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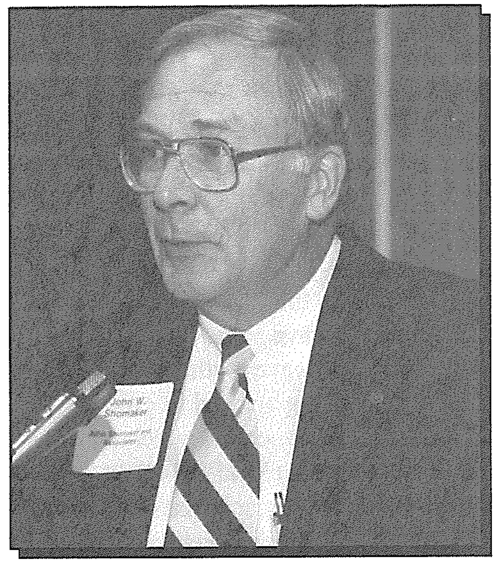

TRANSMISSIVITY OF THE ALBUQUERQUE AQUIFER: ESTIMATES BY ADVANCED LOGGING TECHNIQUES

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We now know that the conception of Albuquerque's aquifer as a great thickness of more-or-less uniform, highly transmissive, sand and gravel is inaccurate. The aquifer includes beds of relatively low hydraulic conductivity, and it appears that the only part of it that corresponds with our earlier picture is limited to the uppermost 600 to 1,000 ft below the water table. We also have learned that drawdowns have been, and are likely to continue to be, much greater than we had been expecting. It has become important to develop a better understanding of the aquifer, and that includes the need for a better grasp of the variation in hydraulic conductivity with depth.

Hydraulic conductivity has been estimated directly from pumping tests, and empirically from lithologic descriptions and interpretation of lithology from geophysical logs. The former has the disadvantage of integrating the properties of the aquifer over the entire open interval of the well, but giving no information about the unperforated intervals, and the latter provides hydraulic conductivity only through analogy with tests of other wells. There has been no direct way of estimating hydraulic conductivity for short intervals, in a new well, except for very cumbersome and expensive packer tests.

Our firm's (John Shomaker & Assoc.) work in support of Intel Corporation's application for a new groundwater permit included a multilayer groundwater flow model, and we wanted to have hydraulic conductivity information in foot-by-foot detail, to define quantitatively the principal layers in the aquifer. We asked Dr. Collier, our geophysical-log consultant, for help, and he recommended a new technique based on the Stoneley-wave response derived from the fullwave sonic log.

The Stoneley-wave method is a few years old, and is only now being applied to groundwater studies. There are two processing techniques: one offered by Schlumberger, and the other developed by a consortium at the Massachusetts Institute of Technology and being further developed and applied by New England Research, Inc. (e.g., Tang et al. 1991). We are planning a workshop for the National Ground Water Association meeting in May 1995, in which the techniques themselves will be explored; in this paper we will simply describe some early results, so that others may consider using the method to refine understanding of variation in hydraulic properties with depth.

A sonic-log tool generates several types of acoustic waves in a borehole. The Stoneley wave, sometimes referred to as the tube wave, is the acoustic wave that travels along the borehole wall. The geophysical-logging community has long recognized that the Stoneley-wave amplitude correlates with permeability. The reason for the correlation with permeability is this: as the wave travels along an impermeable borehole wall, it loses little energy, but along permeable formations the Stoneley wave loses energy by forcing borehole fluid into the pores of the formation.

The relation between attenuation of the wave and permeability is very complex, but a simplified model has been developed by Tang and others at New England Research. The input parameters required are:

- Stoneley-wave spectral amplitudes at each depth and receiver
- bulk density, compressional velocity and shear velocity of the permeable material
- porosity and pore-structure tortuosity
- density, acoustic velocity and viscosity of the pore fluid
- borehole diameter
- a reference hydraulic conductivity of some depth interval

Stoneley-wave data, compressional velocity, and shear velocity are derived from a full-wave form sonic log. Older types of sonic tool record only the compressional wave, which is the first to arrive at the receiver; a full-wave form sonic tool is required to record the entire wave train.

