DEEP GROUND-WATER EXPLORATION IN THE FLAGSTAFF, ARIZONA AREA USING CSAMT

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ABSTRACT

Based on background geology, hydrology, and land restrictions, 14 different sites in and around Flagstaff, Arizona were selected for geophysical controlled source audio-frequency magnetotellurics (CSAMT) surveys for the purpose of siting deep ground-water wells. This is a difficult exploration environment, since the presence or absence of faults and fracture zones, below the deep ground water table, has a significant impact on the well production. Given that well costs in this area can be on the order of 1.5 million dollars, and that good production and very poor production locations can be separated by very short distances, well site selection is extremely important. The CSAMT surveys utilized very distant transmitters in order to acquire low frequency, deep data. At some sites, lines were added and re-oriented in order to aid in differentiating between the effects of cultural features (such as power lines, pipelines, fences, etc.) and the effects of valid subsurface changes. On the basis of all information, sites were prioritized, and the highest priority site, in the middle of a racetrack at the county fairgrounds, was drilled and completed early in 2008. The well has been successfully tested at over 1340 gpm, one of the highest production wells in the Flagstaff area.

Key Words: CSAMT, exploration, ground water, electromagnetic, resistivity, Flagstaff

BACKGROUND

As in many rapidly-growing southwestern cities, providing sufficient water for the community is becoming an increasingly difficult and important problem for Flagstaff, Arizona. Ground water production in this area is not from a traditional alluvial basin-like aquifer, but is heavily dependent on successfully intersecting deep fault and fracture zones. Two wells in the Lake Mary area, south of Flagstaff, are a good example of this problem- the Lake Mary 8 produces over 1,100 gpm, while the Lake Mary 5, just 2,000 feet away, barely produces one quarter of that amount. Approximately two miles away, the Lake Mary 7 well produces only 165 gpm, even though all three wells are in close proximity to the same fault mapped at the surface (City of Flagstaff, 2007). Given the deep ground water table, each production well costs in excess of $1,000,000, which makes site selection very important.

In preparation for new wells, 14 locations in and around Flagstaff were chosen for geophysical surveys; 43 lines of data were acquired, totaling over 110,000 line feet (21 miles) of coverage. Line location and orientation was determined on the basis of cultural features, property access, and known or suspected geologic structure.

The geophysical method used to further evaluate these sites was controlled source audio-frequency magnetotellurics (CSAMT), which is a resistivity sounding method used commonly in the minerals, geothermal, and ground water exploration industries, and is well-documented and described in detail in the peer-reviewed literature (Zonge and Hughes, 1991; Zonge, 1992). This method typically has better lateral resolution at depth than other resistivity methods, and is often logistically more efficient. In addition, it is our experience that as a far-field electromagnetic technique, CSAMT is less susceptible to cultural influences than near-field, galvanic techniques. Cultural influences include both active and passive man-made noise sources: active sources include features that generate electrical noise, such as power lines, cathodically-protected pipelines, and radio towers, while passive sources include features that distort the transmitted CSAMT signal such as fences, metal pipelines, and other man-made electrical conductors. The environment in and around Flagstaff, Arizona contains numerous cultural features, and was one of the primary reasons we selected CSAMT as the preferred geophysical method.

The CSAMT method involves transmitting a controlled signal at a suite of frequencies using a large grounded dipole antenna from one location, and in the target area, measuring the received electric and magnetic fields. For the Flagstaff surveys, the data were scalar, meaning that only the electric field parallel to the transmitter and the magnetic field perpendicular to the transmitter were acquired. The ratio of these two measured parameters is used to calculate the apparent resistivity at each frequency (also called the Cagniard resistivity). Vector and tensor CSAMT surveys are also possible, but are often substantially more expensive to acquire. Data were acquired for fundamental frequencies of 2 Hz to 8192 Hz in binary increments (2, 4, 8, ...Hz), in addition to the odd harmonics of these fundamental frequencies.

