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Abstract

Core samples from the upper ~1500 ft of the Santa Fe Group in the Albuquerque West Mesa area provide a first-hand look at the sediments and at subsurface stratigraphic relationships in this important part of the basin-fill aquifer system. Two major hydrostratigraphic subunits consisting of a lower coarse-grained, sandy interval and an overlying fine-grained, interbedded silty sand and clay interval lie beneath the water table at the 98th St core hole. Borehole electrical conductivity measurements reproduce major textural changes observed in the recovered cores and support subsurface correlations of hydrostratigraphic units in the Santa Fe Group aquifer system based on geophysical logs. Comparison of electrical logs from the core hole and from nearby city wells reveals laterally consistent lithostratigraphic patterns over much of the metropolitan area west of the Rio Grande that may be used to delineate structural and related stratigraphic features that have a direct bearing on the availability of ground water.

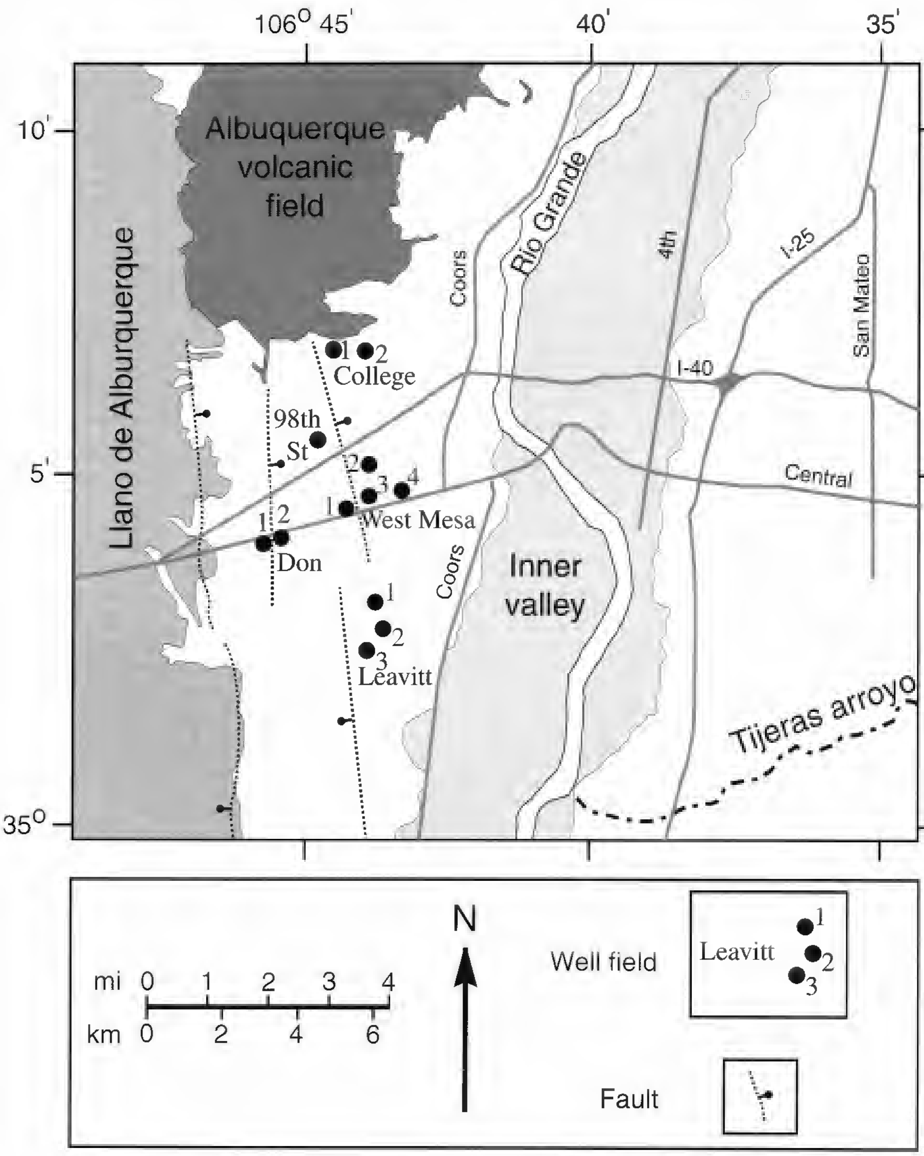

FIGURE 1—Generalized geologic map showing 98th St site and West Mesa well fields.