A density log with caliper provides bulk density and porosity of the aquifer material, and the borehole diameter; a neutron or sonic log also can provide porosity values. The tortuosity is estimated at 3 for porous rocks, and 1 for fractures. The pore fluid is assumed to have the same properties as the fluid in the hole. Where no independent hydraulic-conductivity value is available, the depth-interval with the greatest Stoneley-wave amplitude is assumed to have zero conductivity.

The locations of the two Intel wells in which we have applied the technique are shown on Figure 1. Figure 2 is a simplified cross section, showing the aquifer layers as they were defined for our model, based on standard log interpretation. Layer I, from the water table to about 445 ft, includes the highly productive braided-stream and other basin-floor alluvial and fluvial beds. These are mostly fine sand with thin lenses of coarse sand and fine gravel. Layer II, from 445 to 1,440 ft, represents an underlying sequence made up of both the conductive sands typical of Layer I, and basin-floor alluvial and playa-lake beds; Layer III, below about 1,440 ft, is made up of the clay-rich basin-floor playa lake and alluvial flat deposits. The Upper and Middle Santa Fe units are defined as in the work of Hawley and Haase (1992).

The construction of the completed Intel Well No. 2 is shown in Figure 3. Although the water level in the well is at about 265 ft, and the most permeable beds are in the uppermost few hundred feet, the perforated interval is from 730 to 2,000 ft. The highly productive interval from the water table to 730 ft was left "behind the pipe," and a bentonite seal was placed in the annulus from about 350 to 550 ft, to help protect the upper part of the aquifer from drawdown effects due to pumping. This was

