northeast of Lamy. Some isolated Pennsylvanian outcrops are present on the west flank of the Sangre de Cristo Mountains.

The oil test wells and reflection seismic data imply that pre-Tertiary rock units in the Galisteo basin-Santa Fe embayment were beveled to the Precambrian basement by erosion during the Laramide orogeny. This erosion is evident between the Yates No. 3 and Yates No. 2 wells (Fig. 2). The orientation of the axis of this older uplift was northwest–southeast and was located several miles west of the present mountain range (Fig. 3).

Faulting and fracturing of consolidated bedrock might be expected beneath the Tertiary cover in the embayment, especially near the mountain front. Minor faults may be present, but major faults in these pre-

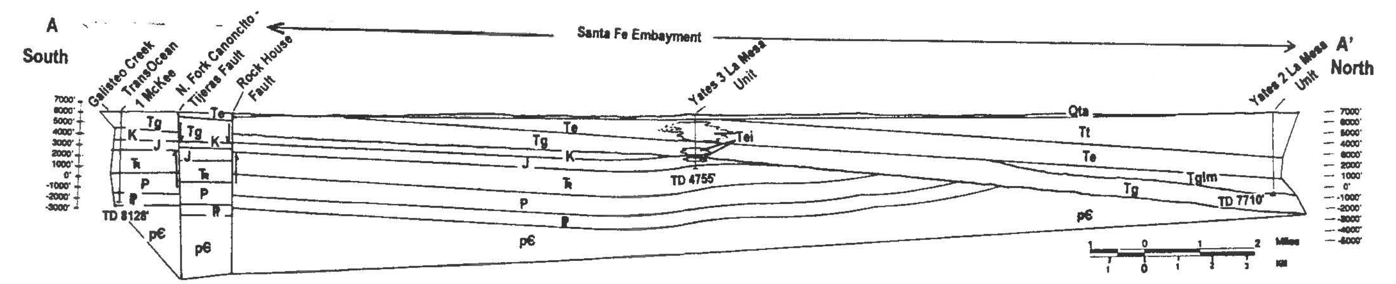

FIGURE 2. Cross section A–A' south to north through the Santa Fe embayment. See Figure 4 for location of cross section.

Tertiary horizons are not necessary to achieve these subsurface relationships, nor are they evident in the geophysical data.

The Santa Fe embayment was part of a much larger depression, with its western margin in the vicinity of the Nacimiento uplift through Eocene time. After the thick sequence of rocks of the Galisteo Formation filled it, volcanic activity commenced in early Oligocene time that severely modified its configuration. The range of low hills and mountains extending north from the vicinity of Golden through La Cienega are mostly laccolithic intrusions. Various igneous rocks were injected into sedimentary units at least as old as Jurassic in the western part of the present embayment (Fig. 2) as well as in the Cerillos Hills. Collectively, the intrusions and large volumes of extruded material are part of the Ortiz porphyry belt. Volcanic fans extending from the volcanic centers are designated as the Espinaso Formation (Disbrow and Stoll, 1957).

The intrusions bowed the overlying rocks upward, forming a structural rise that divided the single syncline into two. The eastern syncline is the present Santa Fe embayment. Part of the western element is preserved between the Cerrillos Hills and the La Bajada fault, but most of this portion foundered during subsequent rifting and is now at great depths in the Santo Domingo sub-basin of the Albuquerque basin. The geophysical map of Keller and Cordell (1983) indicates that the Precambrian basement was also structurally raised on the intrusive alignment.

The Santa Fe embayment plunges north in the subsurface on top of the pre-Tertiary unconformity. Of interest, however, is that there is no major structural relief on the Precambrian basement in the embayment's center. A deep oil test, the Trans Ocean No. 1 McKee in C NW¼ NE¼ sec. 4, T13N, R9E, is just south of the Canoncito-Tijeras fault and roughly in the center of the structural saddle separating the Santa Fe embayment north of it from the Estancia basin to the south. It bottomed at 8128 ft in Pennsylvanian Madera Limestone, about 200 ft above where Precambrian rocks would be expected at 2400 ft below sea level. Ten and one-half miles north, in the center of the embayment, the Yates No. 3 La Mesa Unit well in NE¼ NE¼ NE¼ sec. 13, T15N, R8E bottomed at 4755 ft in Triassic rocks, suggesting Precambrian rocks are at about 9600 ft (3300 ft below sea level). A projection of the depth to the Precambrian basement in the vicinity of the Yates No. 2 La Mesa Unit well in the NW¼ NW¼ SE¼ sec. 24, T17N, R8E, based on geophysical data and well samples, indicates that granite would be encountered at about 9000 ft beneath a sedimentary package that includes nothing but Tertiary rocks, or at about 2400 ft below sea level.

These wells suggest less than 1000 ft of structural relief on the Precambrian basement in a south–north distance of 21 mi through the center of the embayment. In this interval more than 8000 ft of older Mesozoic and Paleozoic strata have been eroded and replaced by similar thicknesses of Tertiary rocks.

Comparatively flat in its center, the embayment steepens on its east side. About 5 mi west of Precambrian outcrops near the junction of I-25 with US-285, gravity data (Keller and Cordell, 1983) show a steepening of contours into the basin, which could indicate a fault downthrown to the west or, more likely, the rapid thickening of Paleozoic and Mesozoic strata as these units are encountered below the Tertiary-Eocene-Galisteo erosion surface.

Española basin-Buckman bench?-northern Santa Fe embayment

Most structure maps, including Kelley's (1978, 1979), show the La Bajada fault west of the basalt-capped Cerros del Rio volcanic field. From the east side of the Hagan bench-embayment north to cross the Rio Grande several miles north of Cochiti Dam, and terminating about 3 mi southeast of St. Peter's Dome, it is downthrown to the west. It is presumed to be a basement fault that separates the Santo Domingo part of the Albuquerque basin from the southern part of the Española basin.

Faults are conspicuous in the surface rocks at the northern end of the Albuquerque rift basin, but there is little direct evidence that all of them are basement faults. On most maps the La Bajada fault is shown terminating at its northern end west of the Rio Grande and less than 2 mi from the Pajarito fault. In this area, the Pajarito fault is east of St. Peter's Dome and is sharply downthrown in that direction. Both faults are presumed to penetrate basement rocks and are considered to be major rift boundary faults, with the Pajarito fault defining the (restricted) western side of the Española basin and the La Bajada fault edging the eastern side of the Santo Domingo sub-basin of the Albuquerque basin. In order to "fit" geologically, these two faults would have to join with a "scissors" at the northern end of the La Bajada fault, with it becoming downthrown to the east at this point (which a close examination of Kelley's 1978 map shows) or for the two to be separated by a very narrow graben. The former would make the La Bajada fault become a "stair-step" fault on the Española basin's west side, with the deepest depression east of it, and require either another fault downthrown to the west farther east, or a very steeply west-dipping shelf to mark the boundary between the deepest basin and the Santa Fe embayment. The graben explanation would require the presence of a constricted and structurally unreasonable fault-bounded feature that would need to be extended and opened northward to accommodate the deep part of the Española basin.