Introduction

Basin-fill deposits of the middle to upper Tertiary and lower Quaternary Santa Fe Group (Spiegel and Baldwin, 1963; Hawley et al., 1969; Lozinsky and Tedford, 1991; Chapin and Cather, 1994) form an important aquifer system that extends from Las Cruces, New Mexico into southern Colorado. The cities of Albuquerque and Rio Rancho form the core of a metropolitan area (Albuquerque metropolitan area) with the largest population in the State of New Mexico. Almost all the ground water that is the sole source of supply for nonagricultural uses in the Albuquerque metropolitan area is derived from aquifers in the upper part of the Santa Fe Group and the inner-valley fill of the Rio Grande. Recent concerns about the long-term availability and recharge of groundwater in the Albuquerque metropolitan area and other parts of the Middle Rio Grande Basin have resulted in new efforts to characterize the aquifer system.

Many deep water wells have been drilled in the Albuquerque metropolitan area during the last 40 years, and information collected during construction of these wells provides a substantial inventory of subsurface data for Santa Fe Group deposits. Recent investigations (Hawley and Haase, 1992; Hawley et al., 1995; Hawley, 1996) have used data from deep water wells and oil and gas test holes to constrain the hydrogeology of the aquifer system underlying the northern Albuquerque Basin. An important aspect of these investigations was the use of borehole geophysical data, in particular logs of electrical conductivity, to delineate map-scale changes in sediment texture in the subsurface. Although drill cuttings and driller's logs were available for many of the city wells, undisturbed core samples of Santa Fe Group sediments that could be used to corroborate lithostratigraphic interpretations on the basis of borehole geophysics were virtually nonexistent.

This situation changed in the Fall of 1996 when the City of Albuquerque, in cooperation with the US Geological Survey (USGS) and the New Mexico Bureau of Mines and Mineral Resources (NMBMMR), drilled a 1,560-ft borehole on the west side of the city (West Mesa area), near the intersection of 98th St and I-40 (Fig. 1). The borehole locality is here designated the 98th St site. The upper 1,500 ft of the 98th St borehole was continuously cored, with about 50% recovery, and on completion a full suite of geophysical logs was collected by Schlumberger, Inc. Comparison of core samples from the 98th St site with accompanying geophysical logs allowed, for the first time, a direct comparison of textural changes in the Santa Fe Group and their corresponding geophysical response. This article provides a brief description of the subsurface basin-fill stratigraphy of the 98th St site and illustrates the use of borehole electrical conductivity logs to characterize hydrogeologic features of Santa Fe Group deposits.

Subsurface stratigraphy at the 98th St site

Core samples at the 98th St site were examined, described, photographed, and prepared for storage at the drill site by USGS and NMBMMR geologists. Depth intervals are noted here in English units, as used by the drilling crew. Most of the drilled sequence consists of sand-sized sediments, although pebble gravels were found in the upper and lower parts of the hole and substantial amounts of silty clay were recovered in the middle. Carbonate-cementation in sandy intervals was of minor extent, and although thin cemented zones were found throughout the sequence, the bulk of the core consists of loose to moderately compact sediment.

Three major stratigraphic intervals in the Santa Fe Group were penetrated at the 98th St site (Fig. 2, Table 1). From top to bottom, the three units consist of an upper coarse-grained interval (19–97 ft), a middle fine-grained interval (97–786 ft), and a lower coarse-grained interval (786–1,560 ft). The upper coarse-grained interval consists of fine to coarse sand with granules and pebble gravels and is overlain by ~19 ft of post-Santa Fe Group (valley-fill) alluvium. The middle fine-grained interval contains interbeds of silty fine sand and silty clay in an overall upward-coarsening sequence. The lower coarse-grained interval consists of fine to medium sand with interbeds of pebble gravels, pebbly coarse sand, and silty fine sand.

