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New Mexico Geology, v. 20, n. 1 pp. 2-7, Print ISSN: 0196-948X, Online ISSN: 2837-6420.
https://doi.org/10.58799/NMG-v20n1.2

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Subsurface stratigraphy of the Santa Fe Group from borehole geophysical logs, Albuquerque area, New Mexico

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Abstract

Interpretation of electrical and gamma-ray logs from water-supply wells in the Albuquerque area, central New Mexico, reveal laterally consistent stratigraphic patterns that provide a basis for local differentiation of Santa Fe Group basin fill, the principal aquifer for communities along the Rio Grande valley. A sequence of fine-grained silty sand and clay, first characterized in detail in a core hole drilled near the intersection of 98th St and I–40 on Albuquerque's west side, is traceable in the subsurface. This unit, informally named the Atrisco member of the middle red formation (Santa Fe Group), can be traced for several kilometers. The top of the Atrisco member separates coarse-grained sand and gravel of the Sierra Ladrones Formation (upper Santa Fe Group) from underlying fine- to medium-grained silty sand and clay of the middle red formation.

Beds of the Atrisco member and other marker units in the Sierra Ladrones and middle red formations are also useful in delineating several faults that are poorly exposed or buried by younger alluvium. Initial findings do not support projections of the Rio Grande fault beneath Albuquerque. The east margin of the basin is recognized as a series of north-striking, down-to-the-west normal faults that influenced Santa Fe Group deposition.

Introduction

Since 1991 the Albuquerque Basin of central New Mexico has been the subject of geologic investigations that have focused on characterizing the ground-water resources of the Albuquerque metropolitan area, the largest urban region in the state (Thorn et al., 1993). Surface geologic mapping yields important clues to the distribution of faults and alluvial aquifer units in the region (Cather et al., 1995; Connell, 1997; Hawley, 1996; Hawley and Chamberlin, 1995; Hawley and Haase, 1992; Kirby et al., 1995; Love, 1997; and Love et al., 1996); however, several geologic structures are obscured by Quaternary alluvium that locally covers basin fill of the Santa Fe Group.

The study area contains a wealth of subsurface information provided by closely spaced municipal water-supply and ground-water-monitoring wells that have been installed during the past 40 years. Integration of geologic mapping with borehole geophysical logs, driller's logs, and well-completion reports and examination of cuttings from selected wells provide information on the spatial distribution of faults and lithofacies beneath the study area. Subcrop mapping can also provide first-order approximations of stratigraphic throw across poorly exposed faults. Albuquerque is especially suited to this study because information from many water wells is available (Hawley, 1996; Hawley and Haase, 1992; and Wilkins, 1995). This paper demonstrates the use of borehole geophysical logs for correlation of aquifer units in the Albuquerque Basin and its potential application to basin-fill deposits in other parts of the Rio Grande rift.

Methods

Geophysical logs of selected wells in the Albuquerque area (Fig. 1) were used to graphically correlate marker horizons and sequences in the Santa Fe Group. Digital log data were obtained from the U.S. Geological Survey geophysical log database (Wilkins, 1995), geophysical logging contractors, or digitized from analog paper logs.

Logs of electrical conductivity and gamma-ray activity are commonly recorded prior to casing and development of municipal water-supply wells and are useful for graphical correlation in the Albuquerque area. Electrical conductivity logs measure variations in the electrical response of the formation, drilling mud, and interstitial fluid to an induced electrical current. These logs are produced by taking the reciprocal of long-normal or deep-induction resistivity logs and are reported in units of millimhos per meter. In fresh-water aquifers, electrical conductivity can serve as an indicator of texture (Alger, 1966). Sand and gravel generally possess low electrical conductivity, whereas silt- and clay-rich beds have higher values and are typically recognized by abrupt increases in electrical log response. Natural gamma-ray logs measure the activity of radiogenic elements, such as potassium, uranium and thorium. Clay-rich units are recognized by higher gamma-ray values because clays typically possess more radiogenic constituents than a well-sorted quartz-rich sand.