It would be more appropriate and geologically sound to depict the La Bajada fault trending northeast instead of northwest from several miles north of the mouth of the Santa Fe River, and extend it beneath the Cerros del Rio volcanic field to a point approximately between Española and Chimayo that is the eastern boundary of the Española basin in this area. This interpretation would conform with the gravity map of Keller and Cordell (1983) and the model of the Albuquerque-Española basins part of the Rio Grande rift presented by Heywood (1992). It would place the main body and deepest part of the Española basin west of the Rio Grande, bounded by the Pajarito fault on the west and the La Bajada fault on the east. It would also make a structural, synclinal "bench," relatively undeformed by rifting, out of the large region east of the river through the southern end of the Santa Fe embayment. And it would open the Española basin directly to the Albuquerque basin south of it. There is precedent in the rift, where a similar basin-uplift configuration occurs in the southern Albuquerque basin on the Hubbell bench, which is hinged on the east, flattens to the west, drops sharply into a deep basin west of it, and defines its deepest basin elements by major fault relief on its western boundary.

Rapid thickening of Tertiary sediments occurs on the piedmont (here named the Buckman bench for a Rio Grande crossing east of White Rock and about 15-mi northwest of Santa Fe) northwest of I-25 between the river and Santa Fe. In the Yates No. 2 La Mesa unit well 5 mi west of Santa Fe, the Tertiary suite is estimated to be about 9000 ft thick, at least 4000 ft of which is rift-related Tesuque Formation. Seventeen kilometers south, in the Yates No. 3 La Mesa Unit oil test near the center of the Santa Fe embayment, the entire Tertiary package is about 3800 ft thick, less than 300 ft of which is material in the Tesuque-Ancha formations that was deposited contemporaneous with rifting.

Placing a fault between these wells to account for the Tesuque sediments absent in the southern well and separating the embayment from the bench, would not be unreasonable, but there is no other supporting data. Noted however, is that Spiegel and Baldwin (1963, p. 70–71, pl. 5) described a northeast–southwest-trending fault, downthrown to the north, south of the Santa Fe River. They indicated that its placement could not be supported by the limited geophysical data available to them and, if it was present, probably had a displacement of not more than a few hundreds of feet.

Of interest is the observation that northwest of the Buckman bench-Santa Fe embayment in the expanded region of the Española basin that includes the Abiquiu embayment, structural conditions mirror those described here. Baldridge et al, (1994, p. 1538) determined that, "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-trending Embudo (Pajarito) transfer fault, which appears to act as the northern bounding fault of the main basin." These data support the premise that both embayments are relatively unaffected by rifting and were previously joined across the present deep (rift) basin as part of the larger Laramide Chama-Estancia basin.

Española basin

Manley (1979, p. 71) describes the southern part of the Española basin as structurally "separated from the Santo Domingo sub-basin (of the Albuquerque basin) to the south by the northwest-trending La Bajada fault, which has displacement down to the southwest." As suggested above, the La Bajada fault may not be present here, and the two basins may not be significantly separate from one another.

Gravity information (Keller and Cordell, 1983; Heywood, 1992) indicates that the Rio Grande rift between Abiquiu on the north and San Acacia to the south is a single element separated by several inter-depression structural highs that, for the most part, are deeply buried. The structural basement high separating the Española basin from the Albuquerque-Santo Domingo basin is beneath St. Peter's Dome. This is evident on the gravity map as well as in outcrops on and near the dome where rocks in the Galisteo Formation of lower Tertiary age are exposed.

It is doubtful, however, that basement elements effectively or efficiently "seal off" the subsurface basins from each other, at least hydrologically. As suggested by Hawley and Grant (1997, p. 60), "...the Albuquerque geohydrologic basin is not isolated from the Española basin to the northeast, the 'Valles-Toledo' basin to the north, or the Socorro-La Jencia (Popotosa) basin to the south." If most of the rift basins are intimately interconnected, it could have a profound influence on depicting the geohydrology of the region.

STRATIGRAPHY

Introduction

The Española basin and nearby regions have been the focus of significant and detailed investigations of Tertiary stratigraphy. Perhaps the most specialized of these are encountered in publications by Bryan (1938), Stearns (1943, 1953), Galusha and Blick (1971), Spiegel and Baldwin (1963), and Kelley (1978). Although highlighting the Albuquerque basin, a Ph.D. dissertation by Lozinsky (1988) contains a wealth of detail on Tertiary sediments and their depositional processes.

The deep oil tests in the Santa Fe embayment not only tend to confirm basement structural configurations represented in the geophysical map of Keller and Cordell (1983), but also show that as Precambrian rocks dip into the subsurface on the western flank of the Sangre de Cristos, geologically younger beds of Paleozoic and Mesozoic age are encountered beneath the Tertiary in a westerly and southwest direction from the mountains (Fig. 3). On the western side of the embayment, a relatively complete suite of Mesozoic and Paleozoic rocks through the Pennsylvanian are present. North and west of the Cerrillos Hills and beneath the Jemez Mountains, Mesozoic rocks were probably stripped by Tertiary erosion, but Paleozoic sediments, absent in the northeastern Española basin, are present beneath the Jemez Mountains and in the Abiquiu embayment. These wells also reveal lithologic packages in Tertiary formations that have not been encountered elsewhere in the region.

Galisteo Formation

The lowermost unit of Tertiary rocks was derived by erosion of the initial rise of the Sangre de Cristo and Nacimiento Mountains during the Eocene epoch (55–37 Ma). While the pre-Tertiary strata on these uplifts were being eroded, the region between them sagged to form a large syncline of regional extent within which sediments of the Galisteo Formation were deposited on a low-relief eroded surface of truncated Mesozoic and Paleozoic sediments and Precambrian rocks.

The Galisteo Formation was first described by Hayden (1873) and was mapped and redefined by Stearns (1943), who established its age based on fossil evidence. The formation is mostly fluviatile in origin, and is composed of red and white sandstones, conglomerate, clay, some limestone, and water-laid tuff. Petrified wood is common in outcrops near Cerrillos. In many outcrops the beds are severely deformed, so that complete thicknesses are difficult to obtain. Near La Cienega, Spiegel and Baldwin (1963) measured 1300 ft of red-brown sandstone and mudstone with some conglomerate beds. Disbrow and Stoll (1957) mapped deposits of Galisteo near La Bajada and Cerrillos, where the formation was about 3000 ft thick. The greatest thickness is reported by Lisenbee (1976), who estimated 4700 ft are present north of the Canoncito-Tijeras fault northwest of Galisteo. Rocks of Galisteo age were encountered in deep oil tests in the Albuquerque basin, where thicknesses approach 1500 ft (Lozinsky, 1988).