As predicted in previous studies (Lozinsky and Hawley, 1992, p. II–5, fig. II–3) the entire stratigraphic sequence below a depth of 19 ft appears to have been deposited in a fluvial environment, with coarse-grained intervals reflecting deposition in river channels and finer-grained intervals in overbank and floodplain environments. Various lithologies are represented in gravel-sized fractions. The presence of chert derived from the Abiquiu Formation and red granitic clasts suggesting a Nacimiento–San Pedro Mountain source area (Woodward, 1987) supports an inference that the upper part of the sequence was deposited by an ancestral Rio Puerco fluvial system (north to northwest source). The lower coarse-grained interval includes a mixed-clast assemblage, including metasediments, silicic to mafic volcanics, and igneous porphyries from north to northeast sources, and may represent a facies deposited primarily by an ancestral Rio Grande fluvial system.

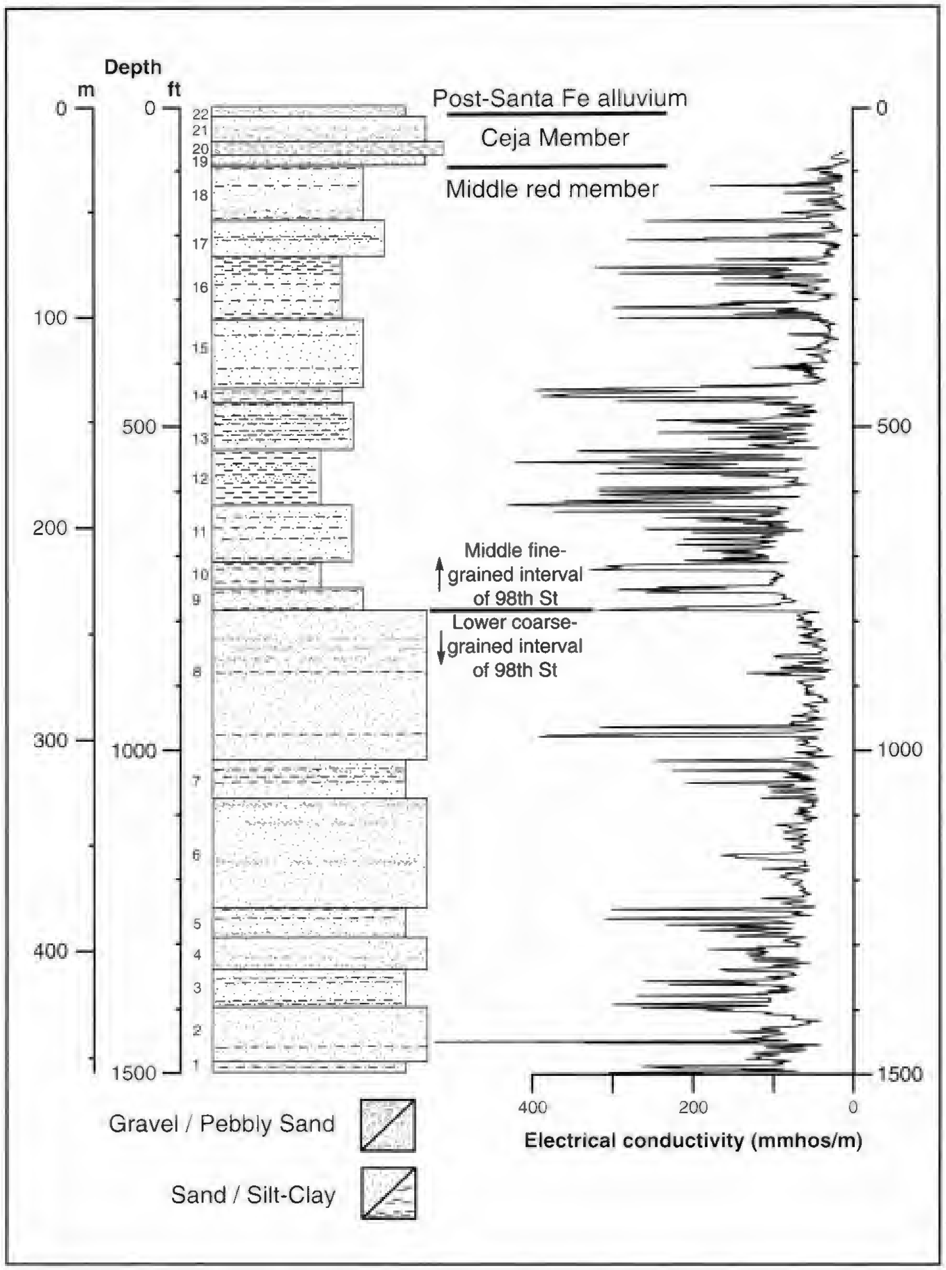

FIGURE 2—Textural summary for the 98th St drill hole. See Table 1 for description of textural units numbered on left side of column. Width of stratigraphic column indicates relative grain size of textural units, with narrower width corresponding to finer grain size. See text for discussion of lithostratigraphic units indicated to the right of column. Electrical conductivity log shows correspondence between sediment texture and borehole electrical response.

Visual comparison of electrical conductivity values with gross textural changes reveals a strong correspondence between texture and electrical response (Fig. 2). Fine-grained intervals (e.g. textural units 10 through 14 in Fig. 2) coincide with larger values of electrical conductivity, whereas coarse-grained intervals (e.g. units 6 and 8) are marked by lower values of electrical conductivity. Although electrical response in fresh-water aquifers depends on various factors that affect the conductance of electrical current along the water/grain interface (Alger, 1966; Kwader, 1985), the 98th St comparison supports the application of petroleum industry electrical logs as a proxy for gross changes in sediment texture in these sediments (Haase, 1992). This observation is important because many standardized geophysical logs have been obtained during past decades from the Albuquerque metropolitan area. ☞

TABLE 1—Description of textural units from the 98th St drill hole as identified in Fig. 2. Color designations are from Munsell soil-color charts (Munsell Color, 1975).

