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LITHOLOGIC, HYDROLOGIC AND PETROPHYSICAL CHARACTERIZATION OF AN UNCONSOLIDATED COBBLE-AND-SAND AQUIFER CAPITAL STATION SITE, BOISE, IDAHO

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ABSTRACT

The shallow unconfined aquifer in the Boise, Idaho area commonly consists of coarse, unconsolidated Quaternary braided-stream deposits (Qal) over unconsolidated late-Tertiary sands with a clay or tight silt zone (Tgf) forming a local base to the unconfined system. This shallow aquifer hosts numerous contaminant plumes so characterization of the variability of the system is applicable to site investigations, modeling and remediation designs. Subsurface information from conventional drilling methods tends to be generalized. However, analysis of natural gamma (G), epithermal neutron (N) and electromagnetically induced resistivity (IR) geophysical log data obtained in "deep" (~20 m) wells at the Capital Station site indicates that a high degree of vertical resolution of saturated units is possible, and that successions of units in Qal differ between wells only 6 m apart. Several lines of evidence (permeability profiling, core from one well, and FFT analysis) support the division of Qal and Tgf into fine-scale units (<0.3 to 1 m thickness) with log data. Also, N-G crossplots show distinctions between Qal and Tgf, and between sand and cobble-dominated units within Qal. Principal component analysis (PCA) provides a way to analyze IR data with N and G data. PCA separates sand and cobble-dominated units, and also provides the means for differentiating cobble-dominated units. Measurements of hydraulic conductivity in individual wells with flowmeter and slug test methods yield similar results for units and wells tested: Tgf sands are more permeable than Qal cobble units. Estimates of porosity are generated from N data, and estimates of "shape-factor" are generated from these porosity logs with IR data. High-IR cobble units recognized with PCA also have high shape-factor values; sedimentologic and hydrologic implications of cobble-unit distinctions are being investigated.

INTRODUCTION

Aquifers in unconsolidated cobble-and-sand (braided-stream) deposits are ready sources of groundwater for a variety of uses, but such aquifers also are vulnerable to contamination. Ground water remediation in these aquifers is complicated by the marked lateral and vertical variability of sedimentologic facies. The field characteristics of coarse braided-stream deposits have received considerable attention from examination of modern braided streams (e.g., Williams and Rust, 1969; Boothroyd and Nummedal, 1978), and of recent and ancient deposits in outcrop (e.g., Ore, 1964; Jussel et al., 1994). In subsurface investigations, however, drilling methods such as auger or rock-bit drilling mix and/or grind cobbles with the sand matrix so only generalized information is recovered from these units.

This paper addresses the general problem of recognizing and characterizing, in boreholes, the variation in coarse, unconsolidated alluvial sediments such as braided-stream deposits. Recognition of the location or nature of sedimentologic and associated hydrologic, geophysical and petrophysical variations within and between coarse-grained units is valuable for hydrogeologic or

engineering investigations in such aquifers, and for reconstructing sedimentary environments. Investigations at the Capital Station site in Boise, Idaho indicate that detailed lithologic, hydrologic and petrophysical characterization of cobble and sand deposits is possible using accessible borehole methods. We report here primarily on results from borehole geophysical logs, petrographic analysis and single-well hydrologic tests; additional borehole geophysical investigations with vertical seismic profiling at the Capital Station site are reported elsewhere (Michaels and Barrash, 1996, 1997; Michaels, in review).

BACKGROUND

The Capital Station site in downtown Boise, Idaho (Fig. 1) is about 0.5 km from and <10 m elevation above the present Boise River. Shallow deposits at the site belong to two stratigraphic units below a soil/industrial fill zone (Fig. 2). The upper unit is late-Quaternary alluvium (Qal), glacial outwash consisting of cobble and sand lenses, that originated in the upper Boise River drainage. The Capital Station site lies on the lowest, youngest terrace (Boise terrace) of a series of such deposits (Othberg and Stanford, 1992; Othberg, 1994). The lower unit is Pliocene Glens Ferry formation (Tgf) of the Idaho Group (Squires et al., 1992; Wood, 1994) which locally consists of sand, silty sand, and clay over a tight silt that forms the base of the shallow, unconfined aquifer at the site. Static water levels are 5-6 m below land surface, depending on seasonal fluctuations in a given well.

Tetrachloroethylene contamination was discovered in the shallow aquifer at Capital Station in 1990 prompting a site investigation (USPCI, 1992) and subsequent remediation with an air sparging system (Anderson Associates Inc., 1994). To date more than 50 wells have been emplaced at the site including shallow wells across the water table for monitoring or vapor extraction, and deep monitoring or air injection (sparge) wells that generally are screened over 0.3 to 1.5 m intervals in Tgf sand (Fig. 2). This paper discusses results from investigations in the 14 "deep" monitoring wells completed to ~20 m with 5-cm diameter PVC casing and screen. Only generalized lithologic logs are available from these wells (Fig. 3), although more detailed information and core have been recovered from several monitoring wells emplaced in the last several years (Anderson Associates Inc., unpubl. data; Barrash et al., 1997).

RECOGNITION AND RESOLUTION OF LITHOLOGIC UNITS

Borehole geophysical log data were collected by the U.S. Geological Survey as part of a cooperative study with Boise State University. Data are available from natural gamma (G) and epithermal neutron (N) logs run in 14 wells, from electromagnetically induced resistivity (IR) logs run in eight of the 14 wells, and from heat-pulse flowmeter logging in conjunction with pumping in one of the 14 wells. For G, N and IR logs, digital data were collected at 0.06 m intervals and resulting logs have been smoothed with moving average filters to remove high-frequency noise. Only data collected below the water table are presented and discussed in this paper.

As noted above, some detailed lithologic data and analysis of samples from drilling and coring are available for comparison against geophysical log responses. These data support log interpretations where: intervals with relatively low N and G count rates correspond with sands, intervals with relatively high and somewhat parallel trends of N and G count rates correspond with cobble-dominated units, and intervals with high G and relatively low N count rates have clays. Following these interpretations, borehole geophysical logs indicate that there are frequent vertical sedimentologic variations in the deposits at Capital Station, and that these variations commonly

cannot be traced laterally between wells even over distances as small as 6 m (Fig. 4).