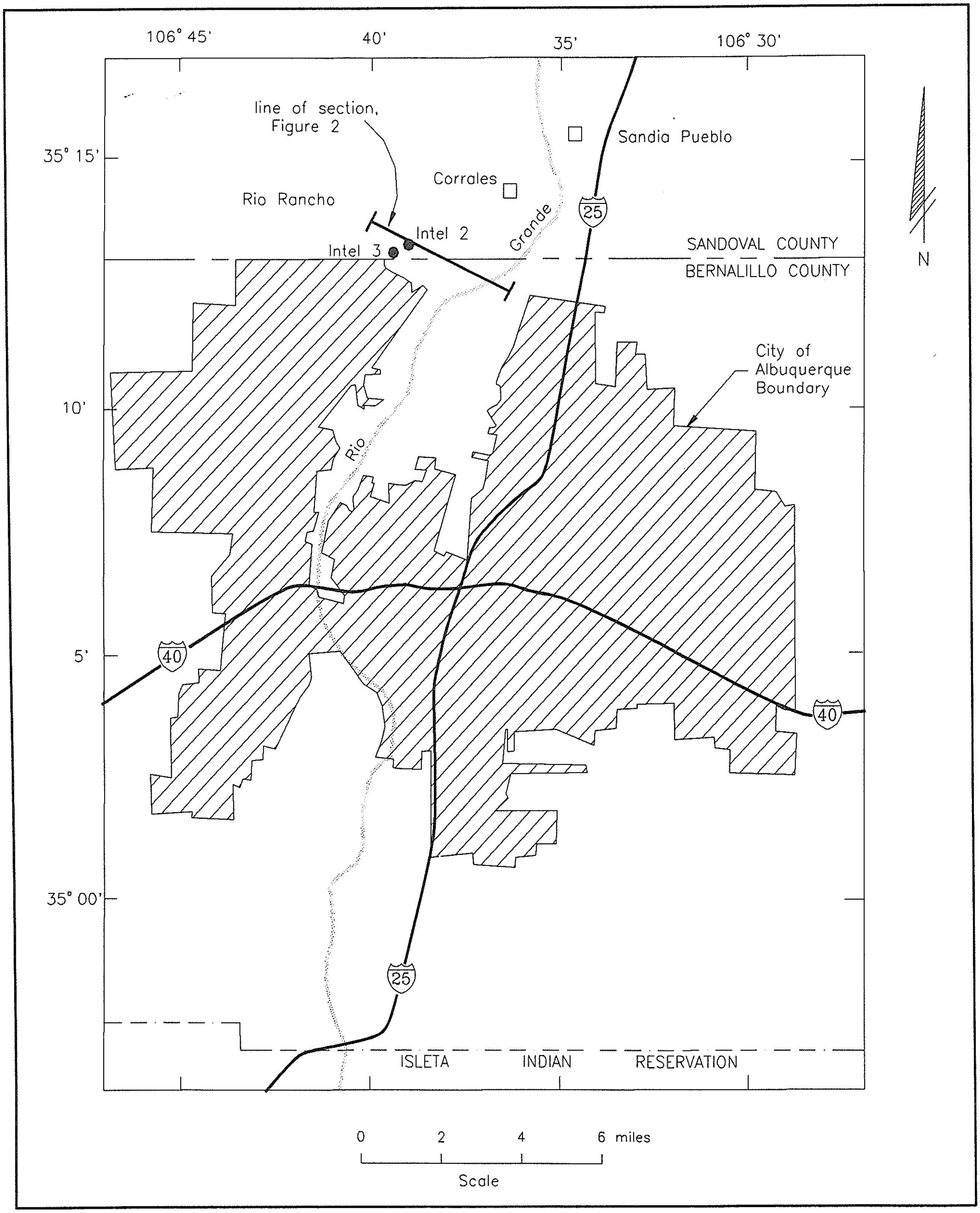

Figure 1. Map showing locations of Intel Corporation wells 2 and 3.