Unit	Depth (ft)	Description
22	0–19	Fine- to medium-grained sand with scattered coarse-grained sand and granular to pebbly sand intervals. Moist color: 10YR 6/3–5/4 (0–13 ft) and 7.5 YR 5/6 (13–18.8 ft).
21	19–60	Fine- to coarse-grained sand and silty sand with granular and pebbly sand intervals. Moist color: 10YR 6/4–4/4.
20	60–80	Pebble gravel.
19	80–97	Fine- to coarse-grained sand and silty sand with scattered interbeds of granular sand and pebbly sand. Moist color: 7.5–10YR 5/4.
18	97–183	Fine- to coarse-grained sand and silty sand with interbeds of silty fine-grained sand grading into thin (< 1 ft) silty clay and clay layers. Granular pebbly sand from 158.9 to 164.1 ft. Moist color: sand and silty sands, 7.5–10YR 5/4–4/4, clays 5–7.5YR 5/4–4/4 and 2.5–5YR 6/4–4/6.
17	183–237	Fine- to coarse-grained sand. Sandy, silty clay interbed from 204.5 to 210.9 ft. Moist color: sand, 7.5YR 6/4–4/6, clay 5YR 5/4.
16	237–336	Interbedded silty fine- to medium-grained sand and clay and silty clay. Thick clay beds (>1 ft) from 237.2 to 264.0 ft. Moist color: sand and silty sands, 7.5YR 6/4–4/4 and 7.5YR 5/6, clay 2.5–5YR 6/4–4/4 and 5YR 5/6.
15	336–441	Fine- to medium-grained sand and silty sand with stringers and thin interbeds of silty clay and clay. Moist color: sand and silty sand, 7.5YR 6/6–4/6, clay 5YR 5/4.
14	441–464	Interbedded silty fine-grained sand, silty clay and clay, and fine- to medium-grained sand. Some clay interbeds more than 2 ft thick. Moist color: sand and silty sand, 7.5YR 5/4–5/6, clay 5YR 5/4–4/6. *Top of Atrisco member of Connell et al., this issue.*
13	464–535	Fine- to medium-grained sand and silty sand with thin interbeds of silty clay and clay. Moist color: sand and silty sand 7.5YR 6/4–5/6 and 10YR 6/4–5/4 (508–534 ft), clay 5–7.5YR 5/4–4/6.
12	535–624	Clay and silty clay with interbedded fine- to medium-grained silty sand. Finely laminated clay beds from 544 to 606 ft. Moist color: clay 5–7.5YR 5/4–4/6, and 10YR 6/3–5/4, sand and silty sand 7.5–10YR 6/4–5/4.
11	624–710	Fine- to medium-grained sand and silty sand with silty clay interbeds. Moist color: sand and silty sand 10YR 6/3–4/4 and 7.5YR 6/4–4/4, clay 7.5–10YR 5/4–4/4.
10	710–751	Silty fine-grained sand with laminated clay interbeds at 712.9 to 723.5 ft and at 748.2 to 750.7 ft. Moist color: sand and silty sand 2.5Y 6/2–4/2, clay 2.5Y 5/2–4/2.
9	751–786	Silty fine-grained sand with silty clay interbeds, fine- to medium-grained sand with scattered coarse-grained sand between 770 and 780 ft. Pebble gravels near 776.5 ft. Moist color: 10YR 6/6–5/4 and 10YR 6/2, clay interbeds near 784 ft 5YR 5/4. *Base of Atrisco member of Connell et al., this issue.*
8	786–1,017	Fine- to medium-grained sand and silty sand with coarse-grained sand layers, scattered granules and pebbles. Pebble gravels recovered near 825, 833, 843, and 860 ft. Thin (< 1 ft) silty clay and clay interbeds between 850 and 880 ft and near 978 ft. Moist color: 10YR 6/3–4/4 and 7.5YR 6/4–5/4.
7	1,017–1,076	Interbedded fine- to coarse-grained sand and silty sand with thin silty clay interbeds. Pebbly sand layer near 1,031 ft. Moist color: 10YR 6/3–4/4 and 7.5YR 6/4–5/4.
6	1,076–1,246	Fine- to coarse-grained sand with granular and pebbly sand layers. Pebble gravels recovered near 1,085, 1,113, and 1,183 ft. Moist color: 10YR 6/2–5/4.
5	1,246–1,291	Fine- to medium-grained sand with scattered thin interbeds of silty fine-grained sand and clayey silt. Pebbly sand near 1,261 and 1,284 ft. Moist color: 10YR 6/3–5/4.
4	1,291–1,341	Fine- to coarse-grained sand with granular and pebbly sand layers. Pebbles recovered near 1,323 and 1,338 ft. Moist color: 10YR 6/2–4/2 and 10YR 5/4.
3	1,341–1,399	Fine- to medium-grained sand and silty sand with thin interbeds of compact silt and clayey silt. Moist color: 10YR 6/2–4/3.
2	1,399–1,483	Fine- to medium-grained sand with scattered coarse-grained and granular sand layers. Moist color: 10 YR 5/1–4/1 and 10YR 6/2–4/3.
1	1,483–1,500	Fine- to medium-grained sand with interbedded compact silty fine-grained sand and clayey silt. Moist color: 10YR 5/3–4/3.

Lithostratigraphic and hydrostratigraphic correlations

To examine lithostratigraphic changes in Santa Fe Group deposits over a wider geographic area, geophysical logs for city production and test wells near the 98th St site (Fig. 1) were digitized using a flat-bed scanner and NIH Image software (Rasband and Bright, 1995). Correlation of wells in the West Mesa area using electrical logs is facilitated by a distinct shift in electrical conductivity values found at 786 ft deep in the 98th St borehole (Fig. 2) that corresponds to a change from coarser-grained sediments (below) to finer-grained deposits (above).