Resolution of Fine-Scale Units

Fine-scale units (<0.3-1 m thick) are picked where changes in two or three logs coincide or where change in one of the logs is significant (Fig. 5). We recognize that these criteria are somewhat subjective and that some fraction of changes may be due more to variation associated with Poisson nuclear decay statistics than lithology (more of an issue with G than N logs here because of lower G count rates [e.g., Keys, 1990]). Also, the meaning of a given fine-scale unit may be ambiguous because of volume averaging by the logging tools (greater effect for thin units) and/or the influence of large cobbles. Still, picking units at such fine scale may be useful for: (1) assigning physical properties to sedimentologic units to assess the variation of properties with variations in lithology; (2) gaining interpretive or statistical insight into relations between and among physical properties and sedimentologic character; (3) recognizing facies associations, and quantifying vertical succession occurrence and geostatistical parameters; and (4) providing reference locations for comparing positions in various data-exploration crossplots (e.g., N-G and principal component analysis - see below).

The validity of resolving fine-scale units (while not assuring correct selection in all cases) can be demonstrated in three ways. First, where core was recovered in well BSU1 through 3 m of a composite cobble-dominated unit, several clean gravel zones ~0.2 m thick intercalated with the cobbles can be recognized in core and in geophysical logs, especially in the IR responses (Figs. 6-7). Second, where hydraulic conductivity (K) was measured at 0.6 m intervals in well SPT2 (by logging with the heat-pulse flowmeter while pumping [see below]), recognizable variations in K correlate well with fine-scale lithologic variations that can be recognized from N and G log responses (Fig. 8). Third, Fast Fourier Transform analysis, or FFT (e.g., Brigham, 1974), of digital data from individual N, G and IR logs recorded at regular 0.06 m intervals shows that meaningful frequencies (i.e., unit thicknesses) for each log type occur at ~0.2 m thickness, which is well above the Nyquist frequency of 8.2 cycles/m, or an equivalent minimum theoretically resolvable (full wavelength) unit thickness of 0.12 m.

Lithologic and Stratigraphic Identification

N-G Crossplots

Examination of crossplots of N and G count rates from the 14 deep wells at Capital Station reveals substantial diversity in detail between wells, but also an underlying pattern related to sedimentology and stratigraphy. Using data points labeled as fine-scale unit numbers along with coring/drilling information from several wells for reference, it is evident that: (1) Qal sands plot in a region with a linear trend at relatively low N and G counts per second (cps); (2) Qal cobble-dominated units plot in a region with relatively high N and G cps; (3) anomalously high G count rates occur in units having clay influence; and (4) Tgf sands generally plot separately from Qal sands and at lower G cps for a given N cps (Fig. 9).

The Quaternary alluvial deposits have favorable characteristics for interpretation based on G, N and IR logs. In particular, these deposits generally are unlithified, unaltered and uncompacted. Silt or clay lenses are rare to nonexistent, although minor amounts of silt and clay are included within some sand and cobble-dominated units. The source material for the Quaternary braided-stream deposits is almost entirely high-gamma-producing Cretaceous and Tertiary "granitic" plutons (Swanberg and Blackwell, 1973), with minor Tertiary basalts, Tertiary felsic volcanics and dikes,

and Paleozoic and Precambrian metasediments (Mitchell and Bennett, 1979a,b; Worl et al., 1991; Fisher et al., 1992) (Fig. 10). That is, the source factors which can complicate the interpretation of G, N and IR logs in clastic sedimentary rocks are limited in Qal from the upper Boise River drainage: sediment composition is nearly uniform; natural gamma-production rates are well above background; cementation is minimal; and primary or diagenetic clays (i.e., effects of increased presence of radioisotopes due to adsorption and ion exchange, bound water and electrical conductivity) are minimal or concentrated in few units. It should be noted that these assumptions can be verified in mixed lithology sediments of similar deposits if boreholes are completed with ≥ 7.5 cm PVC casing. Larger boreholes permit larger diameter dual-detector neutron (i.e., porosity) and gamma-gamma (i.e., bulk density) tools to be used instead of the smaller diameter single-detector neutron and natural gamma tools that do not directly yield porosity or bulk density results in mixed lithology settings.

As a first approximation, then, responses in Capital Station wells to the G log represent saturated bulk density (nearly uniform high-gamma-producing, clay-poor, uncemented sediment), responses to the N log (as cps) similarly represent saturated bulk density (clay-poor, uncemented sediment), and responses to the IR log represent some combination of surface area and interconnected porosity of the saturated bulk sediment. The linear N-G relationship for Qal sands (Fig. 9) corresponds to an inverse relationship between saturated bulk density (or sorting, packing) and porosity; this relationship is not valid for cobble-dominated units where grain-size distribution and texture are bimodal and the sampling volumes of the logging tools may not be large enough to adequately average the cobble rock types in the immediate vicinity of boreholes. Figure 11 is a crossplot for all Qal sand units and shows their linear N-G trend.

Qal sands can be distinguished from Tgf sands on N-G crossplots by relative position as noted above. Petrographic data also support this stratigraphic differentiation. Qal composition and texture are consistent with the limited "granitic" provenance of the Boise River drainage, whereas the more varied composition and textural inversion in rounding of the Tgf sand are consistent with the more diverse provenance of the Snake River drainage. The mixed provenance of Tgf sands explains why these units have lower relative G cps for a given N cps than the pluton-derived Qal sands. Also, the differentiation of Qal and Tgf sands based on N-G responses is consistent with relative stratigraphic position; data points referencing fine-scale unit locations in crossplots demonstrate that Tgf sands are always at the base of the section and Qal sands are always above the base and intercalated with cobble units.

Fine-scale units influenced by clay have significantly higher G count rates for a given N count rate (Fig. 9). It is common for one prominent clay-influenced unit to occur immediately above Tgf. However, this unit was cored in SPT3 and is dominantly a coarse sand. And clay or silt units per se have not been observed above the Tgf sand at the Capital Station site or in nearby outcrops or quarries in Qal. Hence the term "clay-influenced" unit.