Recent studies of the hydrogeology of the Santa Fe Group under Albuquerque suggested that lithostratigraphic units and lithofacies can be mapped in the subsurface based on geophysical logs (Hawley, 1996). Hawley and Haase (1992, section V) recognized a prominent silt- and clay-rich zone that could be correlated among several wells on Albuquerque's west side. This unit was recently described in a core hole (98a, Fig. 1) drilled just north of I–40 (Allen et al., this issue). Studies of this core hole demonstrate the strong correspondence between borehole geophysics and texture in Santa Fe Group deposits in the Albuquerque Basin.

Regional geology and Santa Fe Group stratigraphy

The Albuquerque Basin is one of the largest sedimentary basins of the Rio Grande rift, a chain of linked basins that

New Mexico GEOLOGY

• Science and Service

ISSN 0196-948X

Volume 20, No. 1, February 1998

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Circulation: 1,700

Printer: University of New Mexico Printing Services

extend south from central Colorado into northern Mexico. In the study area, the east margin of the Albuquerque Basin is abrupt and marked by steep, north-trending, rift-flanking basement-cored uplifts of the Sandia and Manzanita Mountains. The west margin forms a topographically subdued, faulted monoclinal ramp underlain by rocks of the adjacent Colorado Plateau structural province.

Upper Cenozoic deposits of the Albuquerque Basin have been generally referred to as the Santa Fe Group (Hawley, 1978). Details of Santa Fe Group stratigraphy have not been fully established in the Albuquerque Basin and a full treatment of the subject is beyond the scope of this paper. The reader is referred to Tedford (1981, 1982), Lozinsky and Tedford (1991), and Lucas et al. (1993) for discussions of the stratigraphic nomenclature of the Albuquerque area. The Santa Fe Group is as much as 5 km (3 mi) thick and has been informally divided into three units, in ascending stratigraphic order (Bryan and McCann, 1937): lower gray, middle red, and upper buff formations. The "Santa Fe" has been inconsistently ranked as either formation or group in the Albuquerque Basin (Lambert, 1968; Kelley, 1977; Hawley, 1978; and Tedford, 1981, 1982). For this paper, we refer to the lower, middle and upper divisions of the Santa Fe Group as the lower gray formation, middle red formation, and Sierra Ladrones Formation (upper buff formation) of the Santa Fe Group, respectively.

The lower gray formation, now considered part of the Zia Formation of Galusha (1966), is a Miocene eolianite and fluvial sandstone (Beckner, 1996) that occurs below the range of most water-supply wells in Albuquerque. In the Rio Rancho area, where this unit is structurally higher, a few wells produce potable water from this unit. The middle red formation, volumetrically the largest component of the Santa Fe Group in the Albuquerque Basin, consists of a thick sequence of predominantly reddish-brown, fine-grained sand, silt, and clay with minor gravel (Kelley, 1977).

The upper buff formation, named by Bryan and McCann (1937) for deposits exposed along the Ceja del Rio Puerco escarpment (Fig. 1), is the youngest basin-fill unit of the Santa Fe Group. The upper buff formation contains a mixture of well-sorted and poorly cemented sand and gravel with silty sand to silty clay interbeds. Lambert (1968) extended this term eastward into the Rio Grande valley area, including Albuquerque. Machette (1978) later introduced the term Sierra Ladrones Formation for similar strata along the south margin of the basin. Deposits of the Sierra Ladrones and upper buff formations were laid down by broad fluvial systems of the ancestral Rio Grande and its tributaries, including the