CSAMT RESULTS

Our prior work in this environment in northern Arizona indicates that faulted, fractured zones below the ground-water table are often characterized by decreased resistivities relative to surrounding material (Carlson, et. al., 2005). It is important to note, however, that in other environments, increases in resistivity are associated with areas of good groundwater production, hence the importance of correlating the geophysical results with known or suspected geological and hydrological information in the interpretation process (Carlson, et. al., 2007). The presence of ground water is not indicated by specific resistivity values, but may be indicated by a change to lower-than-background resistivities (indicating more saturation, more fracturing, or better connectivity of pore spaces) **or** by a change to higher-than-background resistivities (indicating less clayey materials or lower TDS water). Based on background hydrological studies and the City's prior production results, in the Flagstaff area the target was deep (approximately > 2000 feet) low resistivity zones that may indicate productive faults and fractures.

At the Fort Tuthill site near the Coconino County Fairgrounds, data were acquired originally on four lines, called Lines 0, 1, 2, and 3 (see Figure 1). These lines were oriented perpendicular to one of several suspected faults. Although several low resistivity zones were evident on these lines, there were also numerous cultural features intersecting or located very close to the lines, including fences, pipelines, buried utilities, and overhead power lines. Since most of these types of cultural features are often manifested as low resistivity effects in the CSAMT data, the interpretation of the low resistivity anomalies on the original lines was ambiguous. Several extension lines, called EX-0, EX-1, EX-2, and EX-3, were added in an effort to better evaluate anomalies. These lines were oriented roughly perpendicular to the original lines, in order to intersect the cultural objects at a different angle.

All of the data were then analyzed and modeled to produce resistivity versus depth plots. An anomalous zone that appears to have an attractive depth extent on Line EX-2 at station 875 was interpreted as the most likely location at this site for deep fractures that may be productive. Figure 2 shows the resistivity cross section for this short line, with higher resistivities shaded darker than low resistivities. Cultural features are noted along the surface, and formation tops (from the subsequent drilling) are noted down the right side of the cross section for reference.

As is often the case, a clear change in resistivity is not seen between several of the units, such as between the Coconino and the Supai formations; most rock types exhibit a range of resistivities, and many of these ranges of resistivity overlap. As a result, the resistivity sections sometimes do not provide well-defined contacts, particularly between similar types of lithologies. The low resistivity zone at depth beneath station 875 appears to extend fairly high in the section, but does not extend to the surface, suggesting that it is not a shallow feature that is artificially affecting everything beneath it (called a near-surface static effect). Although there is a suspected fault in this area, there is no mapped surface expression of the fault, which seems to agree with the CSAMT model. In examining the raw resistivity curves, it is important to note that the deeper data in this area extends into the "near-field" regime, meaning that modeling and interpretation are significantly more difficult. The deep data at station 875, however, are so low in resistivity that they do not go in to the near-field regime (unlike all surrounding stations), adding confidence to the interpretation that this location is strongly anomalous at depth (see Figure 3).

DRILLING RESULTS

In late October, 2007 using the dual rotary technique, drilling began at the Fort Tuthill site near station 875 of extension Line EX-2, and continued until late January, 2008 to a depth of 2520 feet (ADWR Well 55-907084). The dual rotary method proved its superiority in this hydrgeologic environment, known for caving, lost circulation, and deteriorating borehole conditions, with advancement of the casing as the well is drilled. During the drilling process, there was significant concern about the fact that the Coconino sandstone appeared to be extremely uniform with no indication of fractures, even though the CSAMT results suggest significant changes in resistivity beginning in the Coconino SS and continuing to the maximum depth of investigation at this location. This discrepancy could have several explanations. In the worst case scenario, the discrepancy could have been an indication that the mid- and low-frequency CSAMT data at that specific station were noisy or contaminated (perhaps by unknown cultural features), which would mean that the interpretation of a low resistivity fracture zone extending deep in the section was incorrect. An alternate explanation would be that the CSAMT modeling was significantly off in the vertical dimension, and that the low resistivity zone was deeper than indicated. A third explanation was that changes did occur within the Coconino SS that affected the resistivity, but that these changes weren't visible while drilling. [Note: while this third alternative probably could have been evaluated by downhole geophysical resistivity logs, the well was cased to 2000 feet, so no resistivity log could be performed to include the Kaibab, Coconino, or most of the Upper/Middle Supai formations (HSI, 2008).]