Principal Component Analysis of Qal Units

Barrash and Morin (1996, in review) applied principal component analysis (PCA) to N, G and IR data for all Qal units in the eight deep wells at Capital Station having IR data in order to gain resolution not otherwise evident in the cobble-dominated field of N-G crossplots (Fig. 9). PCA is a multivariate data analysis technique that combines statistical and data transformation methods (e.g., Davis, 1986). Because the relative percentages of variance explained by the three principal components (PCs) are unequal, such that a large majority of the variance may be explained by two PCs, the dimensionality of the system was reduced from three to two, thus simplifying plotting and

interpretation. Physical meanings of the PCs are discussed in Barrash and Morin (1996, in review). Sand and cobble units plot in distinct fields on PC3-PC2 crossplots across a line equivalent to ~450 N cps, as on N-G crossplots. PCA revealed that cobble-dominated units may be divided into relatively high- and low-IR units with the divide occurring at ~135 Ω -m. In addition, relative positions for cobble units within high- or low-IR fields can be further characterized as having relatively higher or lower N cps (i.e., lower or higher porosity, respectively) (Fig. 12).

HYDROLOGIC CHARACTERIZATION

Two types of single-well methods have been used to measure hydraulic conductivity (K) at the Capital Station site: logging with a heat-pulse flowmeter while pumping (Molz et al., 1989) and slug tests. The logging method was performed in well SPT2 which has a long screen; the investigated section has ~6 m of Qal cobbles and ~3 m of Tgf sand and silt (Fig. 8) with measurements taken at 0.6 m intervals. In the cobble section of SPT2, K is below 0.01 cm/s (the lower K threshold is constrained by the resolution limit of the flowmeter). In the Tgf sand and silt of SPT2, K ranges from <0.01 to 0.11 cm/s depending on the porosity and sorting of fine-scale units recognized in core and with N and G logs (Fig. 8, Table 1).

Slug tests provide K estimates consistent with logging results, albeit at a larger scale of investigation. Slug test K estimates are reported here for six deep wells with analytic and repeatable test results (Table 2); one well is screened in a Qal cobble unit and five wells are screened in Tgf sands. BSU1 is screened in a cobble-dominated section with three thin (~0.2 m) gravel zones (Figs. 6-7). The K estimate from slug tests in BSU1 interpreted with the Bouwer and Rice (1976) method is 0.004 cm/s, which is consistent with logging results for the cobble unit in SPT2 where K is less than the 0.01 cm/s logging threshold (Fig. 8, Table 1). Results from four wells screened in Tgf sands were interpreted with the Bouwer and Rice (1976) method and range from 0.01 to 0.025 cm/s. Oscillatory (underdamped) head responses in RSMW17 were matched (Fig. 13) with the van der Kamp (1976) method using the routine of Wylie and Magnuson (1995). Results indicate that K in Tgf sand in RSMW17 is greater than in other wells which exhibit more-typical (overdamped) slug test responses in Tgf sands (Table 2). The interpretation of higher K in well RSMW17 also is consistent with higher specific capacity in RSMW17 than other wells screened in Tgf based on pumping tests at the Capital Station site (W. Barrash, unpubl. data; Barrash et al., 1997).

PETROPHYSICAL CHARACTERIZATION

Porosity

Porosity (ϕ) logs can be generated from N logs in a given geologic environment with an empirical relationship (Wood et al., 1974; Hearst and Nelson, 1985) if two calibration points can be established for low N cps (high ϕ) and high N cps (low ϕ) units:

$$N = A + B (\log \phi) \quad (\text{eqn. 1a})$$

$$\phi = 10^{(N-A)/B} \quad (\text{eqn. 1b})$$

where A and B are determined using the maximum and minimum values of N recorded with the neutron log.

For the Qal deposits at Capital Station, calibration points must be estimated because ϕ measurements are lacking. The lowest N count rate for all Qal sands in the 14 deep wells is about 250 cps. Sand units in coarse braided-stream deposits generally occur as either laminar planar bedforms or as solitary or grouped cross strata associated with cross-stratified cobbles (e.g., Miall, 1985) (Fig. 2). Petrographic observation and limited grain-size analysis data are consistent with the

Qal sand being emplaced by fluvial processes. If we assume the sand unit with the lowest N cps is close to the expected ϕ limit ($\phi = .45-.5$) for natural alluvial sands (e.g., Johnson et al., 1968; Lambe and Whitman, 1969; Pettijohn et al., 1973), then 250 cps corresponds with $\phi = .475 \pm .025$.

For cobble units at Capital Station, N count rates range from about 450 to 800 cps, with few units at the high count rate (low ϕ) end of the range. Jussel et al. (1994) measured ϕ on samples from similar deposits in Switzerland where the average for the lowest ϕ cobble-dominated lithologic unit was .14. Hough (1957) gives a minimum ϕ of .12 for silty sand and gravel. A value of .09 results from a very low ϕ fractional-packing model (e.g., Koltermann and Gorelick, 1995) of cobbles (ϕ of .30 alone) with dirty sand matrix (.30 ϕ of matrix alone). If we assume the cobble unit with the highest N count rate is close to a low ϕ limit for natural cobble-sand mixtures, then as a first approximation, we may say that 800 cps corresponds with $\phi = .12 \pm .02$.

Example ϕ logs for Capital Station wells are given in Fig. 12.

Shape Factor

Plots of scores on PC3-PC2 crossplots indicate that cobble units occur as either low- or high-IR units, and that these can be further distinguished based on relative N count rates (i.e., relative porosity). We infer that composite or fine-scale units which plot in different regions of principal component space represent different lithofacies associated with coarse braided-stream deposits, but independent lithologic control is not sufficient at the present time to demonstrate this inference. It is useful here to consider Archie's Law which gives the empirical relationship between electrical resistivity, porosity and a factor associated with aquifer matrix geometry (Archie, 1942):

$$R_o / R_w = FF = \phi^{-n} \quad (\text{eqn. 2})$$

where R_o = resistivity of the saturated formation ($\Omega\text{-m}$),
 R_w = resistivity of the saturating pore fluid ($\Omega\text{-m}$),
 FF = formation factor = ratio of resistivities (dimensionless),
 ϕ = porosity (dimensionless), and
 n = "cementation" factor (dimensionless).