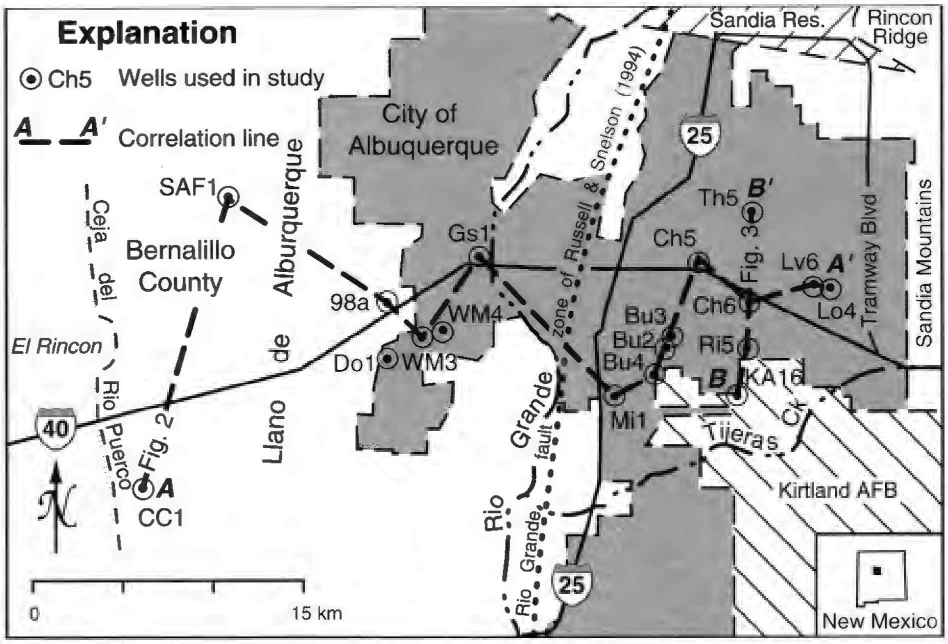

FIGURE 1—Study area illustrating stratigraphic correlation lines and wells referred to in text. Correlation diagrams are in Figs. 2 and 3.

ancestral Rio San Jose and Rio Puerco (Rio Chacra of Bryan and McCann, 1937). The term Sierra Ladrones Formation has been recently applied to deposits of the upper buff formation in the Albuquerque area (Hawley, 1996; Lucas et al., 1993). Although upper buff formation has precedence (Bryan and McCann, 1937; Lambert, 1968), it is an informal designation. We, therefore, prefer the term Sierra Ladrones Formation for these strata.

Mapping by Kelley (1977) resulted in delineation of the Ceja Member of the Santa Fe Formation. The Ceja Member, with its type section along the Ceja del Rio Puerco escarpment (Fig. 1), is typified by coarse sand and gravel in basin-floor areas, primarily west of the Rio Grande valley (Lucas et al., 1993). The Ceja Member is a subdivision of the Sierra Ladrones Formation and forms the uppermost unit of the upper buff formation under the Llano de Alburquerque (Fig. 1). Nearly all of the Ceja Member sits above the water table and therefore is not differentiated in this study.

The east margin of the basin is characterized by well-sorted extrabasinal axial-fluvial facies that interfinger with more poorly sorted alluvial-fan deposits derived from the Sandia Mountains. The upper Santa Fe Group forms the principal aquifer for communities east of the Rio Grande valley; however, only the upper 500 m (1,640 ft) has been extensively developed for municipal use in the Albuquerque–Rio Rancho metropolitan area.

Subsurface stratigraphy

Differentiation of the Sierra Ladrones Formation and middle red formation in the subsurface was accomplished by comparing electrical conductivity and gamma-ray logs to available lithologic logs of several wells. Two stratigraphic correlation diagrams have been prepared to illustrate regional stratigraphic patterns and structural interpretations across the study area (Figs. 2 and 3). Abrupt shifts in the elevation of distinctive log responses suggest tilting or fault-separation of marker horizons.