At 2000 feet the hammer bit became inoperable because of increased groundwater creating hydraulic resistance on the bit with a significant loss in the borehole penetration rate. This necessitated switching over to open borehole drilling with a tricone bit. Drilling encountered sizable fractures as shown in Figures 4a , 4b, and 4c. The driller terminated the borehole at 2520 feet and commenced air lift development (without foam) measuring the flow at approximately 500 gpm. With air lift development complete, testing of the well occurred by setting a submersible pump controlled from a variable speed drive at the surface.

Aquifer testing for the City of Flagstaff has a history of mixed results-some good and some bad (HSI, 2008). Some wells indicated fractured conditions and apparently favorable development observations, but resulted in low water production. Conversely, some wells experienced terrible drilling conditions, compromised well construction, and poor development but became the better water producing wells. Testing of the Fort Tuthill Well surprised everyone.

Prior to commencing aquifer testing, brief equipment operational testing of the well showed a pumping rate of 800 gpm with only 40 feet of water level drawdown. Based on this observation, the first step for aquifer testing had a pumping rate of 1225 gpm, which resulted in 97 feet of drawdown for a specific capacity of 12.63 gpm/ft after pumping the well for 18 hours. The specific capacity is simply a ratio comparing performance of a well expressed as production in gpm/ft of drawdown. The second step commenced the continuous rate test lasting slightly over five days having a pumping rate of 1340 gpm, 115 feet of drawdown, and ending specific capacity of 11.65 gpm/ft. Figure 5 shows the drawdown curve for testing at 1340 gpm. Sand produced from the well amounted to 1.76 ppm. The City has recenty equipped the Fort Tuthill Well to pump 1200 gpm into the distribution system. The Fort Tuthill is the highest production well owned and operated by the City. The specific capacity is almost double that of the existing City wells. The Fort Tuthill is truly a remarkable well when compared with many wells in this part of the Colorado Plateau.

CONCLUSIONS, CAVEATS, AND CONCERNS

Based on logistics, geology, and hydrology, with specific targeting using CSAMT, a very successful ground water well was drilled at Fort Tuthill by intersecting deep fractures below the piezometric surface (if the aquifer is confined or unconfined). Subsequently, two additional wells have been drilled by the City, also based on CSAMT survey data/results. One has been tested at over 325 gpm and the other well will be tested in the near future. While these and other successes certainly show the value of this method, it is important to reiterate that the CSAMT results must be modeled correctly and analyzed in the light of years of trained and experienced hydrogeologic interpretation. As we have noted, there is not a specific, fixed resistivity value that indicates water, and in some environments, the high resistivity features may represent the best target, while in other environments, it is the low resistivity features that should be targeted for ground water production. In addition, interpretation must include cultural features at the surface or near surface (ie pipelines), as well as method-specific considerations, such as resolution, multidimensional effects, and near-field/far-field effects. Like any surface-based observation or measurement, be it geological, hydrological, or geophysical, the extrapolation to the subsurface involves interpretation, which must be based on background supportive information and experience.