The exponent "n" is a fitting parameter with different physical meanings in different lithologic settings. For reservoir rocks, n depends on rock type and on the degree of cementation among individual grains. Atkins and Smith (1961) demonstrated that (eqn. 2) also holds for cohesionless particles, so n may be considered a "shape" factor for unconsolidated sediments (Jackson et al., 1978). A number of experimental studies have examined what controls the magnitude of n for unconsolidated media and have concluded that n is not related to the size of constituent grains or the grain-size distribution of the medium as a whole (Biella et al., 1983), although substantial spreads in grain sizes (poorly sorted samples) tended to increase the value of n slightly (Jackson et al., 1978). Rather, n appears to be related to the shape of constituent grains such that low n values are associated with more spherical grains and higher n values are associated with less spherical grains (Wyllie and Gregory, 1953; Atkins and Smith, 1961; Jackson et al., 1978). In particular, n increases for media consisting of grains with a platy shape, or consisting of mixtures of spherical and platy grains (Atkins and Smith, 1961; Jackson et al., 1978). However, media with very large clasts or bimodal grain-size distributions have not been studied experimentally.

Archie's Law can be used to evaluate the relationship between IR log responses (R_o) and n for Capital Station wells if we assume that R_w is constant (reasonable based on available water chemistry from the site [W. Barrash, unpubl. data]) and if we estimate porosity values from N log data using (eqn. 1a-1b). Then, knowing ϕ and FF (computed from R_o [IR log data] and R_w [water

samples]), the vertical distribution of n can be generated for each well from Archie's Law:

$$n = - \log FF / \log \phi \quad (\text{eqn. 3})$$

Example "logs" of n (Fig. 12) show that marked increases in n generally coincide with high-IR cobble units. There are significant fine-scale variations in this trace which may be a result of departures from assumptions of constant R_w or specific porosity bounds, but the "log" can nonetheless be evaluated in terms of significant shifts in magnitude that correlate with resistivity. Sands generally have low n values (1.1-1.4) suggesting relatively equant grains (substantiated by petrographic analysis); low-IR cobbles have similar n values, suggesting they may also have mostly "spherical" clasts (Wyllie and Gregory, 1953; Atkins and Smith, 1961; Jackson et al., 1978) even though their size is substantially larger.

However, the high-IR cobbles have n values of about 1.5-2+ (Fig. 12). Several possible explanations for the meaning of n in high-IR cobble units are: (1) cobbles in these units have a more platy shape, perhaps identifying imbricated cobble zones; and/or (2) cobbles are so large compared to the zone of investigation that the IR values are intermediary between "solid" rock and granular materials (Hearst and Nelson, 1985). Both imbricated zones and zones with large cobbles are common in analogous Qal cobble and sand deposits in roadcut and quarry outcrops nearby. We anticipate investigating the IR-shape relationship as new wells are drilled at Capital Station or other sites in the Quaternary braided-stream deposits of the Boise River.

SUMMARY AND CONCLUSIONS

Although unconsolidated cobble and sand deposits commonly are difficult to characterize from conventional drilling returns, coring for high-percentage recovery of samples is possible and data from borehole geophysical logs (N, G and IR logs) collected in 5-cm diameter PVC wells at the Capital Station site can be analyzed for detailed lithologic/stratigraphic, hydrologic and petrophysical information. In particular, smoothed plots of these logs (below the water table) can be interpreted for general lithologic variation, recognition of the stratigraphic contact between Qal and Tgf, and fine-scale resolution of sedimentologic variation. N-G crossplots separate lithologic and stratigraphic units into different fields. PCA on N, G and IR data for Qal units provides a method for distinguishing among cobble-dominated units as high- or low-IR units, with additional variability due to relative N count rates (attributed to differences in porosity). Two types of permeability testing in individual wells give similar results for the few measurements available: Tgf sands (K range ~0.01 to >0.1 cm/s) are more permeable than cobble-dominated units (K <0.01 cm/s). Porosity and shape-factor logs can be generated from geophysical logs and supporting water-quality data; cobble units with high shape-factor values also are high-IR units recognized with PCA.

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Table 1. Hydraulic conductivity results in well SPT2; heat-pulse flowmeter and pumping method

Interval BLS (m)	K cm/s	Fine-Scale Unit Interpretation (see Fig. 8)
9.8 - 14.0*	<0.01	Qal - cobble-dominated unit
14.0 - 14.6	0.072	Qal - cobbles floating in sand
14.6 - 15.2	<0.01	Qal - cobble-dominated unit
15.2 - 15.85	0.11	Tgf - sand
15.85-16.45	0.037	Tgf - sand and silty sand
16.45-17.1	0.037	Tgf - sand and silty sand
17.1 - 17.7	0.079	Tgf - sand and silty sand
17.7 - 18.3	<0.01	Tgf - silt and clay

* Seven measurements were taken at 0.6 m intervals between 9.8 and 14.0 m; all measurements were below the detection limit of 0.01 cm/s for this logging run.

Table 2. Slug test results, Capital Station site, Boise, Idaho.

Well	Analytical Method	Number of Tests	K range cm/s	ave K cm/s	Unit
RSMW12	Bouwer & Rice, 1976	2	0.01 - 0.01	0.01	Tgf sand
RSMW13	Bouwer & Rice, 1976	2	0.013-0.015	0.014	Tgf sand
RSMW14	Bouwer & Rice, 1976	2	0.025-0.025	0.025	Tgf sand
MWCP18A	Bouwer & Rice, 1976	2	0.021-0.023	0.022	Tgf sand
BSU1	Bouwer & Rice, 1976	5	0.0035-0.0045	0.004	Qal cobble, sand
RSMW17	van der Kamp, 1976	4	0.09-0.11*	0.1*	Tgf sand

* The van der Kamp method is based on a fully penetrating well in a confined aquifer. The tests were conducted in a partially penetrating well in Tgf sand (~12 m below the water table) overlain by a less-permeable cobble-and-sand deposit. Results are semi-quantitative and are thought to be within an order of magnitude of the correct value, which must be greater than 0.025 cm/s (the highest K value in wells exhibiting overdamped responses to slug tests in Tgf sand).