Units are depicted as "continuous" sequences or horizons in Figs. 2 and 3 to illustrate correlations among wells. These units are offset by several faults. A distinctive and laterally extensive sequence of interbedded, fine- to medium-grained sand, silt, and clay is recognized on geophysical logs (Allen et al., this issue, units 9–14). Unit Tma is a 85–100-m-thick (280–330-ft-thick) sequence of light yellowish-brown to yellowish-red, fine-grained, interbedded silty sand and clay (Fig. 2). The bottom of unit Tma marks the base of a upward-coarsening sequence of fluvial sand and gravel. A lower finer grained interval (Tmu1) can be correlated among only a few wells. Unit Tmu1 is at least 100 m (330 ft) thick at well 98a (Allen et al., this issue, units 1–5) and consists of fine- to medium-grained sand with interbedded compact, silty, fine-grained sand and clayey silt. A 134–207-m-thick (440–680-ft-thick) sequence of fine- to coarse-grained sand with scattered, pebbly sand interbeds (Tmu2) is recognized between units Tma and Tmu1.

We informally name unit Tma the Atrisco member of the middle red formation (middle Santa Fe Group). The Atrisco member is named for the Town of Atrisco Grant, the location of well 98a near the

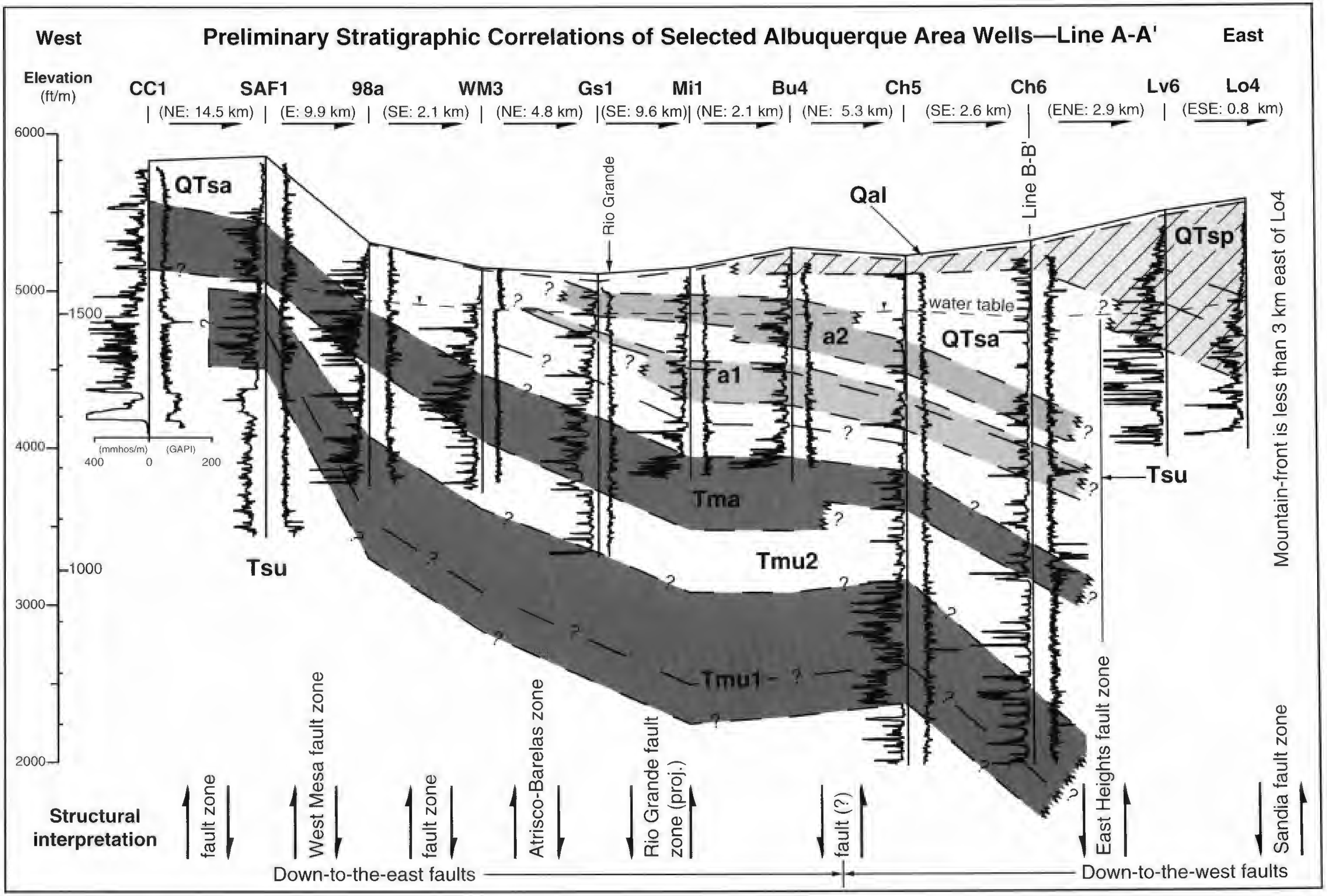

FIGURE 2—Preliminary stratigraphic correlation diagram along line *A–A'* of Fig. 1 illustrating correlations of basin-floor and piedmont-slope facies of the Santa Fe Group and interpreted faults. Geophysical-log curves denote electrical conductivity (**EC**, on left) and gamma-ray intensity (**GR**, on right). The Santa Fe Group (**Tsu**) is provisionally divided into the Atrisco member (**Tma**) and upper (Tmu2) and lower (Tmu1) unnamed members of the middle red formation. Upper Santa Fe Group deposits are assigned to basin-floor fluvial (**QTsa**) and piedmont-slope (**QTsp**) facies of the Sierra Ladrones Formation. Unit QTsa is locally subdivided into upper (**a2**) and lower (**a1**) unnamed members on the basis of electrical log responses. Variations in unit thickness may be the result of interfingering and syndepositional faulting. Units are depicted as "continuous" to illustrate correlations among wells. These units are offset by several faults noted at the bottom of figure. Unit **Qal** denotes undivided Quaternary alluvium.