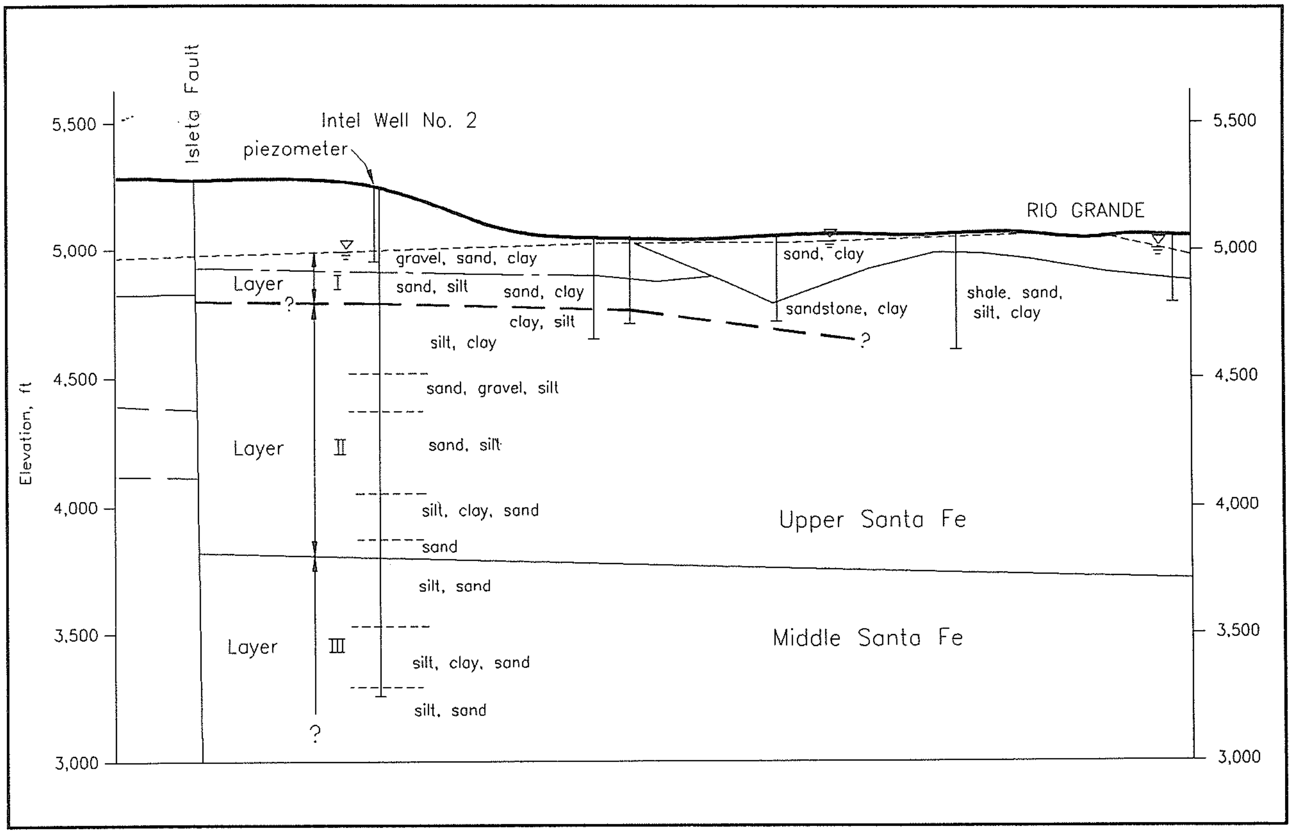

Figure 2. Simplified cross section showing aquifer layers as defined for the Intel Corporation groundwater flow model. See Figure 1 for line of section.

done in order to minimize effects on nearby shallow wells.

The log suites for the Intel wells were very elaborate; Figure 4 shows the induction-log response for the upper part of the Intel No. 2 well, to show both the large variation in character, and the way that the layers were defined. The resistivity log indicates a change, to generally lower resistivity and fewer high-resistivity beds, at about 450 ft, and the synthetic conductivity log (the word here refers to electrical, rather than hydraulic conductivity) shows a change to higher values, suggesting higher clay content.

A plot of calculated hydraulic conductivity versus depth is shown as Figure 5. This is the New England Research version. Transmissivity was calculated by summing the conductivity-times-thickness values for each one-half-foot increment of depth. Figure 5 also includes the gamma-ray, caliper, and density-log-based porosity.

Incremental hydraulic conductivity ranges from very low values, less than 0.1 gpd/ft^2 (0.01 ft/day) in clay beds, to high values for a few particularly clean sand or gravel intervals a few feet thick, approaching 1,000 gpd/ft^2 (130 ft/day). There is a very clear break at about 670 ft, above which the section includes very few low-conductivity clay beds, and in which hydraulic conductivity of the sands is in the range 100 to 400 gpd/ft^2 (13 to 53 ft/day). The mean hydraulic conductivity for this sequence is 407 gpd/ft^2 (54 ft/day) and the transmissivity is 87,500 gpd/ft (11,700 ft^2/day).

Below 670 ft, clay beds form a much larger proportion of the sequence, and the frequency of clays increases downward. In addition to that, the hydraulic conductivity of the cleanest beds is less than it is above 670 ft. The typical range is 40 to 150 gpd/ft^2 (5 to 20 ft/day).

In terms of hydraulic conductivity, it is clear that the major stratigraphic break is at about 670 ft, rather than at 445 ft as the conventional log inter-