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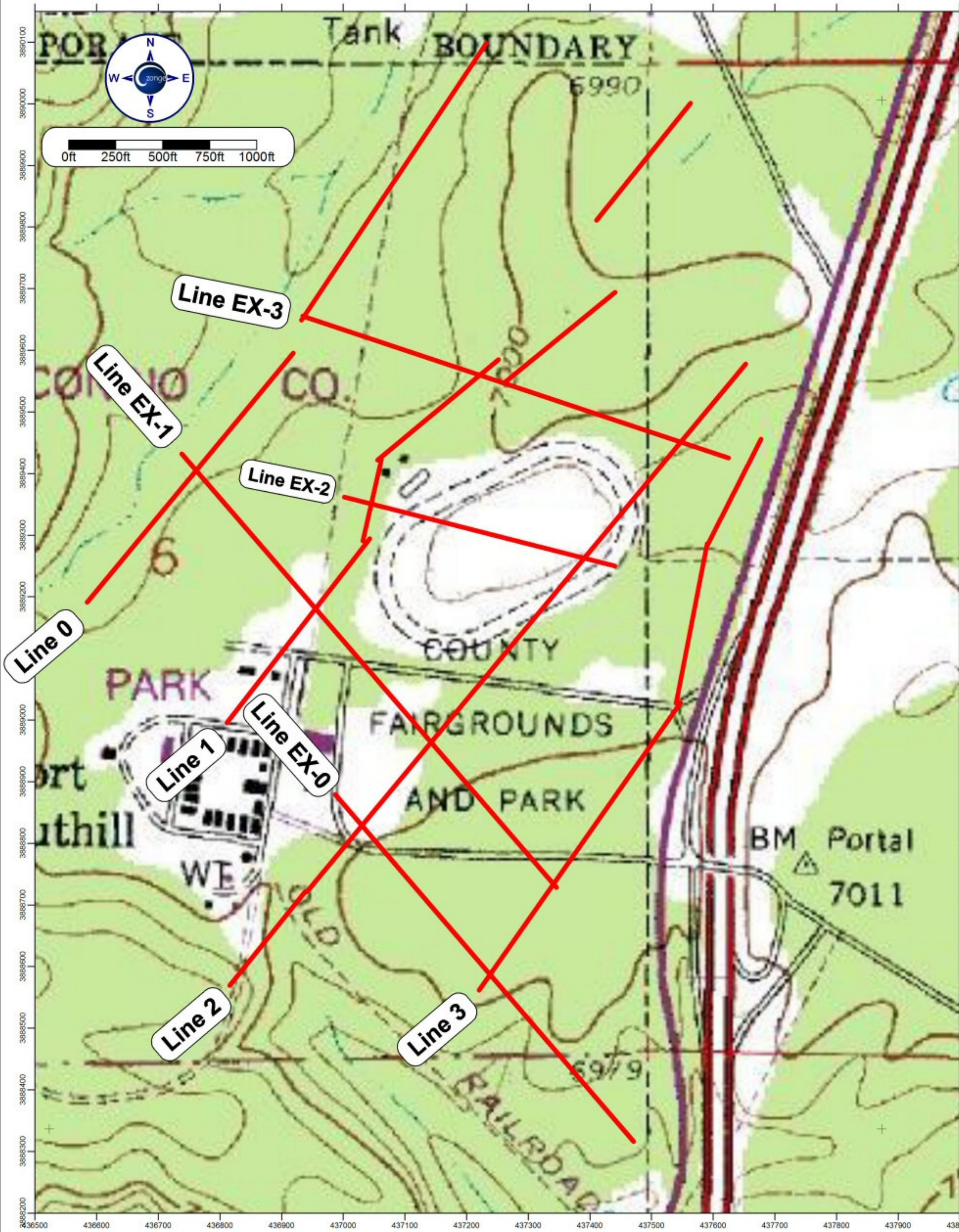

Lines 0-3 Receiver Data:
Length = 200 ft
Orient. = varies
October 7-9, 2004

Lines EX-0, EX-1, EX-2, EX-3 Receiver Data:
Length = 250 ft
Orient. = varies
December 2-4, 2004

Northwest Bipole Transmitter Data:
Length = 4200 ft
Orient. = N34E
Center at 1419840E,12769987N
Distance = 16100 ft (Line 0)

Northeast Bipole Transmitter Data:
Length = 2624 ft
Orient. = S75E
Center at 1433251E, 12777326N
Distance = 15945 ft (Line EX-3)

FIGURE 1: CSAMT line locations (heavy black lines) at the Fort Tuthill County Park near Flagstaff, Arizona.