intersection of 98th St and I–40 on Albuquerque's west side. The Atrisco member is introduced as an aid in local differentiation of Santa Fe Group strata because of its widespread occurrence in the subsurface. The base of Tma is sharp and can be identified in at least 15 boreholes that fully penetrate the unit. The top is gradational, but distinctive on electrical logs, and can be identified in more than 20 wells that penetrate at least 40 m (130 ft) into this unit. Deposits overlying the Atrisco member are assigned to the Sierra Ladrones Formation. The Atrisco member represents a transitional sequence of beds between the Sierra Ladrones Formation and the middle red formation. The upper boundary of the Atrisco member is chosen to mark the middle red formation–Sierra Ladrones Formation contact primarily because it is found in numerous boreholes, and thus, can be traced over longer distances in the subsurface (Fig. 2). The Atrisco member coarsens eastward of the Charles 5 well site (Ch5) and pinches out into interfingering fluvial and piedmont sand and gravel approximately 6 km (3.7 mi) west of the mountain front (Fig. 2).

Deposits of the Sierra Ladrones Formation are approximately 85 m (280 ft) thick at the Cerro Colorado 1 well site (CC1), where these sediments are above the water table. Sierra Ladrones strata thicken eastward to about 580 m (1,900 ft) at the Charles 6 well site (Ch6) where approximately 440 m (1,450 ft) are saturated under the Northeast Heights section of Albuquerque (Fig. 2). Piedmont deposits prograde across basin-floor fluvial facies near the top of the section. Geophysical logs indicate two prominent sand and silt-clay sequences (a1 and a2) in the Sierra Ladrones Formation (Figs. 2 and 3).

Structural geology

The northern Albuquerque Basin forms an east-tilted half-graben (Kelley, 1977; Russell and Snelson, 1994); however, it is segmented into smaller subbasins (Hawley et al., 1995). An intrabasinal graben is recognized by abrupt shifts in the elevation of marker beds between wells SAF1 and Bu4 (Fig. 2). The Atrisco member is displaced, in steps, by approximately 315 m (1,035 ft) across a series of down-to-the-east fault zones west of the West Mesa 3 well (WM3, Fig. 2). Unit Tma is downthrown to the east by approximately 100 m (328 ft) across the northwest-striking Atrisco–Barelas zone of Hawley et al. (1995). Borehole stratigraphic relationships indicate that down-to-the-west faults predominate east of the Rio Grande (Fig. 2). The base of the Atrisco member is only locally penetrated in deep wells east of Gonzales 1 (Gs1, Fig. 2). The top of this marker tilts northeastward where it loses much of its distinctive geophysical log character east of the Burton 4 well (Bu4, Fig. 2); however, lithologic logs of the Charles 5 (Ch5) and Charles 6 (Ch6) wells report thick sequences of silt and clay (JSAI, 1990ab) that are interpreted as a slightly coarser-grained facies of the Atrisco member.