About two-thirds of the formation is well-indurated, generally calcite-cemented, clay-filled sandstone and conglomerate. The rest is multicolored but predominantly red clay and shale. Clasts of the coarser material are varied, consisting of chert, chalcedony, quartz, quartzite, granite, gneiss, schist, porphyry, and limestone that, in this region, were most likely derived from erosion of Precambrian granites and Pennsylvanian Madera limestone in the nearby Sangre de Cristo Mountains.

Stearns (1943) said that much of the detritus was delivered from the source area by streams of considerable volume and gradient to the

Galisteo basin, where it was deposited in river channels, flood plains, and temporary lakes. In a generic description of the formation, Stearns (1953, p. 467) reported that it "...comprises 900 to at least 4000 ft of sandstone, sand, clay, and shale, generally variegated in color, with minor amounts of conglomerate, fresh-water limestone (emphasis added), and water-laid tuff. The beds were deposited by rivers flowing into and through a broad basin, which was deepened and enlarged by warping contemporary to deposition." Galisteo rocks are overlain gradationally by volcanics of the Espinaso Formation in the Hagan basin, but these units are separated by an unconformity elsewhere (Gorham and Ingersoll, 1979).

"La Mesa Limestone"

Five miles west of Santa Fe, in the NW¼ NW¼ SE¼ of sec. 24, T17N, R8E, Yates Petroleum Co. drilled a 7710-ft-deep petroleum exploratory well in the spring of 1985. The No. 2 La Mesa Unit well began in beds of the Tesuque Formation and bottomed in rocks here interpreted as the Galisteo Formation.

In the interval between 6018 and 7534 ft, the well encountered more than 1500 ft of white to light gray and tan, soft, chalky, dense, fossiliferous limestone, interbedded with generally fine- to coarse-grained, angular-to-sub-angular, friable white sandstone and dark gray (some brick red), soft, micaceous shale. Limestone is the major constituent in this interval. The fossils are primarily fragments of Paleozoic taxa. Electric logs show the limestone to occur in beds less than 15-ft thick, separated by shale and sandstone.

A limestone sequence like this is unknown elsewhere in the Rio Grande rift. Its location in the section, immediately below more than 2000 ft of volcanic rocks that may be the Espinaso Formation (see below) strongly suggests these rocks are the Galisteo Formation. Beneath the limestone section, in the interval from 7533 ft to total depth of 7710 ft, is a friable, fine- to coarse-grained, angular, glassy clastic material, with orange-stained fractured grains characteristic of some Galisteo Formation sandstones, that occupies the appropriate stratigraphic position for the Galisteo Formation.

Espinaso Formation

Kautz et al. (1981) described these rocks in detail in the type locality on the Espinaso Ridge in the Hagan embayment. Here, they are volcanic detritus up to 1410 ft thick eroded from eruptive centers in the Ortiz Mountains and Cerrillos Hills. In this area, the section is conformable and transitional with the underlying Galisteo Formation, and is overlain unconformably by the Neogene Santa Fe Group or related strata. It primarily consists of braided stream, water-laid immature volcaniclastic sandstones, conglomerates, and boulder conglomerates interbedded with matrix-supported, pebble-to-boulder, debris-flow deposits. Some air-fall and ash-flow deposits and lava flows are interbedded locally.

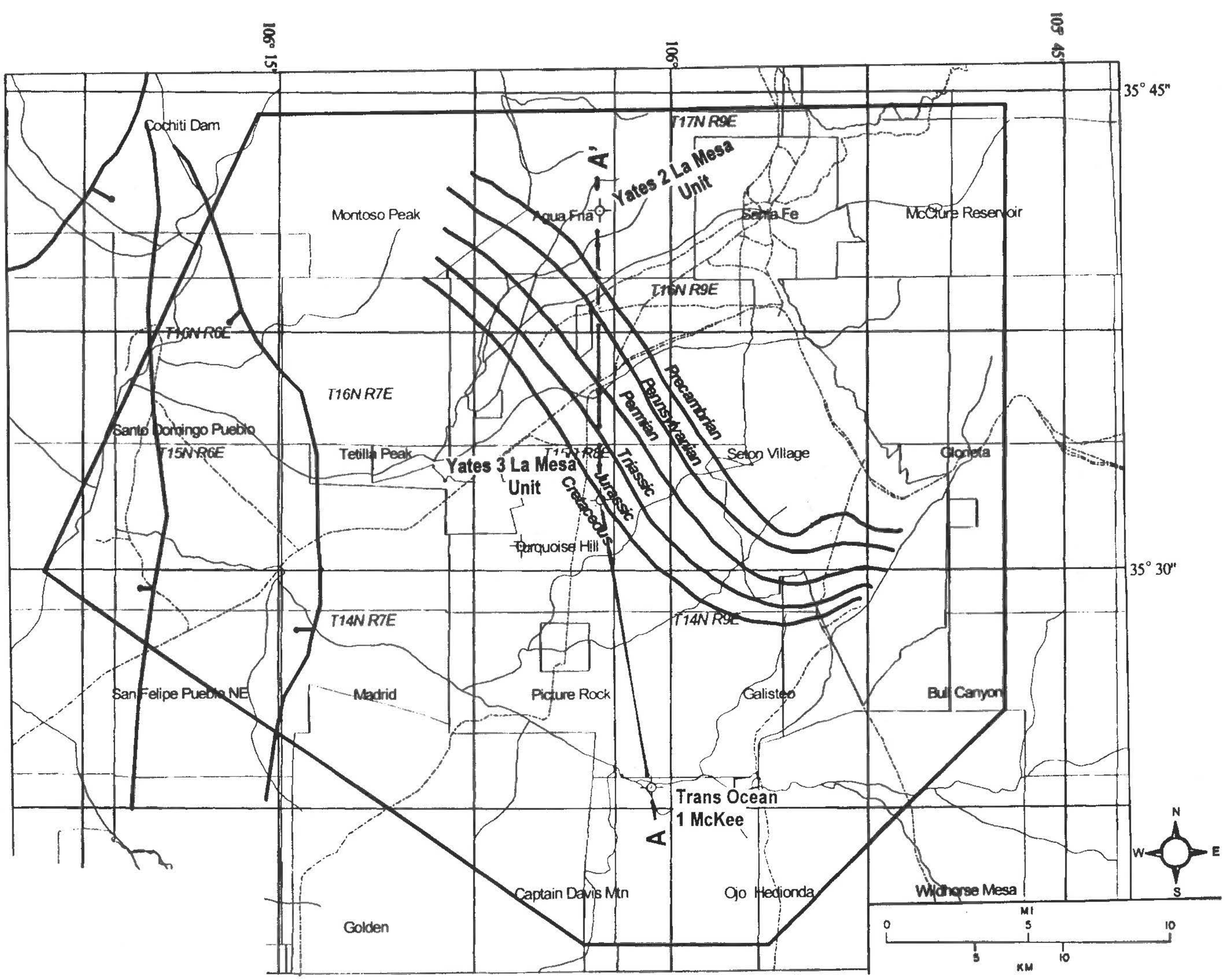

FIGURE 3. Map showing pre-Tertiary subcrop of Mesozoic, Paleozoic, and Precambrian rocks in the Santa Fe embayment. Names and locations of USGS 1:24,000-scale topographic maps are shown.