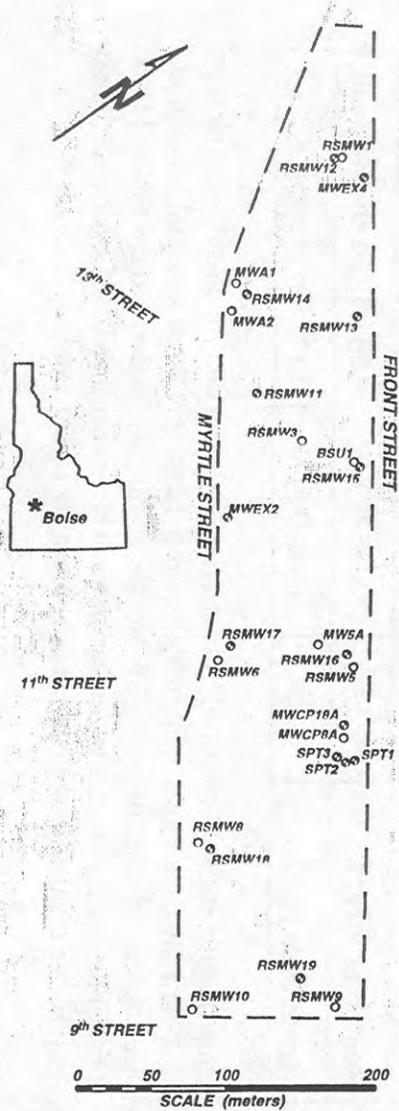


Figure 1. Location map of Capital Station site showing “deep” monitoring wells investigated with geophysical logs, petrography on samples and core, and single-well hydrologic tests.

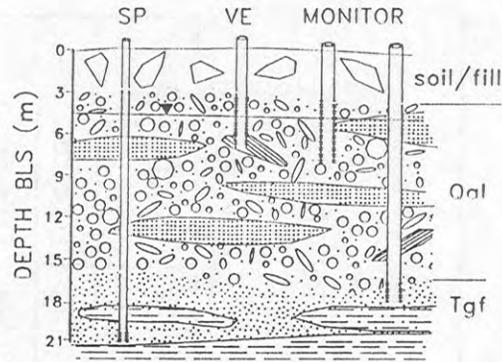


Figure 2. Schematic cross-section at the Capital Station site showing sedimentologic and stratigraphic units and types of wells. SP sponge well, VE vapor extraction well, and shallow and deep monitor wells.

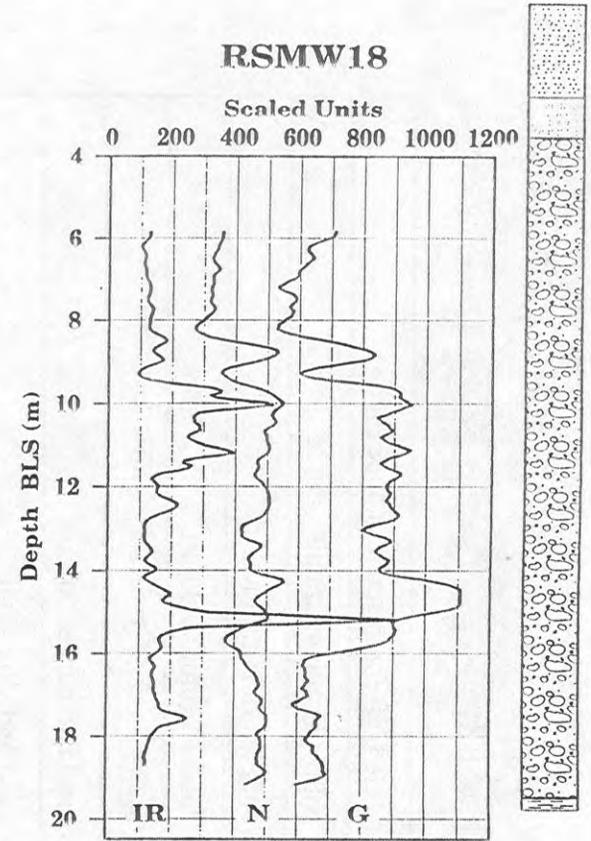


Figure 3. Example lithologic log at well RSMW18, and geophysical logs (N, G and IR) run in this well. N and G logs indicate sands (low N and G values) occur at the top and bottom of this well. Scaled units are used to permit easy comparison of different log responses and may be converted to measured units by: scaled IR = IR (in Ω -m) x 1.5; scaled N = N (in cps) at par; scaled G = G (in cps) x 8.

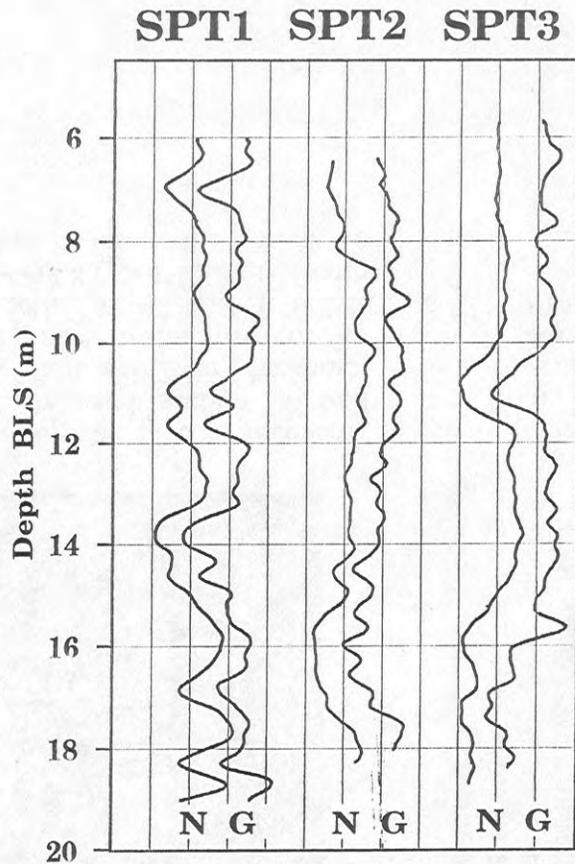


Figure 4. Geophysical logs for wells SPT1, SPT2 and SPT3 demonstrate vertical lithologic variability and general lack of lateral continuity of sedimentologic units over short lateral distances (i.e. ~6 m between SPT1 and SPT2, and between SPT2 and SPT3).