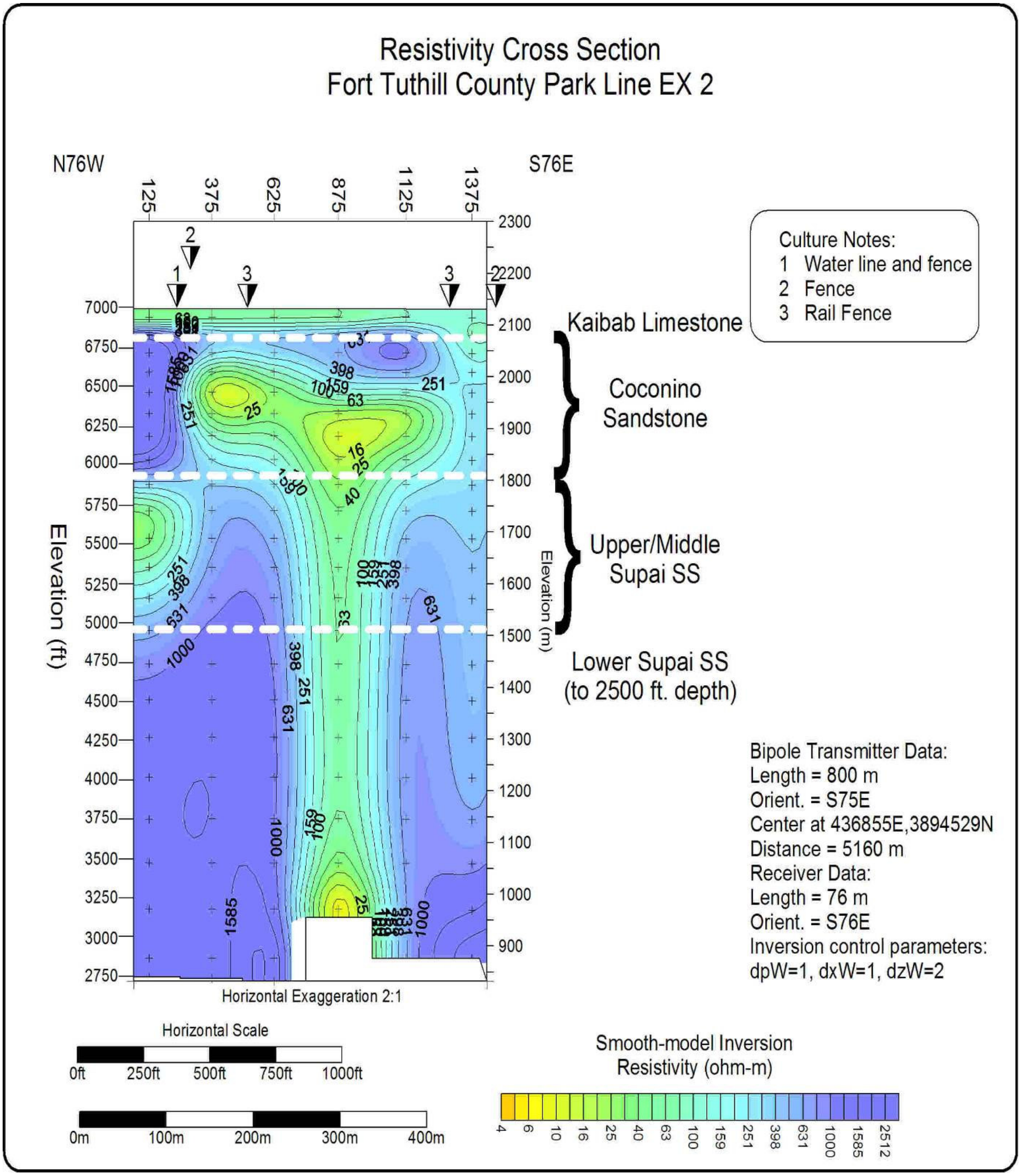

FIGURE 2: Resistivity cross section from the 1D smooth-model inversion of the CSAMT data for Line EX-2, with geologic notes based on drilling. The Fort Tuthill well was drilled on this line near station 875.