Closer to the area of interest, Disbrow and Stoll (1957) provided a wealth of detail on the Oligocene igneous intrusive and extrusive events that were concentrated in the Cerrillos through La Cienega area. They recognize four major periods of igneous activity that resulted in more than 2000 ft of latitic tuffs, tuff-breccia, and flows that unconformably overlie the uppermost massive sandstone of the Galisteo Formation. Associated with the volcanics are a number of intrusive masses that are chiefly monzonitic in composition. The major bodies are stocks or plugs from which radiate tongue laccoliths, sills, and dikes that were emplaced in greatest number and volume in incompetent shale of the upper part of the Morrison and Mancos formations.

Laccoliths in the Yates No. 3 La Mesa Unit well

In January 1986, Yates Petroleum Co. drilled a 4755-ft hydrocarbon exploration test well in the NE¼ NE¼ NE¼ sec. 13, T15N, R8E that began in the Ancha Formation and bottomed in rocks of Triassic age. The well is about 1.5 mi southeast of the New Mexico state prison and 1 mi east of NM-14. Structurally, it is on the western limb of the Santa Fe embayment syncline, about 2 mi west of its structural center. Three miles west of it is the uplifted dome of the Cerrillos Hills, where igneous intrusive rocks are exposed.

At 280 ft the well drilled out of the Ancha Formation into volcaniclastics of the Espinaso Formation, indicating that sediments of the Tesuque Formation do not extend this far south in the embayment. At 700 ft a laccolithic intrusion was penetrated to a depth of 2282 ft, where red-brown shales and sandstones characteristic of the Galisteo Formation were encountered. These were penetrated to a depth of 3070 ft, where a second laccolith appears. At about 3790 ft, 80 ft of rocks resembling the Jurassic Morrison Formation were drilled, beneath which one more laccolith about 220 ft thick was present (Fig. 2, cross section A–A').

Of interest is that there is no evidence of doming on the level surface of the piedmont at this location. The regional gravity and aeromagnetic data of Keller and Cordell (1983) and Cordell (1983) do not indicate the presence of laccoliths beneath the surface in this part of the embayment, but the more detailed geophysical information of Spiegel and Baldwin (1963) does. They note "buried intrusive rocks" (plate 5) associated with a "ground water high" (p. 215) in sec. 17, T15N, R9E, 1 mi east of the Yates No. 3 well.

Intrusions are anomalous and "out of place" at this location in the embayment. The effect of having no surface expression of the emplacement of more than 2500 ft of igneous rocks implies that uplift of the Santa Fe embayment during volcanic activity in the Oligocene was more extensive and covered a greater area than previously expected. The uplift would account for the absence or dramatic thinning of later Tertiary Tesuque Formation sediments in the embayment south of the Santa Fe River. The more than 2000 ft of volcanic detritus in the Yates No. 2 well may indicate that Oligocene volcanic effects were also felt at least 10-mi northeast of their closest surface expression in the

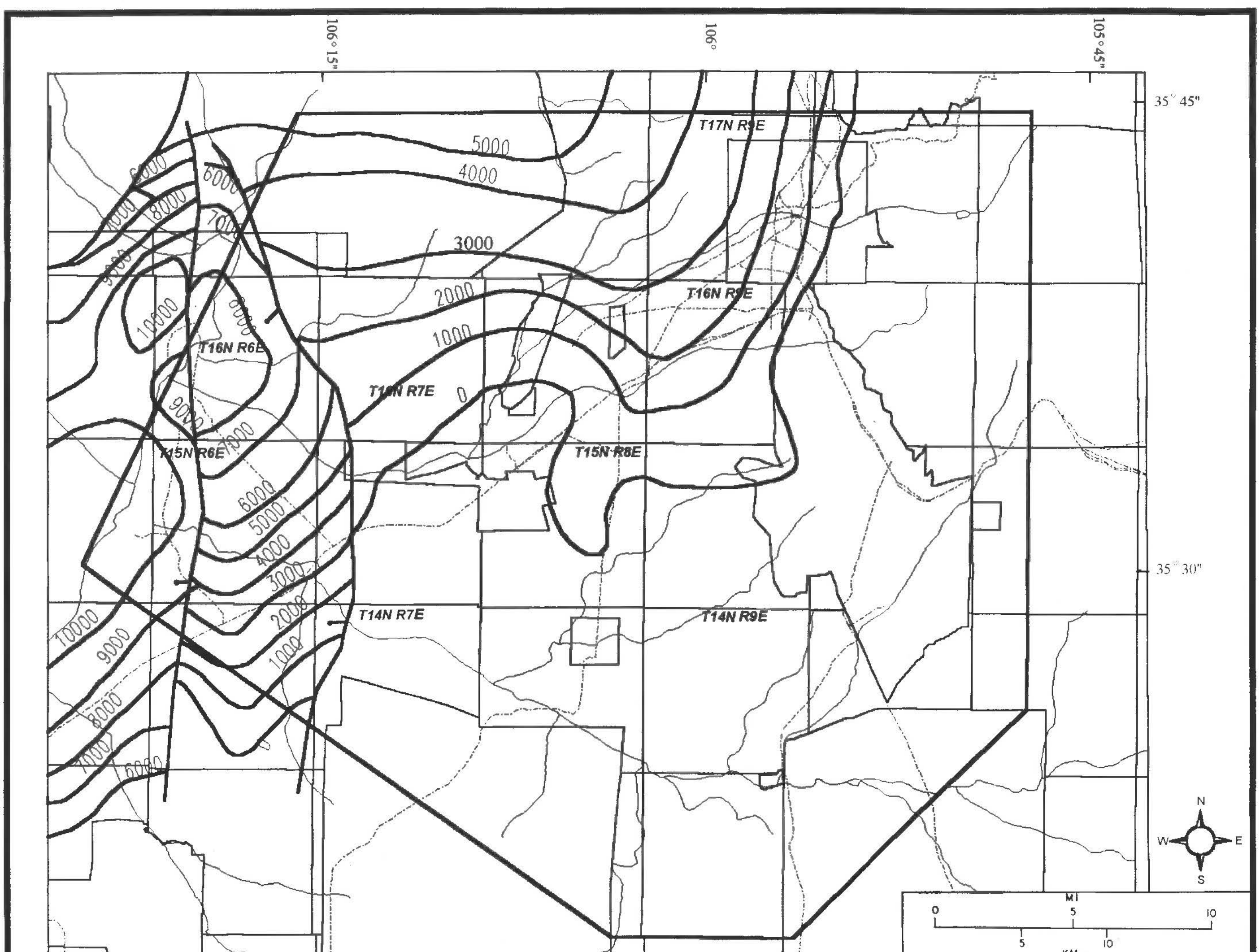

FIGURE 4. Isopach map of the Tesuque Formation in the Santa Fe embayment and nearby areas, countour interval is 1000 ft.