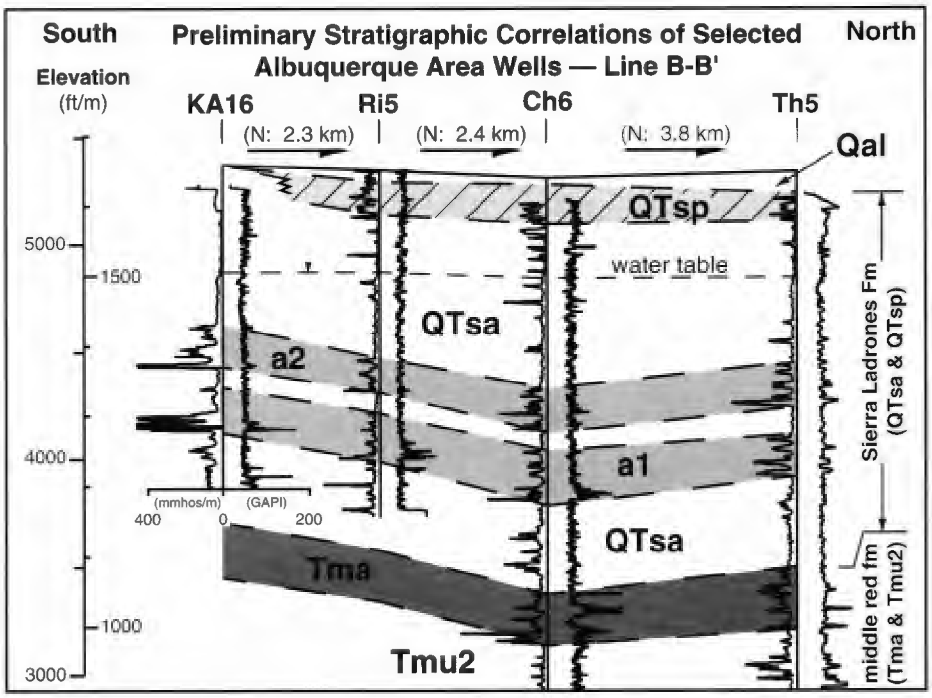

FIGURE 3—Preliminary stratigraphic correlation diagram along line *B–B'* of Fig. 1 illustrating stratigraphic correlations of basin-floor facies of the Santa Fe Group, the Atrisco member and marker beds. Refer to Fig. 2 for explanation of symbols.

Syndepositional faulting is suggested by eastward thickening of Sierra Ladrones strata and local divergence of marker beds (Fig. 2). Variations in thickness of unit Tmu2, between Bu4 and Ch5, may be attributed to faulting of the middle red formation prior to deposition of the Sierra Ladrones Formation. The East Heights fault zone generally marks the east limit of high hydraulic conductivity deposits of the Sierra Ladrones Formation (Table 1). Correlation of deposits east of Ch6 is hampered by abrupt facies changes between piedmont and fluvial deposits and by a lack of deep, closely spaced wells.

Hydrogeology

The Atrisco member marks an important hydrogeologic boundary and forms a confining unit between highly productive strata of the Sierra Ladrones Formation and less-productive aquifers of the middle red formation (Table 1). Wells that produce potable water from the Sierra Ladrones Formation have specific capacity values of 66–75 gallons-per-minute per foot of drawdown (gpm/ft) and saturated hydraulic conductivity values of 40–71 ft/day (~10^{-4} m/s). In contrast, wells completed in the middle red formation aquifer system yield specific capacity values of 6–39 gpm/ft and hydraulic conductivity values of 4–12 ft/day (~10^{-5}–10^{-4} m/s). Aquifer tests of alluvial-fan deposits of the Sierra Ladrones Formation suggest that hydrologic properties are similar to those of the middle red formation (Table 1).