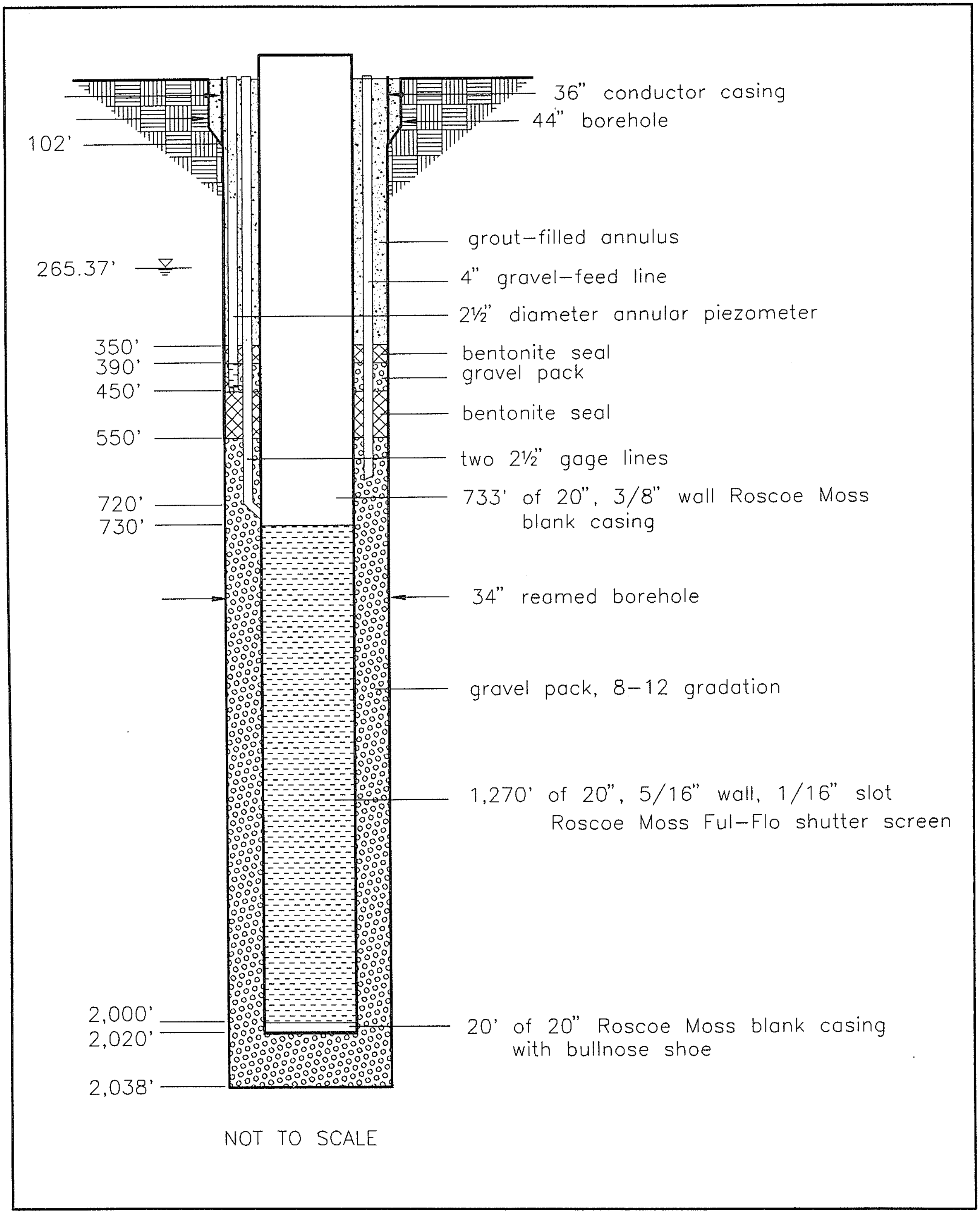

Figure 3. Construction diagram, Intel No. 2 well.