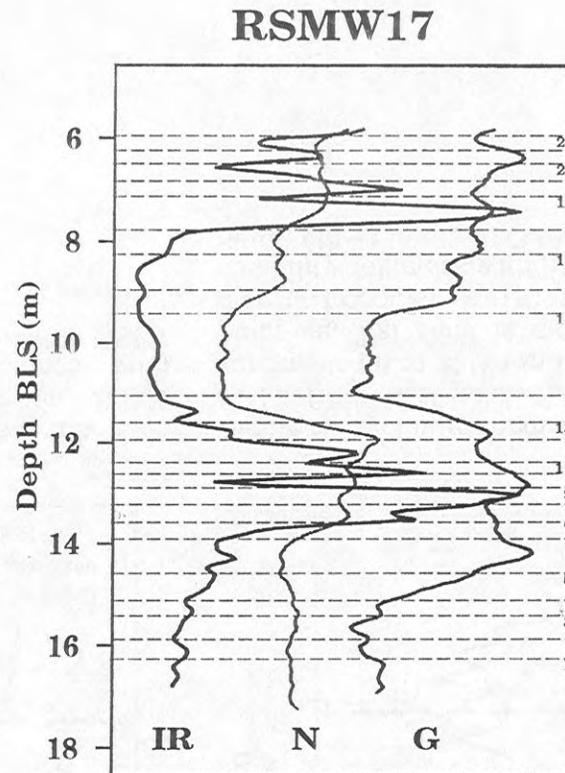


Figure 5. Fine-scale unit picks for well RSMW17.

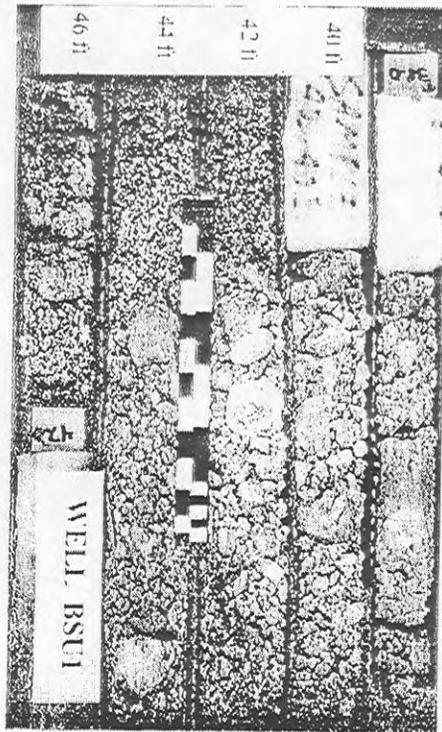


Figure 6. Photograph of core recovered from cobble-and-sand section in well BSU1. Note thin (<0.2 m thickness) clean gravel zones within the cobble-dominated section at 42-42.7 ft (12.8-13 m) and 44-44.8 (13.4-13.6 m). Depth labels are given in feet at the side of the core box.

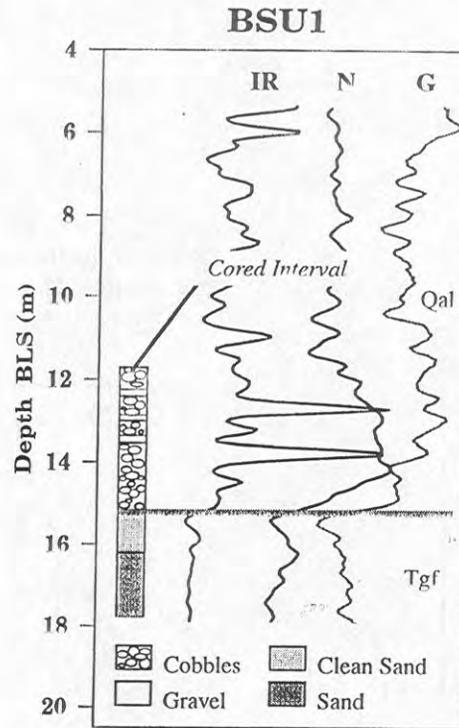


Figure 7. Geophysical logs and lithologic log from recovered core in BSU1 (Fig. 6). Thin gravel zones coincide with low IR zones. Screened interval in BSU1 is 12.8 to 14.3 m BLS.

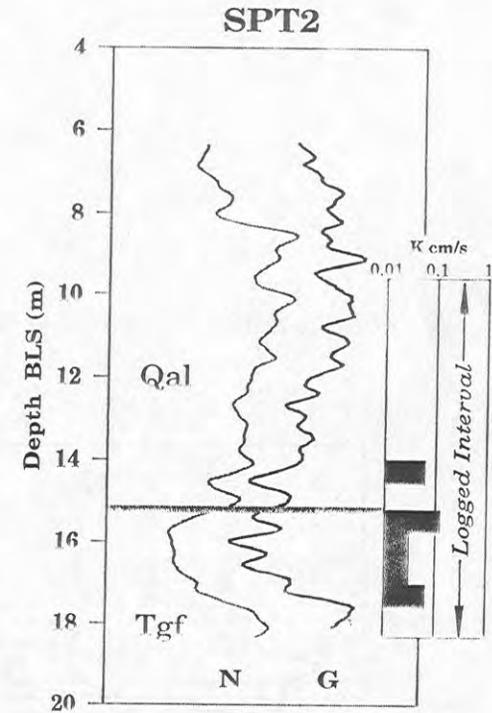


Figure 8. Hydraulic conductivity in well SPT2 from heat-pulse flowmeter measurements taken at 0.6 m intervals while pumping. Tgf sand is more permeable than Qal cobbles; variation in sand permeability coincides with lithologic variations evident in N and G logs.