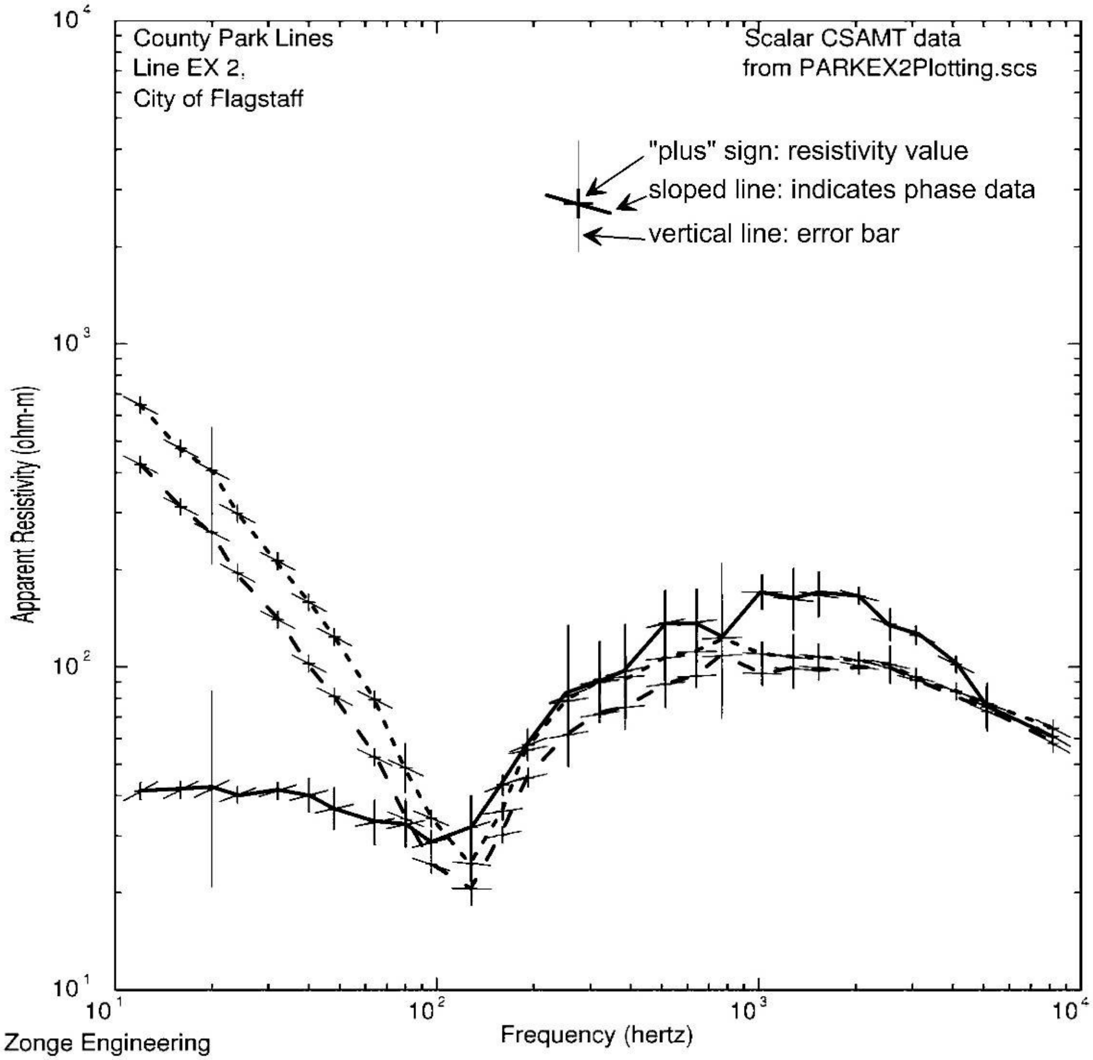

FIGURE 3: Raw resistivity versus frequency plot (before processing and modeling) for Line EX-2, stations 375 (short dashed line), 625 (long dashed line), and 875 (solid line), showing in particular the difference in low frequency data at station 875. The mid-frequencies are admittedly noisy, primarily from local culture.