Electrical conductivity logs for selected wells (Fig. 3) show that major stratigraphic features identified at the 98th St site are mimicked throughout the Albuquerque West Mesa area. In particular, the Santa Fe Group aquifer system in this area consists of a lower, relatively coarse grained interval and an overlying, upward-coarsening, fine-grained interval, as indicated by borehole electrical response. The boundary between these intervals can be placed within several meters using electrical logs, and this boundary provides a stratigraphic marker that may be used to correlate strata beneath the West Mesa area.

Kelley (1977) proposed an informal lithostratigraphic scheme, modified from Bryan and McCann (1937), Galusha (1966), and Lambert (1968) that subdivided Santa Fe Group deposits in the basin into lower (Zia), middle (middle red), and upper (Ceja) stratigraphic units. The Ceja is now considered to be a member of the upper Santa Fe, Sierra Ladrones Formation (Machette, 1978) that is primarily restricted to gravely deposits capping the Llano de Alburquerque (Lucas et al., 1993; Hawley et al., 1995). The upper coarse-

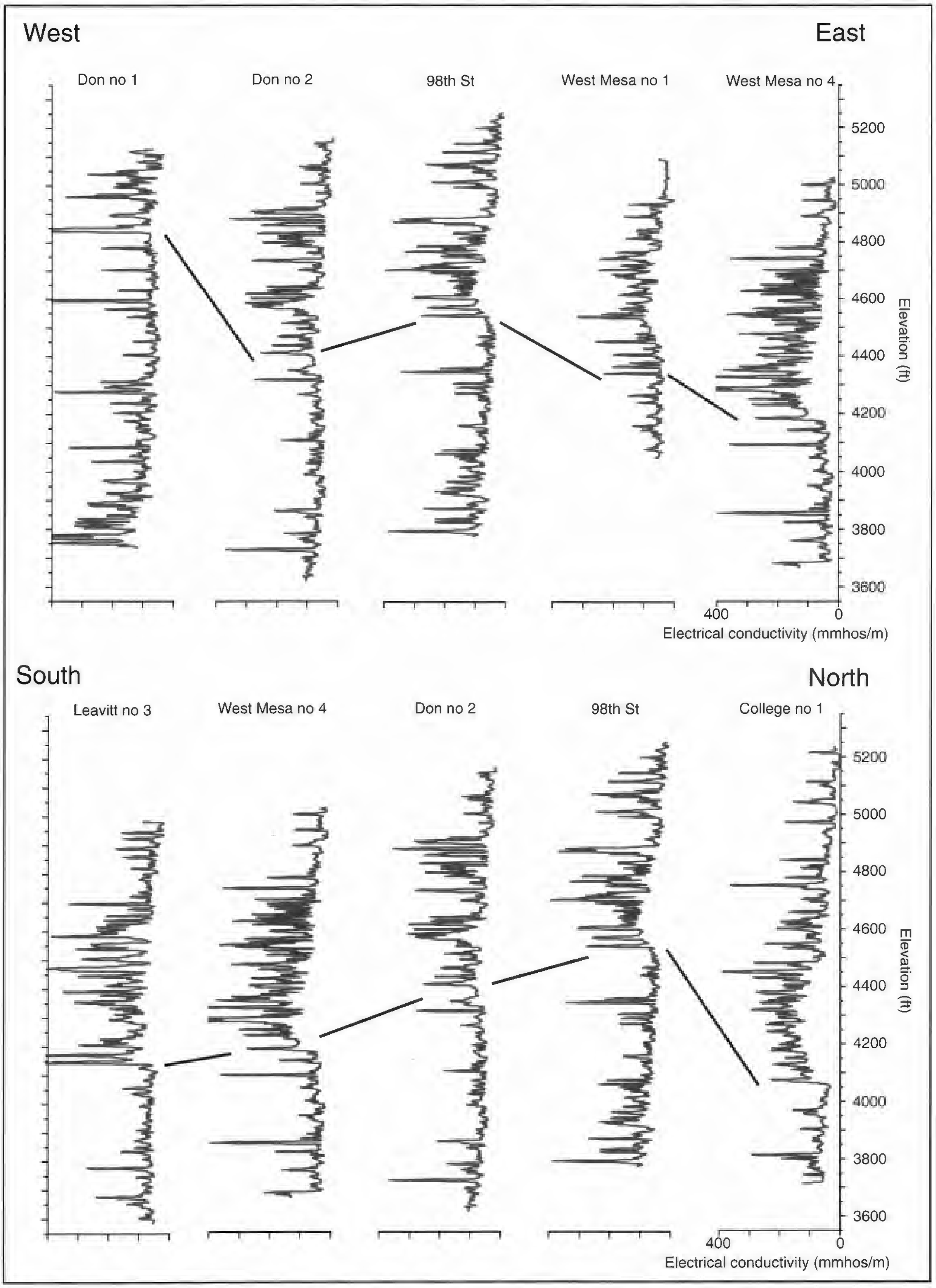

FIGURE 3—Electrical conductivity logs for selected wells showing structural offset of base of fine-grained unit that can be traced throughout the Albuquerque West Mesa area. See Fig. 1 for location of wells and major bounding faults.

grained interval at 98th St (19–97 ft, Fig. 2) probably corresponds to the basal part of the Ceja Member, on the basis of Kelley's (1977) defining criteria for the unit (presence of gravels) and the surface elevation of the 98th St site. All strata below 97 ft at the 98th St site would fall either within the unnamed middle red member of Kelley's (1977) Santa Fe "Formation," or in a gradational zone between Machette's (1978) Sierra Ladrones Formation and an undivided middle Santa Fe Group basin fill.

The lower coarse-grained and middle fine-grained intervals at 98th St cannot be differentiated under present classification systems, although the two units are thick enough and areally extensive enough to be differentiated at most mapping scales. Lithostratigraphic nomenclature for the Albuquerque Basin is currently being revised as the result of a Federal and State cooperative mapping and test-drilling program (Bartolino, 1997). Because of this state of flux, formal assignment of formational and member names to basin-fill units is not presently recommended.