Cerrillos Hills. However, it is important to point out that while the thickness of volcanic rocks in the Yates No. 2 well is commensurate with the Espinaso Formation in nearby outcrop they are distinctly different than the exposed Espinaso Formation in composition. Further work is necessary to resolve the origin and source of these volcanic rocks and the underlying "La Mesa Limestone".

Santa Fe Group-Tesuque Formation

Collectively the rocks deposited in the Rio Grande rift are the result of late Tertiary tectonic pulses that formed the depression are the Santa Fe Group. A large number of investigators have subdivided this package into formations and members locally, but generically little has changed since Bryan (1938) wrote, "The main body of sedimentary deposits of the Rio Grande depression, from the north end of the San Luis Valley, to and beyond El Paso is considered to be of the same general age and to belong to the Santa Fe Formation."

The unit was raised to Group status by Spiegel and Baldwin (1963), who proposed that all the basin fill, whether Tertiary or Quaternary, be included. Broadly, it incorporates all the rocks above the La Cienega-Cerrillos Hills volcanics, including the volcanic sediments of the Abiquiu Formation, through the Ancha Formation. Kelley (1978) removed the Ancha Formation from the Santa Fe Group and described it as a piedmont gravel that had once covered most of the Española basin.

The main part of the Santa Fe Group is the Tesuque Formation, named for the extensive body of pinkish-tan, soft, arkosic, silty sandstone and minor conglomerate and siltstone found in the Española basin on both sides of the Rio Grande and as thick lithologic-equivalent deposits throughout the Rio Grande rift. In the Española valley north of Santa Fe, Galusha and Blick (1971) measured more than 3700 ft of Tesuque. Thicknesses in the deeper parts of the Española basin near the Rio Grande may exceed 8000–9000 ft (Kelley, 1978) and are represented by more than 14,500 ft of equivalent units in the Albuquerque basin (Lozinsky, 1988). Figure 4 shows the extent and thickness of the Tesuque Formation.

Santa Fe Group-Ancha Formation

Overlying the Tesuque and older rocks in the western and southern part of the Santa Fe embayment are fluvial deposits composed of semi-consolidated sands, gravels and silts of the Ancha Formation. Where present, it is difficult to distinguish them from the Tesuque Formation on the basis of lithology. Although it is generally less than 300 ft thick (Fig. 5), the Ancha Formation and the older Tesuque Formation are the primary aquifers in the embayment south of Santa Fe.

HYDROGEOLOGY

Introduction

All of the rocks in the Santa Fe region, including weathered and fractured Precambrian crystallines in the Sangre de Cristo Mountain front, contain water. Not many of them, however, can act as good aquifers and produce potable water in amounts to make them useful economically or

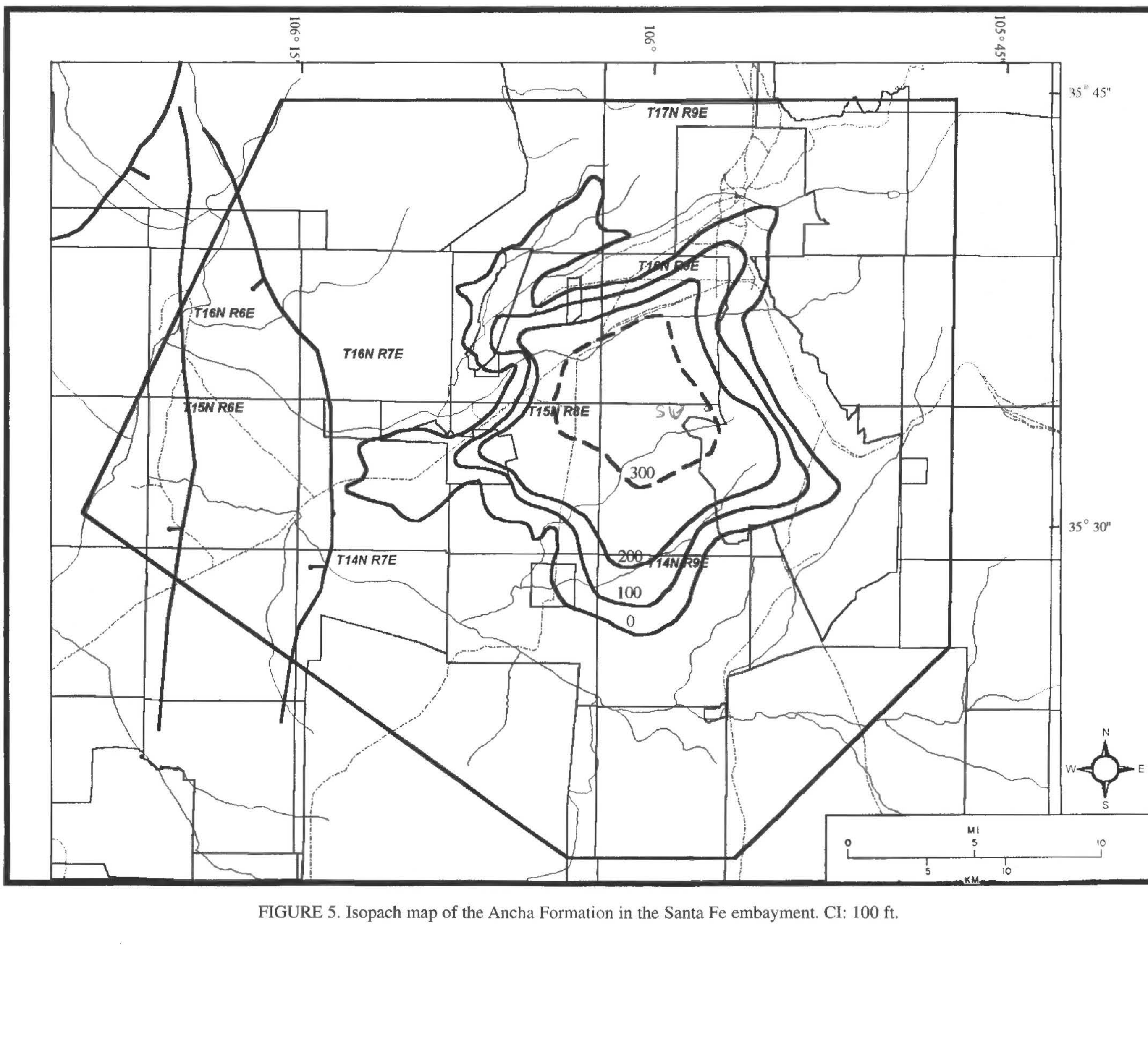

FIGURE 5. Isopach map of the Ancha Formation in the Santa Fe embayment. CI: 100 ft.

socially. Most lack enough permeability and porosity to give up their contained water, or contain impurities that contaminate the resource, and are encountered at depths too great to be accessible for most uses.

Near-surface rocks west of the mountains are unconfined fresh water aquifers with production qualities ranging from superb to barely adequate. This primary aquifer system is the upper part of the Tertiary-Quaternary Santa Fe Group that incorporates the Tesuque and Ancha formations (Figs. 4, 5).