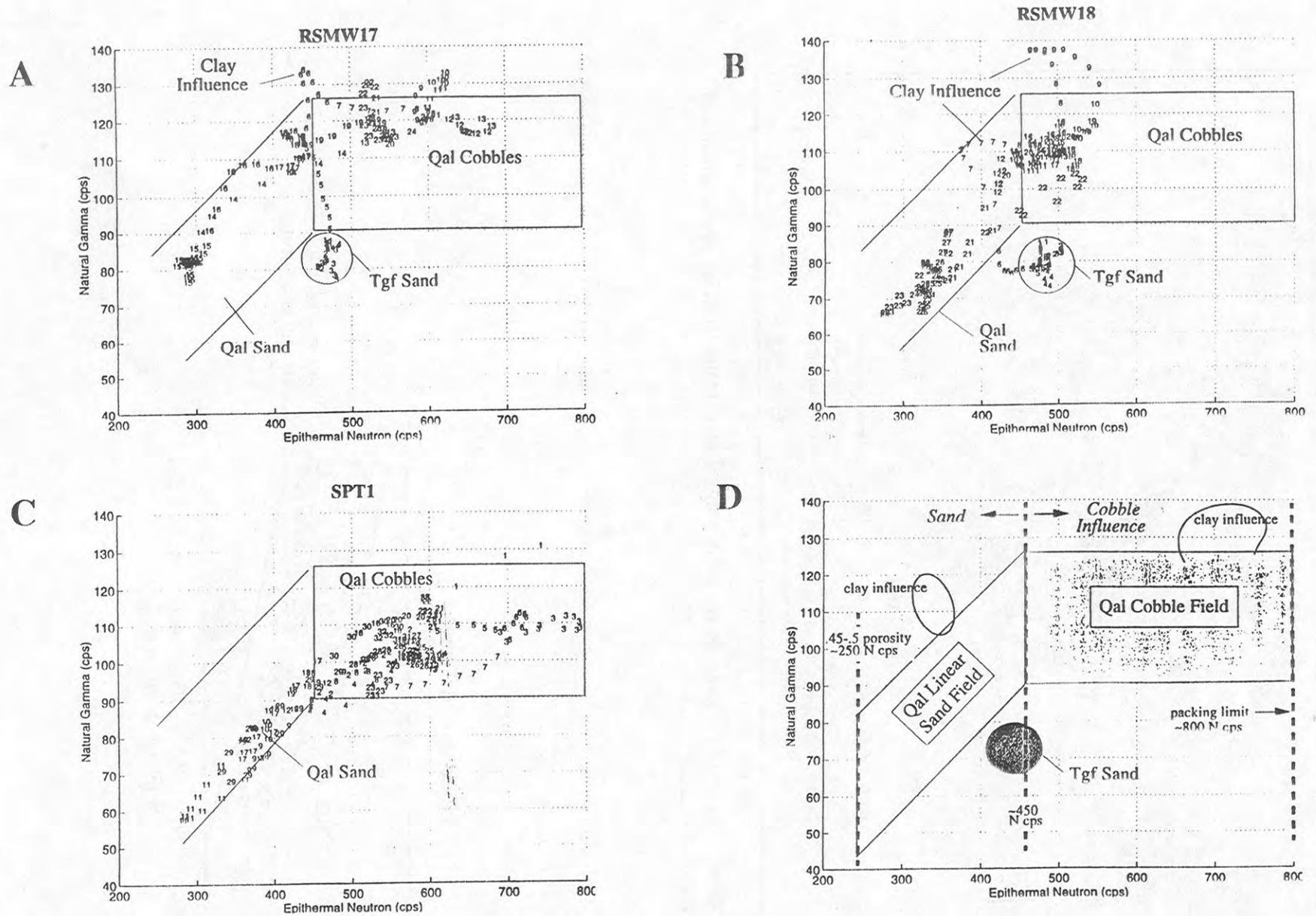


Figure 9. N-G crossplots for wells RSMW17 (A), RSMW18 (B), and SPT1 (C). Each data point is identified by the fine-scale unit which that point is associated with (e.g., see Fig. 5). D. Schematic N-G crossplot for the shallow aquifer system at Capital Station showing fields for lithologic and stratigraphic units.