In the informal classification system being developed for delineation of major hydrologic units in the Albuquerque Basin (Hawley, 1992, 1996; Hawley et al., 1995) the contact between the lower coarse-grained and middle fine-grained intervals in the 98th St borehole corresponds to the base of the Atrisco member of Connell et al. (this issue). In current investigations (Hawley, 1996; Connell et al., this issue), the middle fine-grained interval in the 98th St borehole is correlated throughout much of the Albuquerque metropolitan area with a thick, interbedded clay-silt-sand sequence that has been selected to *mark the top* of the middle Santa Fe hydrostratigraphic unit, rather than the base of the upper Santa Fe unit as originally done by Hawley and Haase (1992, plates 3, 4). This fine-grained interval is here recognized as a transition zone that separates the primary (upper Santa Fe) aquifer system used in much of the Albuquerque area from the underlying, middle Santa Fe hydrostratigraphic unit.

Hydrogeologic implications

Efforts in the central Albuquerque Basin that have focused on the hydrogeology of the basin fill beneath the Albuquerque area (Hawley, 1992, 1996) have increased our understanding of the complex structural and stratigraphic relationships exhibited by deposits of the Santa Fe Group. The borehole and geophysical evidence from Albuquerque's West Mesa presented here are a continuation of these efforts and illustrate the importance of electrical conductivity logs in differentiating major hydrostratigraphic units in the Santa Fe Group aquifer.

Geophysical logs from Albuquerque's West Mesa reveal structural and related stratigraphic relationships that may have a substantial bearing on hydrologic properties of the Santa Fe Group aquifer in this area. For example, down-to-the-east structural offset of more than 200 ft between the 98th St and College No. 1 sites is indicated from the electrical logs of these holes (Fig. 3). As a result of this structural offset a corresponding thickness of comparatively coarse-grained sediment exists on the downthrown structural block containing the College No. 1 well. Hence, coarser-grained and presumably more- permeable strata extend to a greater depth at the College No. 1 site relative to the 98th St site.