Santa Fe Group sediments are exposed on the surface from the mountains on the east to the volcanics of the Cerros del Rio and Jemez Mountains on the west. In the embayment south of the Santa Fe River, older Tertiary rocks of the Espinaso and Galisteo formations are in contact with and bound the main aquifer north of Galisteo Creek and east of the Cerrillos Hills. Throughout the deeper parts of the Española basin and its embayments, Santa Fe Group sediments are on top of these older Tertiary units. On the mountain and foothill margins of the basin and its embayments, the aquifer may encroach on much older rocks of Mesozoic, Paleozoic, and Precambrian age through depositional onlap or, in some areas, may be in fault contact with these units. All of the bounding rocks have much lower permeability than the Santa Fe Group aquifer and, with limited exceptions, are not generally considered good or reliable sources for producible potable ground water.

All of these rocks are hydraulically associated and are parts of the hydrologic system. Some, like the foothill areas with exposures of highly fractured granites, provide significant recharge to the Santa Fe Group aquifer where they are in contact. Others, like the dense basalt-covered mesas, may not provide much recharge from precipitation but offer protection from evapotranspiration to aquifer rocks beneath them.

The Rio Grande is hydraulically connected to the Santa Fe Group aquifer throughout its course in the Española and Albuquerque basins. The water table for the region rises some 1800 ft from the river bed south of Cochiti Lake on a line east 24 mi to the Sangre de Cristo foothills south of Santa Fe (Fig. 6). In most of this region the water table is less than 200 ft from the surface and seldom deeper than 500 ft.

The library of the Santa Fe Office of the State Engineer contains a number of reports that evaluate and assess this region's water supply. Most remarkable about the hydrologic data in these reports is the range of values they present, confirming that many components of the system are unknown and that large uncertainties still exist.

Hydrogeologic conditions

The study region may be divided into four major tectonic elements (Fig. 1), each of which are related to the other but have unique structural and stratigraphic parameters affecting the geohydrology within it: (1) the uplifts where there are no aquifer elements of the Santa Fe Group; (2) the deeper rift parts of the Española and Albuquerque basins, generally west of the La Bajada fault and the Rio Grande; (3) the northern part of the Santa Fe embayment, located mostly northwest of I-25 from La Cienega to Santa Fe; and (4) the southern part of the Santa Fe embayment, bounded by I-25 on the north and east, Galisteo Creek on the south, and the Cerrillos Hills on the west.

Uplifts

Regionally, from south-central Colorado to southeast of Santa Fe, precipitation on the west slope of the Sangre de Cristo Mountains furnishes a substantial part of the water eventually reaching the Rio Grande from streams and most of the recharge to the Santa Fe Group aquifer. The largest volumes of mountain-source water, however, originate in watersheds and drainages north of an east–west line separating Santa Fe and Mora counties from Rio Arriba and Taos counties, roughly at the latitude of Española, that are outside this study area. Most of the water falling in the mountains south of this line, especially in the higher elevations, does not reach the Rio Grande in New Mexico, nor does it recharge the Santa Fe Group aquifer. It is discharged by streams flowing predominantly south to the Pecos River and east through smaller streams of the Canadian River system, and is a primary water source for users in eastern and southern New Mexico on and near these streams.

Locally, snow and rain on the fractured upper parts of the Precambrian crystalline rocks exposed on the western flank of the Sangre de Cristo Mountains east of Santa Fe provide most of the water that recharges the late Tertiary and Quaternary Tesuque and Ancha aquifers east of the Rio Grande. Although not part of the sedimentary units that are the primary focus of this investigation, zones of fractured granite are the source of fresh water for domestic wells at homes in the foothills. The volcanic uplifts of the Cerrillos Hills and the Galisteo basin not covered by aquifer sediments yield little ground water on a sustained basis.

Deep rift basins

The deepest parts of the Española basin and its southern extension into the adjoining Albuquerque basin are west of the Rio Grande. Tesuque and Ancha-Puye Formation rocks that may exceed 9000 ft in thickness contain large volumes of fresh water in these deep rift basins. The Española-Albuquerque basins appear to be a single geohydrologic feature within which ground water entering or leaving will eventually affect all of it. Geophysical data (Keller and Cordell, 1983; Heywood, 1992) imply the presence of another deep rift basin beneath the Jemez Mountains that, if confirmed, would further extend the limits of the Albuquerque basin to approximately the Chama River between Abiquiu and Española.

It is recognized that the Tesuque Formation aquifer is not a homogeneous unit as, until recently, its time-equivalent geologic component in the Albuquerque basin was considered to be. Deposited as the rift formed and derived primarily as a series of coalescing alluvial fans from mountains east of it, its composition is a variety of constituents ranging from boulder to sand through silt and shale size, displaying little regional continuity. In some areas it encloses ancient stream deposits of the Rio Grande that exhibit exceptional porosity and permeability, and store and readily discharge large volumes of water to wells like those on Albuquerque's east mesa (Hawley et al., 1994). Smith and Kuhle (1998 a, b) have recently identified similar deposits in the vicinity of Cochiti Pueblo. In other places, the Tesuque Formation is well indurated and cemented or composed primarily of silt and clay particles that seriously impede water storage, movement and production. Several well fields west of the Rio Grande that are the source of water for the city of Los Alamos, and the Buckman well field east of the river that is a significant provider of Santa Fe's water supply, produce from porous and permeable Tesuque rocks.

Northern Santa Fe embayment

This part of the greater Española basin extends north and west of I-25 from La Bajada to the mountains east of Santa Fe and to the deep rift basin west of the Rio Grande. It roughly coincides with the surface drainage area of the Santa Fe River. Except in the Cerrillos Hills-La Cienega area, the Tesuque Formation aquifer is everywhere present and is 1000 to more than 4000 ft thick. Locally, between the Santa Fe River and I-25, it is overlain by 100–300 ft of the Ancha Formation. These units contain large volumes of producible ground water that are accessed by deep wells for community supplies and at lesser depths for domestic wells.

A number of springs discharge in the channels of the Santa Fe River, Arroyo Hondo, and San Marcos Arroyo, where the aquifer is near or in contact with the impermeable intrusives of the Cerrillos Hills. A large, thick and extensive mass of extruded basalt and cinders, the Cerros del Rio volcanic field, covers the Santa Fe Group aquifer in the west and northwest part of the northern embayment. Although these volcanics interfinger with the Ancha Formation, they do not significantly affect ground-water flow. Faults and dikes penetrating the aquifer may affect flow locally, but these are relatively minor impediments to the water's westward movement down gradient to the deeper rift basins.