Discussion

Correlation of electrical conductivity and gamma-ray logs delineate laterally consistent marker beds in the subsurface. Basin-fill deposits were laid down by the ancestral Rio Grande fluvial system and its tributaries during deposition of the Sierra Ladrones and middle red formations. Variations in the elevation and thickness of marker units indicate a syntectonic influence on basin-fill deposition. Significant thickening of the Sierra Ladrones Formation and local divergence of marker beds suggest structural control of deposition of the upper Santa Fe Group, most notably related to the East Heights and Sandia fault zones (Fig. 2).

The Rio Grande fault, as named by Russell and Snelson (1994), is a major north-striking, listric normal fault that displaces Tertiary sediments by as much as 6.1 km (3.8 mi) down-to-the-west near Isleta Pueblo, which is approximately 19 km (12 mi) south of downtown Albuquerque. They surmised that this structure formed during a westward shift in extension away from the basin-margin master faults during rifting (Russell and Snelson, 1994). The Rio Grande fault is delineated by seismic reflection and deep oil-test data south of Tijeras Arroyo (Russell and Snelson, 1994); however, their northward pro-

TABLE 1—Specific capacity and hydraulic conductivity data determined from aquifer tests (600–1,000-minute total duration) for selected wells in the Albuquerque area (GMI, 1988a,b,c,d; JSAI, 1988, 1990a,b). The Santa Fe Group (**Tsu**) is differentiated into the Atrisco member (**Tma**) and upper (**Tmu2**) and lower (**Tmu1**) unnamed members of the middle red formation. Deposits of the upper Santa Fe Group are divided into basin-floor fluvial (**QTsa**) and piedmont-slope (**QTsp**) facies of the Sierra Ladrones Formation. Well SAF1 is screened in three zones having a total screened length of 31 m (102 ft) (JSAI, 1988). **n.d.**, not determined; **n.a.**, not applicable.

Well name	Map code (Fig. 1)	Elevation of screened intervals (ft)	Specific capacity (gpm/ft)	Hydraulic conductivity (ft/day)	Stratigraphic unit (screened interval)
Burton 2	Bu2	4,859–4,439	66	50	(QTsa)
Burton 3	Bu3	4,857–4,221	83	40	(QTsa), Tma(?)
Burton 4	Bu4	n.d.	n.d.	n.d.	QTsa, Tma
Cerro Colorado 1	CC1	n.d.	n.d.	n.d.	QTsa, Tsu
Charles 5	Ch5	4,594–3,834	67	57	(QTsa, Tma), Tmu2, Tmu1
Charles 6	Ch6	4,688–3,888	75	71	(QTsa, Tma), Tmu2, Tmu1
Don 1	Do1	4,757–3,905	35	10	QTsa, Tma, (Tmu2)
Lomas 4	Lo4	n.d.	n.d.	n.d.	QTsp, Tsu
Love 6	Lv6	4,752–3,996	16	6	(QTsp), Tsu
Gonzales 1	Gs1	n.d.	n.d.	n.d.	QTsa, Tma, Tmu2
Kirtland AFB 16	KA16	n.d.	n.d.	n.d.	QTsa
Ridgecrest 5	Ri5	n.d.	n.d.	n.d.	QTsp, QTsa
Soil Amendment Facility 1	SAF1	4,750–4,437	6	4	QTsa, (Tma, Tmu2), Tsu
Thomas 5	Th5	4,634–3,906	80	51	(QTsa), Tma
West Mesa 4	WM4	4,708–3,821	39	12	QTsa, (Tma, Tmu2)
98th St	98a	n.a.	n.d.	n.d.	QTsa, Tma, Tmu2

jection of this structure(Fig. 1), in the Rio Grande valley, to the Town of Bernalillo is obscured by younger alluvium and has not been verified. Results of this investigation clearly do not support their projection of the Rio Grande fault between wells Gs1 and Mi1 (Fig. 2).