FIGURE 4a:

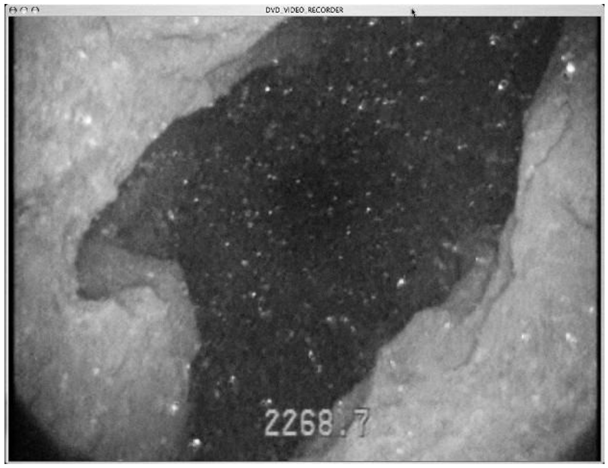

FIGURE 4b:

FIGURE 4c:

FIGURE 4a, 4b, and 4c: Downhole video camera images prior to setting casing showing a void (4a) and large fracture (4c) in the Fort Tuthill well. Depth in feet of the photo is shown on each image.

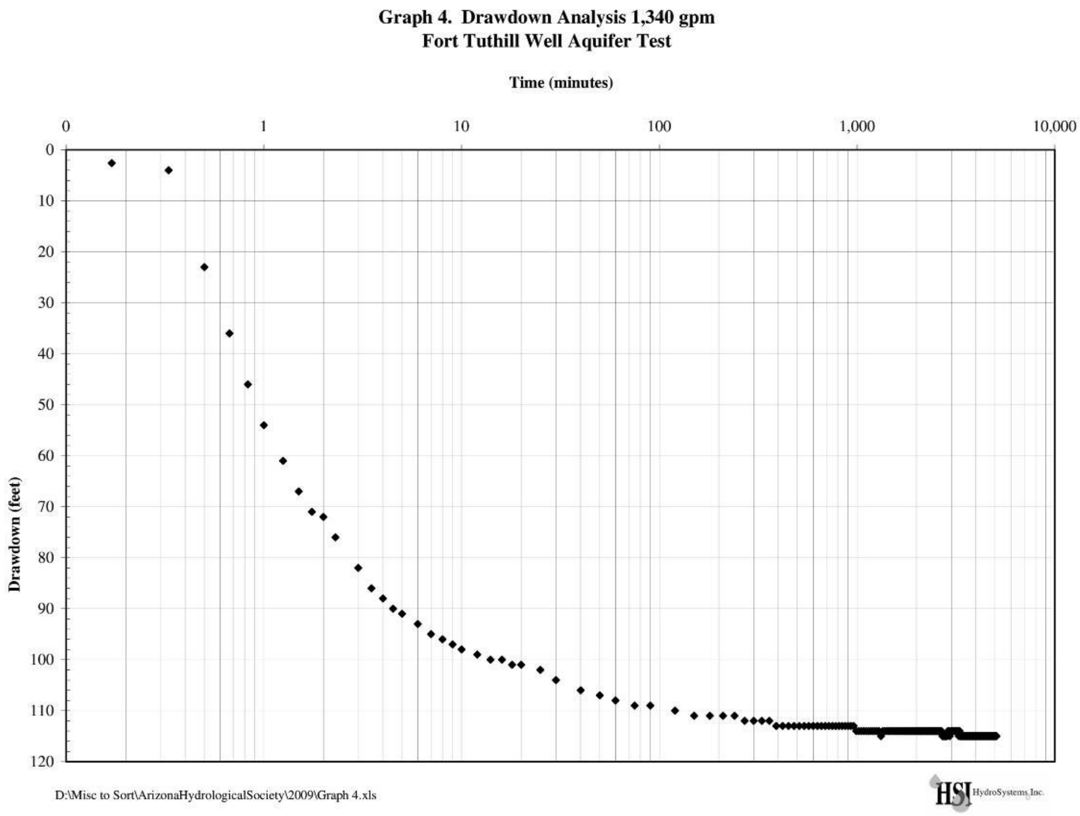

FIGURE 5: Fort Tuthill aquifer test with the discharge at 1340gpm.

FIGURE 6: Water flow during the aquifer test at Fort Tuthill.