Despite ground water being mined locally in and near Santa Fe, the aquifer in this part of the embayment has the best balance between stream and areal recharge and well discharge, and in some places there may be opportunities to expand the supply. Because the Cerrillos Hills were present before Santa Fe Group deposition, Tesuque or post-Tesuque streams originating in the Sangre de Cristo Mountains would have been diverted north around these intrusions on their way to the Rio Grande. Filled with thicker than normal porous and permeable sediments, these older channels are where relatively large capacity community wells might be developed. Successful wells would adversely affect other wells nearby and spring discharges in Arroyo Hondo, but losses would be offset by increased volumes of treated effluent in the Santa Fe River as Santa Fe's population increases and the city's supply is significantly augmented by non-indigenous water imported from the Rio Grande.

Southern Santa Fe embayment

South of I-25 to Galisteo Creek, between the mountains and the Cerrillos Hills, is the region within the study area with the most significant subsurface structural and stratigraphic conditions that adversely affect the movement, storage and production of ground water. The structural uplift formed during Oligocene time by emplacement of intrusions in and near the Cerrillos Hills prevented Tesuque Formation sediments from being deposited and is responsible for their absence in the subsurface in the western part of the southern Santa Fe embayment. The southern, southeastern, and easternmost extensions of this part of the embayment were either too high in Tesuque Formation time for these rocks to accumulate on them or subsequent uplift stripped them away prior to Ancha deposition.

In its central northern part, approximately on line with the course of Arroyo Hondo, the Tesuque Formation may be up to 1000 ft thick and overlain by about 300 ft of Ancha Formation. Like the part of the embayment north of it, ground-water supplies adequate for domestic and some community wells should be present. The region south and east of the New Mexico State Penitentiary has the least aquifer recharge, the thinnest Santa Fe Group sediments, and the greatest demand outside of Santa Fe for ground water. Except in small reentrants and Ancha-filled channels, sediments of the Santa Fe Group have a maximum combined thickness of about 700 ft, averaging less than 300 ft.

South and east of Yates Petroleum Company's La Mesa Unit No. 3, the Tesuque Formation is absent or very thin. In much of this region the Ancha Formation, generally less than 300 ft thick, is the only potential aquifer accessible with shallow water wells. In many places, however, all or much of the Ancha is non-productive because it is above the water table. Subcrops of porous older rocks, fractured Precambrian rocks and Pennsylvanian Madera Limestone of limited extent close to the mountains, thicker Ancha Formation-filled channels on older rock surfaces, and some of the alluvium in the Galisteo Creek valley, may produce potable ground water locally, but whether production from these sources can be maintained is unknown.

Thin and limited in extent, the aquifer in this region will continue to be mined. In local areas of rapid growth and development, it may now be close to its sustainable productive limits. Unlike some other parts of New Mexico facing limitations on the use of ground water, this area has no nearby source or reserve from which water rights represented by "wet water" may be secured, so most new and substantial increases in demand for ground water must ultimately be met by water imported from places with a better supply.

Regional considerations

East of the Rio Grande

Just two significant stream systems within the study area originate in the Sangre de Cristo Mountains. The Santa Fe River begins on the south slope of 12,409-ft Lake Peak and flows south and west about 13 mi

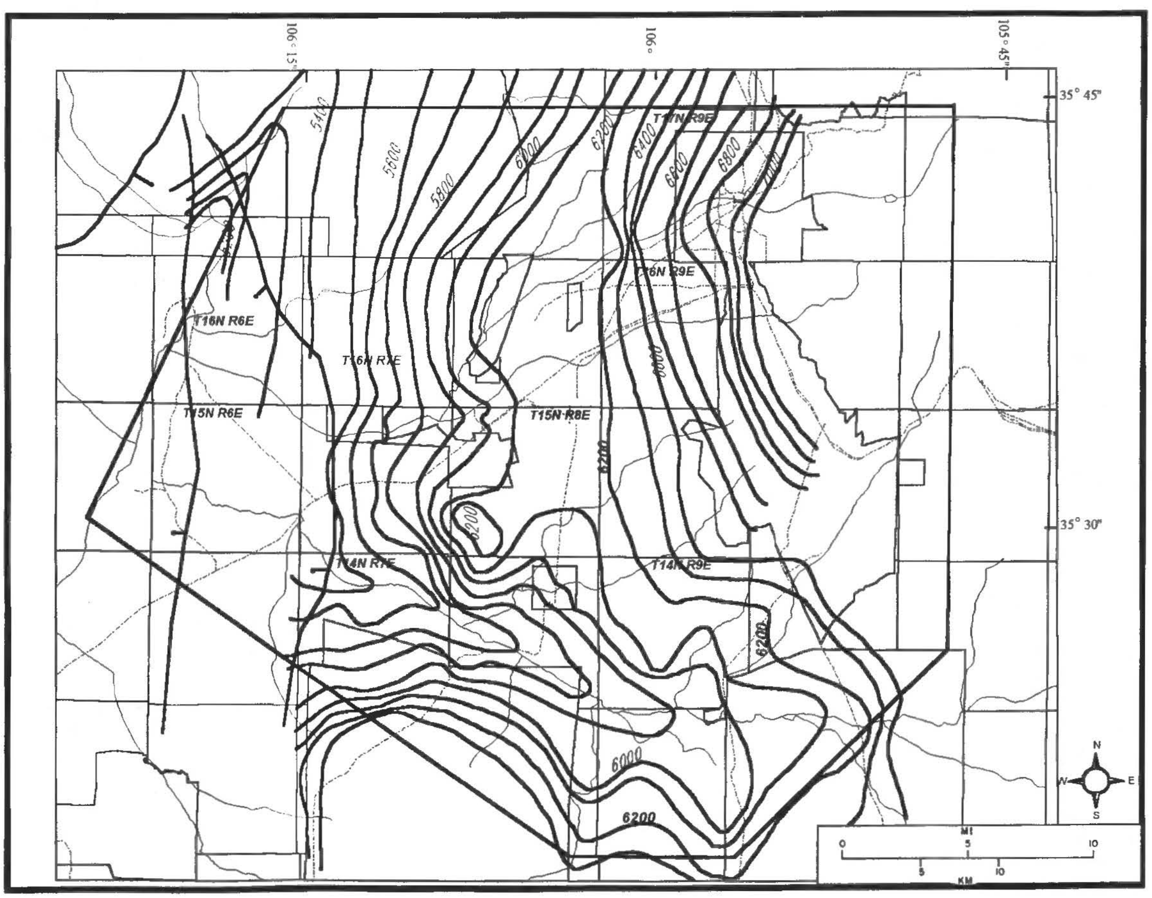

FIGURE 6. Elevation of the water table in the Santa Fe embayment. CI: 100 ft. Modified from Mourant (1980).

through a narrow canyon to its mouth just east of the city. From here its course is west across the Santa Fe embayment piedmont and the east side of the Rio Grande rift about 27 mi to the Rio Grande. Galisteo Creek heads on the west slope of 10,199-ft Glorieta Baldy and flows southwest through Canoncito and Lamy to Galisteo, where it makes a 90° turn to the northwest to discharge into the Rio Grande at Santo Domingo Pueblo, about 43 mi from its origin. Almost all of the region's minor streams and arroyos, which are dry except for brief periods during and after intense local summer thunderstorms, are captured by the two larger streams before they reach the river.