Four interpretations regarding the fate of the Rio Grande fault under Albuquerque are feasible. First, the fault may not exhibit significant displacement of the Sierra Ladrones Formation. Second, it may lie about 12 km (7.5 mi) east of the projected location and be related to the Sandia fault zone (Hawley and Chamberlin, 1995). Third, the fault could swing northwestward and join the Atrisco–Barelas fault zone and form a subbasin accommodation zone. Fourth, this structure may step eastward to join the Rincon fault zone, just south of Rincon Ridge.

The first interpretation implies that the Rio Grande fault accommodated earlier rift extension, which is in contrast to Russell and Snelson's (1994) supposition that this feature formed in response to a basinward shift in faulting during the Pliocene. The second interpretation does not account for seismic reflection surveys (Russell and Snelson, 1994, line 65, fig. 7) or for deep oil-test wells that document approximately 4 to 5 km of basin fill under the Rio Grande valley and West Mesa (Lozinsky 1994). The third interpretation is not likely because it requires the accommodation of 4 to 6 km (2.5 to 3.7 mi) of slip within 10 to 20 km (6.2 to 12.4 mi) along fault strike.

We propose that the Rio Grande fault zone may be part of an older, Miocene to Pliocene(?), rift-basin structure. Segments of this fault may have accommodated Pliocene and Quaternary displacement and step eastward to the Rincon fault, at the base of Rincon Ridge. This inferred step is supported by a 340-m (1,115-ft) increase in the elevation of the range-crest topographic divide of the Sandia Mountains, outcrops of Holocene-aged fault scarps along the base of Rincon Ridge, and a relative lack of preserved constructional surfaces that mark the top of the Sierra Ladrones Formation (Connell, 1996).

Deposits of the Sierra Ladrones Formation thicken eastward in response to increasing tectonic subsidence and may correspond with the development of a relatively deep basin adjacent to the Sandia Mountains. The east basin margin is not distinguished by a single master fault, but rather, by a series of north-striking normal faults that underlie the Northeast Heights section of Albuquerque. These major faults are within 6 km (3.8 mi) of the mountain front (Fig. 2). Thickening of basin fill also corresponds to the location of high-yielding water wells completed in the Sierra Ladrones Formation (upper Santa Fe Group).

Conclusions

This paper provides a brief summary of the use of geophysical-log data for interpreting stratigraphic and structural patterns in the Santa Fe Group. A distinctive and laterally extensive sequence of sand, silty sand, and clay, informally named the Atrisco member of the middle red formation (middle Santa Fe Group), locally separates coarse-grained fluvial deposits of the Sierra Ladrones Formation from underlying deposits of the middle red formation. Mapping of the Atrisco member and other marker units also delineates poorly exposed or buried faults beneath Albuquerque. Initial findings suggest that the Sierra Ladrones Formation thickens considerably to the east and corresponds to high-yielding wells under the Northeast Heights section of Albuquerque. The northern projection of the Rio Grande fault zone under Albuquerque is not supported by the geophysical-log data. This structure may represent an older subbasin structure that has become segmented by younger faults that step eastward to join with the Rincon fault just north of Albuquerque.

Integrating borehole geophysical logs with geologic mapping and hydrologic studies can locally differentiate the Santa Fe Group basin fill in the Albuquerque area. In particular, electrical conductivity logs can aid in the delineation of hydrogeologically significant deposits and faults that segment the basin fill.

ACKNOWLEDGMENTS—We gratefully acknowledge past and ongoing financial support from the New Mexico Bureau of Mines and Mineral Resources, City of Albuquerque, Office of the State Engineer, U.S. Bureau of Reclamation, and the U.S. Geological Survey. Reviews by Dave Love, Dirk Van Hart, and Bill Haneberg helped improve the quality of this paper and are greatly appreciated.

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