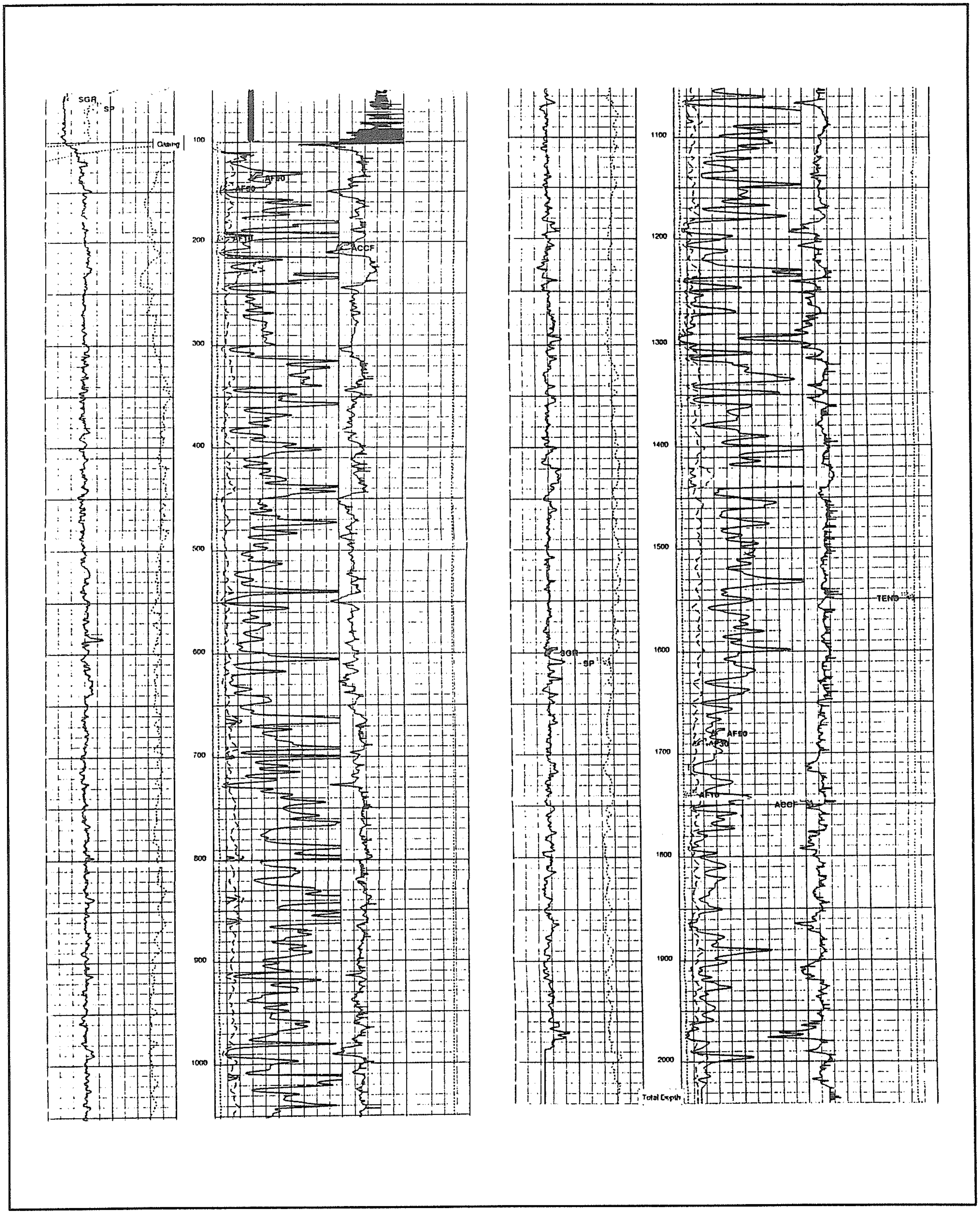

Figure 4. Induction log response for the Intel No. 2 well.