In the College, West Mesa, and Leavitt well fields (Fig. 1) much of the additional thickness of comparatively coarse-grained material includes upper Santa Fe deposits that are above the water table. However, additional, down-to-the-east structural offset occurs to the east of the West Mesa area (Hawley, 1992, plates 3, 4; Hawley et al., 1995), and many city well fields to the east produce entirely from a considerable thickness of highly permeable strata that stratigraphically overlie the middle fine-grained interval of the 98th St site.

Of equal hydrogeologic interest is the coarse-grained unit making up the lower 800 ft of the 98th St borehole. This unit steps down structurally toward the east as discussed above, but on Albuquerque's west side and beneath the West Mesa area it may constitute an important aquifer (Haase, 1992, p. V–13). For example, the Don No. 1 well (Figs. 1, 3), which is screened entirely in the lower coarse-grained interval of 98th St, yielded a specific capacity of 35 gpm per foot of drawdown after 150 min of pumping (GMI, 1988), more than 20 years after the well was completed.

Conclusions

Recently obtained core samples provide a unique opportunity to examine sediments that make up the aquifer system underlying the northern Albuquerque Basin. Comparison of sediment textures from these samples with corresponding logs of electrical conductivity demonstrates the usefulness of borehole geophysics in documenting major hydrogeologic features of the Santa Fe Group aquifer. Correlations between neighboring boreholes show that Santa Fe Group sediments beneath Albuquerque's west side, as for other parts of the Albuquerque Basin, exhibit consistent stratigraphic patterns that can be traced laterally for several kilometers. These stratigraphic patterns constitute the "ground truth" upon which numerical models of the groundwater flow system beneath Albuquerque and surrounding areas should be based.

ACKNOWLEDGMENTS—Drilling and core sampling at the 98th St site was performed by Dan Sweeney, with the assistance of Bryan Bretz, Art Clark, and Steve Grant. Peggy Johnson, Andrika Kuhle, Chris Menges, and Marlo Mikolas assisted in field descriptions and curation of sediment cores. Spencer Lucas and Frank Pazzaglia reviewed an earlier draft of this manuscript.

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Book review

The Hidden Sea, **by Francis H. Chapelle, 1997, Geoscience Press, Inc., Tucson, Arizona, 256 pp., $18.00, ISBN 0-945005-26-1.**

Francis Chapelle's *The Hidden Sea* is about underground water. No technical background is needed to understand the material. Chapelle tells the story of underground water in three parts. The first part, "Myths and Models," is replete with fascinating stories about man's early beliefs about underground water. One interesting tale concerns why water from some wells and springs cured certain diseases. For example, in some iodine-deficient areas many residents developed goiters. When people drank certain spring waters, their goiters were cured because the waters contained trace amounts of iodine. In ancient times, before the connection between iodine deficiency and goiter was known, these waters seemed to have a magical power over disease.

The second part of the book describes the nature of the geological materials that hold underground water and form the aquifers on which many of us rely for our drinking water. Chapelle does a masterful job of describing the nature of aquifers and ground water, as well as explaining why waters in different locations contain differing amounts of dissolved ions.

The third and final section of the book tells how water goes bad. Here Chapelle describes contamination of ground water by human activities. He points out that ground-water contamination is not a new phenomenon. For example, the ancient Romans noticed that the shallow wells they dug to supply drinking water often became too contaminated to drink. Much of this contamination was from sewage in open-hole latrines, often located close to the wells themselves. The Romans did not understand the relationship between sewage and bad water and erroneously concluded that ground water did not make good drinking water. As a result, they expended huge efforts building public aqueducts to bring in clean, pristine surface water from nearby mountains. Chapelle also explains modern contamination of ground water by a variety of sources in an exceptionally readable fashion.

The Hidden Sea is a wonderful introduction to ground water and how it may become contaminated. Chapelle's explanations are always easy to understand and he uses numerous interesting examples. This book is unique in its seamless integration of the history of our understanding of underground water with our present concern for preventing further ground-water contamination and cleaning up previously contaminated waters. *The Hidden Sea* is a must read for anyone concerned with understanding and preserving our natural ground-water resources.

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