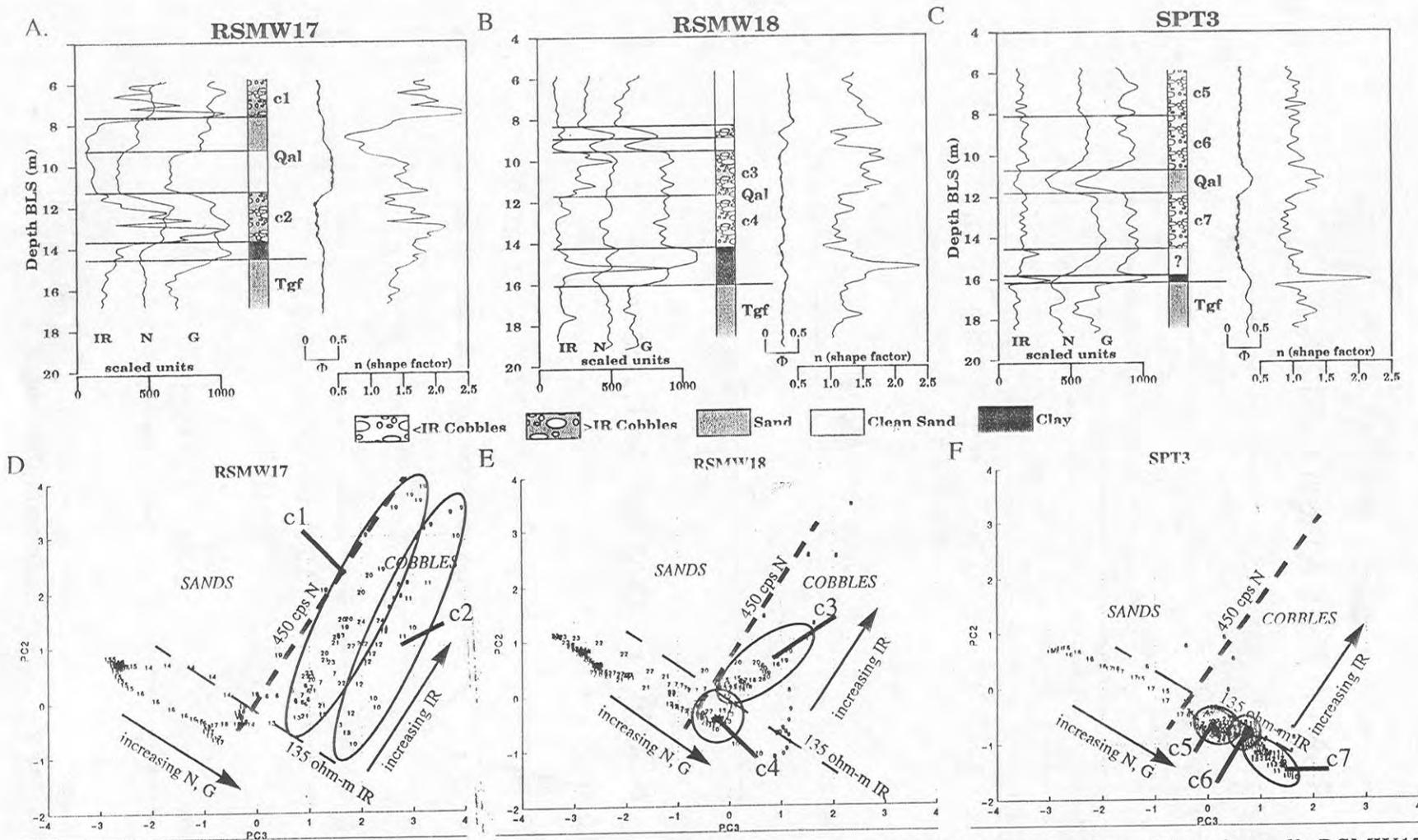


Figure 12. Geophysical logs, porosity and shape-factor logs, and lithologic and stratigraphic interpretations of logs for wells RSMW17 (A), RSMW18 (B) and SPT3 (C) at Capital Station. A set of three porosity log traces is plotted for each well; in each set the left trace is generated from calibration points assuming porosity limits of .1 and .5, middle trace assuming .12 and .475, and right trace assuming .15 and .45. Cobble units with shape-factor values above 1.5 coincide with high-IR cobble units recognized with principal component analysis (PCA). PCA on Qal units (C,D,E) distinguish between sand and cobble units, and divide cobble units into high- and low-IR units (see lithologic log units in A, B, and C) (Barrash and Morin, in review).

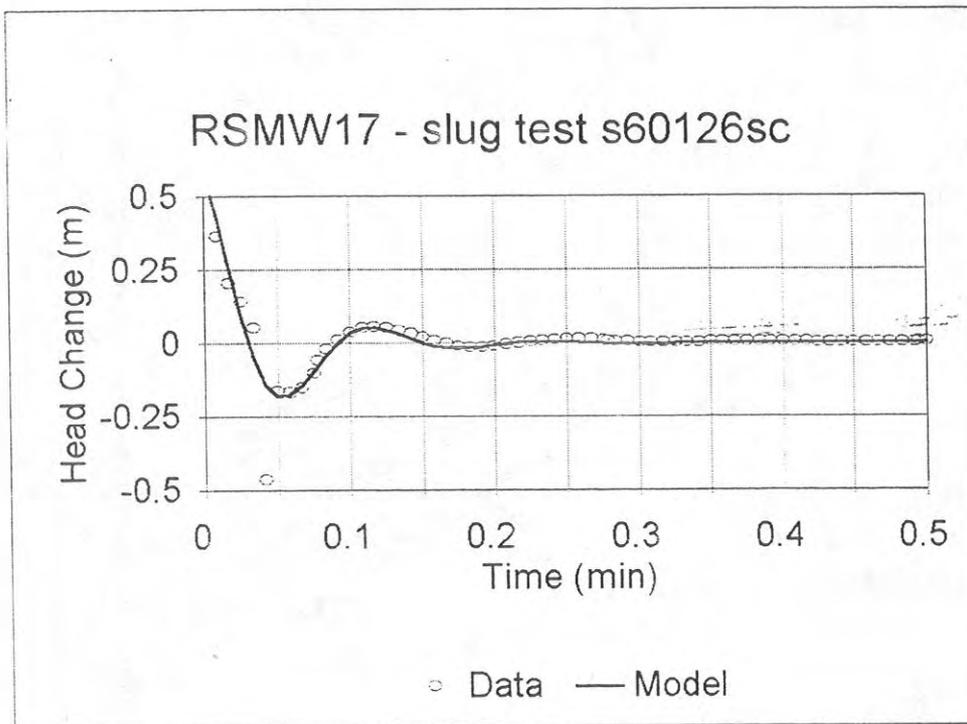
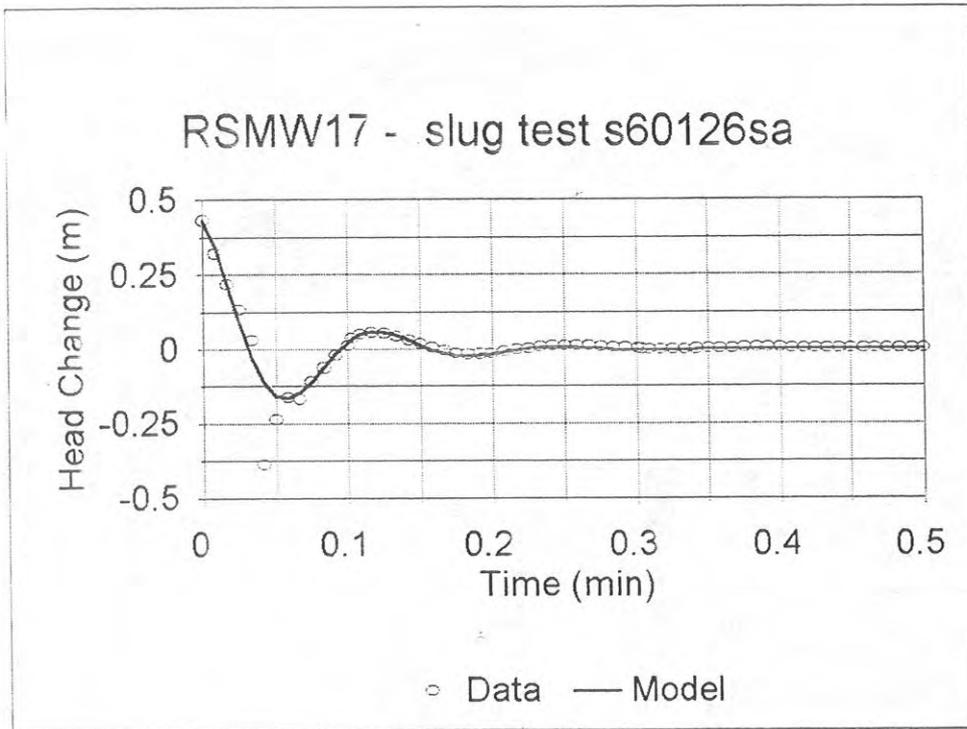


Figure 13. Underdamped (oscillatory) responses of two slug tests in well RSMW17 analyzed with the van der Damp (1976) method.