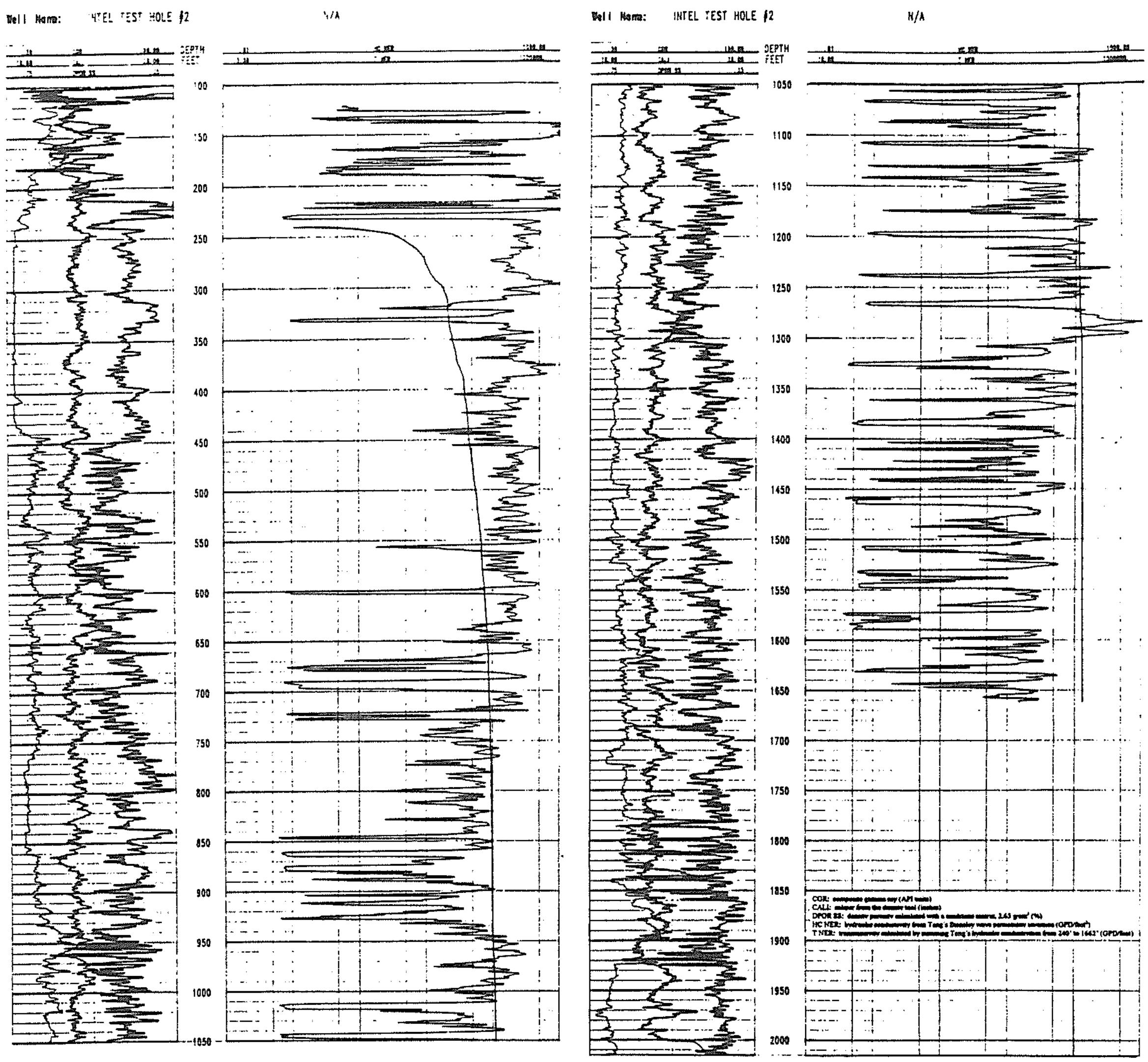

Figure 5. Plot of calculated hydraulic conductivity and transmissivity versus depth, Intel No. 2 well.