The Santa Fe River would likely be a perennial stream in most years if it did not accommodate storage reservoirs capturing its water where it issues from the mountains, and the city did not pump large volumes of water from the aquifer beneath it. As a result, the river through the city is dry most of the year, but flows again west and downstream from the Santa Fe wastewater treatment plant. Galisteo Creek flows during spring runoff and in brief periods following large summer thunderstorms. In years that are not exceptionally dry, it may also exhibit water in its bed for several miles east and west of Cerrillos where it flows upon relatively impermeable igneous and pre-Tesuque rocks that underlie the Cerrillos Hills.

Generally, ground water is expected to flow consistently west to the Rio Grande except where cones of depression at large well fields like those beneath Santa Fe and Buckman interrupt subsurface movement. However, information developed in this investigation indicates that pre-Tesuque laccolithic intrusives in and near the Cerrillos Hills profoundly effect ground-water flow in the Tesuque Formation. They are barriers to west-moving subsurface water in the Santa Fe embayment south and east of a point 2–3-mi north of La Cienega in secs. 19 and 30, T16N, R7E. This would be roughly west of the 6200-ft water table contour south of I-25 shown in Figure 6, and may account for the anomalous flattening and spreading of the contours in this region. Water originating in the Sangre de Cristo Mountains and the piedmont west of them that reaches the Tesuque aquifer is diverted north and northwest by these impermeable surface and subsurface barriers. When it reaches the terminus of the intrusives north of La Cienega, ground water again moves west toward the Rio Grande.

USGS estimates that 29,400 acre-feet of water falls in the Santa Fe River's mountainous watershed above elevations of 7718 ft, yielding 6706 acre-feet (Spiegel and Baldwin, 1963), most of which is stored in reservoirs near the mouth of the canyon and used for domestic consumption in the city of Santa Fe. The catchment basin area for this part of the Santa Fe River occupies about 20 mi², less than 2.5% of the southern Sangre de Cristo's approximately 850 mi² extent. Watersheds, especially those in higher elevations that provide runoff to west-flowing streams in the southern Sangre de Cristo Mountains, are limited in extent. With the rapid population growth occurring in the southern Santa Fe embayment, where the Santa Fe Group aquifer is thin and there are presently no ready alternatives to relying on it as almost the sole source for domestic water, there is reason to view estimates of recharge to the Tesuque-Ancha Formation aquifer conservatively.

On and near the Rio Grande

In the deeper rift basins of the western part of the study area there may be substantially more water moving underground from the Española basin part of the Rio Grande rift to the Albuquerque portion than previously indicated. The absence of significant subsurface structural and stratigraphic barriers to ground water flow within the Santa Fe Group in this region is suggested in this report. The presence of distinctive facies suites of considerably more hydraulic conductivity in Upper Santa Fe sediments has been recently determined (Smith and Kuhle, 1998 a, b). These hydraulically linked units provide unique underground conduits to move ground water freely and relatively rapidly down gradient from north to south.

Detailed geologic investigations of the Santa Fe Group aquifer beneath Albuquerque's east mesa (Hawley and Haase, 1992) defined parameters of an ancestral Rio Grande aquifer that is the primary source of that city's water. Hawley et al. (1994, p. 47) described this feature: "The thickest documented sections of fluvial deposits in the area (greater than 1,000 ft, 300 m) are preserved as a stacked sequence of braided-river channel deposits that is as much as three miles (5 km) in width beneath the 'eastern heights' of metropolitan Albuquerque. This and similar sequences in the Corrales-southeastern Rio Rancho area are characterized by extensive beds of sand and pebble gravel and relatively small amounts of silt and clay." An accompanying schematic drawing shows these channel deposits extending to an area approaching the Española basin southeast of the Jemez volcanic pile, inferring an ancient Rio Grande alignment on and near its present course through significant distances in central New Mexico.

Recent surface geological mapping by Smith and Kuhle (1998a, b) in the Santo Domingo basin area of the northern Albuquerque basin east and west of the Rio Grande between Cochiti Lake and Santo Domingo Pueblo confirms the presence of these axial deposits north of Albuquerque. Their work also determined that the Rio Grande is considerably older than the 3–5 Ma investigators have previously indicated. They "...suggest revisions to existing concepts of stratigraphy and faulting that affect ground-water flow in that area. Ancestral Rio Grande gravel is at least 1600 ft thick, extends over an east–west extent of 15 km (9.3 mi), and dates back to at least 7 Ma. Large areas of vocaniclastic piedmont deposits of the Cochiti Formation (western piedmont facies of the Upper Santa Fe Group) are also dominantly gravel. These two extensive, coarse-grained facies <u>require order-of-magnitude upward revisions to estimated hydraulic conductivity applied to regional flow models</u>" (emphasis added) (Smith and Kuhle, 1998b, p. 21).

Some speculation west of the Rio Grande

Emphasis in this study is on the east side of the Rio Grande rift. When the western part, especially the region occupied by the Jemez Mountain volcanic pile is included, it becomes evident that considerably more water is introduced into the Española-Albuquerque basin hydrologic system than enters from the east, and there may be large volumes of unaccounted for water that recharge the underground system.

During the late 1970s and early 1980s when Union Oil Company and others were actively developing a high-temperature geothermal resource at Redondo Peak in the southwestern part of the Valles Caldera, several deep wells penetrated up to 500 ft of late Tertiary sandstones overlying the Permian Abo Formation in the hydrothermal reservoir (US DOE, 1980, p. 3–23). Although geologic investigations concluded that the high-temperature regime at depth in the caldera was hydrologically separated from the surface drainages and near surface aquifers, they also defined a unique series of "ring faults" at the base of the caldera's inner slopes. These not only enclose the vast region that collapsed to fill the subsurface void left after its most violent eruptions, but are also located beneath the two streams draining it.

Cross sections by Smith et al. (1970) and those presented during the active geothermal investigations indicate that these faults encounter the sedimentary rocks beneath the caldera. These features, other major faults in the Jemez Mountains, porous and fractured rock units, and even ancestral Rio Grande channels beneath the volcanics, could be conduits for substantial volumes of water leaking from beneath the mountain. Hawley and Grant (1997, p. 60), interpreting isostatic residual gravity anomalies presented by Heywood (1992) and other data, came to the conclusion that, "...the ABQ (Albuquerque) geohydrologic basin is not isolated geohydrologically from the Española basin to the northeast, <u>the 'Valles-Toledo' basin to the north</u> (emphasis added), nor the Socorro-La Jencia (Popotosa) basin to the south." This interpretation extends the Albuquerque basin beneath the Jemez Mountains to the vicinity of Abiquiu, incorporating the structural/gravity lows defining the Valles-Toledo basin as well as the Española basin.

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Two of the nameless NMGS volunteers helping out at a stop on the 1994 NMGS fall field conference to the Mogollon slope of west-central New Mexico (photograph courtesy of George Austin).