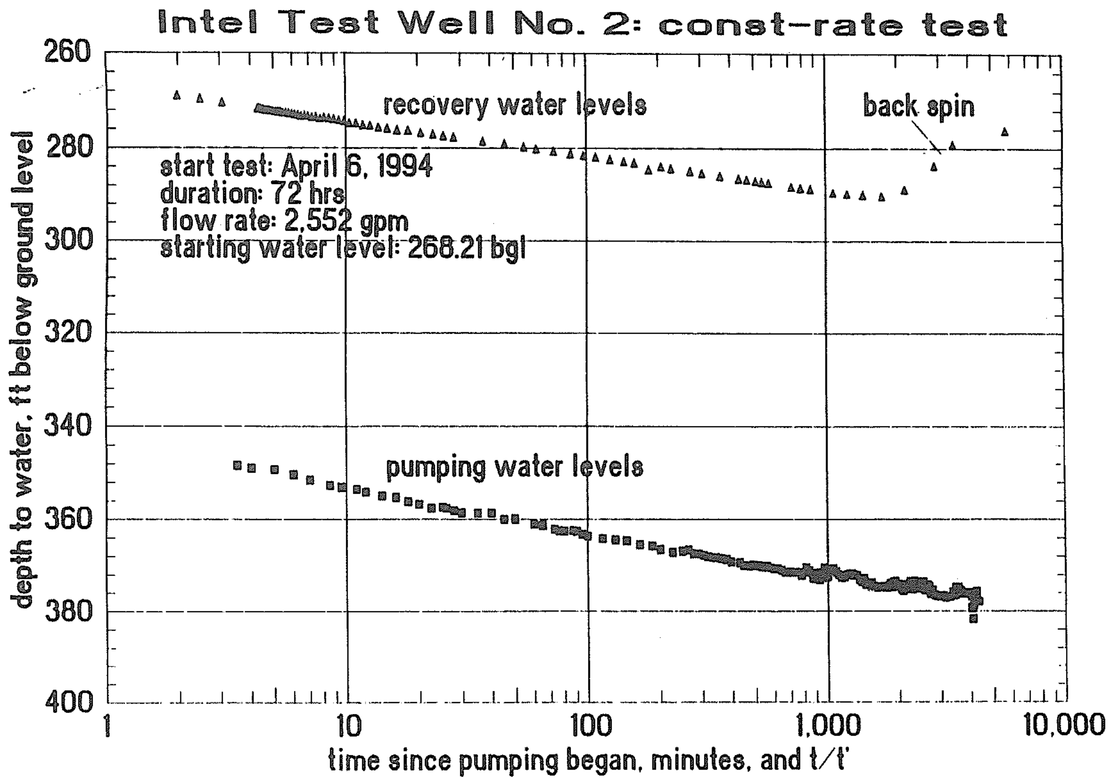

Figure 6. Plots of water-level measurements during drawdown and recovery, constant-rate test of Intel No. 2 well. Time scale for recovery measurements is time since pumping began divided by time since pumping stopped, t/t'.

pretation might suggest. The conventional interpretation would indicate that the interval from about 730 to 900 ft is as good as any interval in the hole, but the hydraulic-conductivity interpretation shows that such is not the case.

The standard against which to measure the Stoneley-wave-derived conductivity values is the result of the actual pumping test, which gives the transmissivity for the perforated interval as a whole. A plot of the constant-rate test of Intel No. 2 is shown as Figure 6; a transmissivity of 88,000 gpd/ft (11,760 ft^2/day) was estimated from the recovery plot. That value may be compared with the transmissivity derived by the New England Research algorithm from the geophysical logs, for the perforated interval in the well, which is 47,000 gpd/ft (6,300 ft^2/day).

It is also possible, of course, to break the producing interval into component parts. For example, the transmissivity of the zone from 730 to 1,440 ft, which was assigned to the second layer of the Intel model on the basis of conventional electric-log interpretation, is indicated to be about 39,000 gpd/ft (5,200 ft^2/day).

The interpreted log also allows us to estimate transmissivity for the intervals that were not completed and tested. Thus, in the Intel No. 2, the interval between the water table and the top of perforations has an estimated transmissivity of 96,000 gpd/ft (12,900 ft^2/day).

The Schlumberger interpretation gave a transmissivity considerably closer to that derived from the aquifer test: for the perforated interval only, the Schlumberger estimate was 72,000 gpd/ft (9,600 ft^2/day), about 18 percent lower than the measured transmissivity.

While the Schlumberger interpretation seems to have given the better value for transmissivity, and gives similar values for hydraulic conductivity in the mid-range, Schlumberger's values are lower for the cleanest sands and gravels, and higher for the clays, than those of New England Research. We have not yet established which interpretative technique is more reliable.

We tried the technique in the second well, Intel No. 3, which penetrated materials with significantly different characteristics. The principal difference in terms of applicability is that the well No. 3 pilot hole was considerably, and erratically, overgage, whereas the diameter of the No. 2 pilot hole was consistently close to the bit size. Because porosity is a principal component of the calculation of hydraulic conductivity, and the porosity estimate is strongly influenced by borehole diameter, the overgage hole in the No. 3 well may be the explanation of a significant underestimation of hydraulic conductivity.

Wall-cake attenuates the Stoneley wave, leading to an underestimation of hydraulic conductivity. The large diameters of the Intel pilot holes, 17-1/2 inches, made it impossible to evaluate wall-cake thickness, and this is likely to be a further source of error.

We are gathering geophysical-log data from more wells, and as time and funds permit, we expect to refine the use of the Stoneley-wave technique so that it can be used with confidence in the Albuquerque Basin and elsewhere.

This technique cannot be used in existing cased wells, but it has promise of offering quantitative information if applied in new monitor wells, or the pilot holes for new production wells. In the case of relatively small-diameter monitor wells, one may be able to have the equivalent of a full-scale pumping test without the expense of reaming, casing, developing, and pumping the well. It also will be possible, as in the case of the Intel No. 2, to estimate transmissivity in parts of a stratigraphic sequence that are not open to a well.

We wish to thank Intel Corporation for releasing the data from their wells, Xiao Ming Tang and New England Research for processing the sonic-log data, and Baroid Drilling Fluids and Tarleton State University's Organized Research Grant for providing financial support.

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