3. CHARACTERIZATION OF STUDY AREA

The following subsections discuss the meteorology, geology, soils, and hydrogeology in the region of the Site, and, in detail, the characteristics of the site-specific geology and hydrogeology beneath the Hematite Site.

3.1 METEOROLOGY

Jefferson County, Missouri, where the Site is located, is characterized by a humid and temperate climate. The annual temperature averages 55°F in Jefferson County, Missouri (USDA 2003). Winters are generally cold to moderate, with temperatures averaging 33°F; however, short periods of cold weather occur during which temperatures frequently drop below 20°F. The coldest weather usually occurs in January with average lows of 15°F. In calendar year 2004, there were 17 days with a maximum temperature of 32°F or below. Summers are moderate to hot, with temperatures averaging 78°F. July is usually the warmest month of the year with average highs of 88°F. In calendar year 2004, there were 19 days with a maximum temperature of 90° or above (NOAA 2005).

USDA (2003) reports that the average annual precipitation in Jefferson County is approximately 38 in. with 45% of this average falling in April through September (data from 1961 to 1976). This is consistent with the value (40 in. per year) reported by Imes and Emmet (1994) for the region around the Hematite Site. Precipitation is generally evenly distributed throughout the year, with the heaviest precipitation commonly occurring in association with spring and summer thunderstorms, most occurring between May and August. In addition, an average of approximately 19 in. of snow accumulates annually. On the average, 18 days of the year have at least 1 in. of snow on the ground (USDA 2003).

3.2 GEOLOGY

The regional geology and physiography are described in Sects. 3.2.1, 3.2.2, and 3.2.3, while the site-specific geology based on data from the RI and previous investigations is presented in Sect. 3.2.4.

3.2.1 Regional Geology and Physiography

The Hematite Site is located within the Ozarks Plateaus Physiographic Province (Fig. 3.1a). The Ozark Plateaus province is a geologic uplift, covering approximately 50,000 miles^2 and is bounded to the north by the Missouri River, to the east by the Mississippi River, to the south by the Arkansas River, and to the west by the Grand and Neosho Rivers. Precambrian igneous and metamorphic rocks that outcrop at the Saint Francois Mountains (Fig. 3.1a) form the basal crust of the entire region and are overlain by Paleozoic sedimentary rocks that range in thickness from 0 around the periphery of the Saint Francois Mountains, to 6000 ft (Imes and Emmet 1994).

The Ozark Plateaus consist of three sections: the Springfield Plateau, the Salem Plateau, and the Boston Mountains. Topography is mostly gently rolling, except in the Boston Mountains, along the escarpments separating the Springfield and Salem Plateaus, and the Saint Francois Range where it is rugged. Karst features such springs, sinkholes, and caves are common in the limestones of the Springfield Plateau and abundant in the dolomite bedrock of the Salem Plateau and Boston Mountains. The Missouri Environmental Geology Atlas (MDNR 2004) did not indicate a significant number of karst features in the vicinity of the Hematite Site.

The Hematite Site is within the Salem Plateau (Fig. 3.1a), which is underlain by flat-lying to gentle northeasterly dipping Cambrian to Lower Ordovician strata that are mostly dolomitic. The Paleozoic rocks are overlain by unconsolidated surficial deposits of Tertiary to Quaternary age. Within the Festus quadrangle where Hematite is located (Whitfield and Middendorf 1992), Ordovician-age Cotter Dolomite outcrops almost entirely throughout the region (Fig. 3.1b). The Ordovician- and Cambrian-age stratigraphic units underlying the Salem Plateau in the vicinity of the Hematite Site include (from youngest to oldest, Imes and Emmet 1994):

- the Cotter Dolomite; the Jefferson City Dolomite; the Roubidoux Formation; the Gasconade Dolomite, which contains a well-defined basal sandstone member called the Gunter Sandstone member; the Eminence Dolomite; and the Potosi Dolomite (these make up the Ozark Aquifer in the area, which is further discussed in Sect. 3.3.1); and

- the Doe Run Dolomite, the Derby Dolomite, the Davis Formation, the Bonneterre Dolomite, the Reagan Sandstone, and the Lamotte Sandstone (these make up the St. Francois confining unit and the St. Francois aquifer).

Numerous fault and fracture zones that exhibit preferential orientations to the northwest-southeast and northeast-southwest have been mapped in the Ozark Plateaus (Imes and Emmet 1994, MDNR MEGA 2004). The northwest-southeast-trending Eureka-House Springs Fault Complex and the St. Genevieve fault zones intersect the northeast and southwest tips of Jefferson County, respectively (McCracken 1966). However, these fault zones are several miles away from the Hematite Site and do not appear to have any influence on the geology or hydrogeology of the area.

Whitfield and Middendorf (1992) map several north-northwesterly trending monoclines on the Festus and DeSoto quadrangles, but nothing in the immediate vicinity of the Hematite Site. Pike (1929) prepared the first geologic map for the Crystal City 15' quadrangle and identified a northeast-southwest-trending structural feature parallel to Joachim Creek (offset slightly to the south of the creek) that was termed the Crystal City Anticline. Later mapping by Schmitz (1965) also shows this anticline, but more nearly coincident with the creek. McCracken (1966) includes the Crystal City Anticline in her survey of Missouri's structural features. Whitfield and Middendorf (1992) do not include it on their map of the area, although the feature is still identified in Missouri's recently published geographic information systems-based geologic atlas (MDNR MEGA 2004).

3.2.2 Bedrock

The Jefferson City Formation and the Cotter Formation are described in Martin et. al. (1961, as referenced in Section 2.4.1, page 9 of LBG 2003) as mostly light-brown to medium-brown, medium to finely crystalline dolomite, and argillaceous dolomite. Chert, which is not abundant, typically is oolitic, banded, mottled, or sandy. Lithologic succession within the formation is complex and varies among locations. Because the two formations are difficult to differentiate without the aid of insoluble residue testing, they are often designated as a combined unit, the Jefferson City-Cotter Dolomite. These two dolomite units average 400 ft thick state-wide and are bounded beneath by the Roubidoux Formation. Imes and Emmett (1994) describe the Roubidoux Formation within the Ozark aquifer system as "…a loosely to well-cemented sandstone or a sandy to cherty dolostone containing several distinct sandstone bodies." The sedimentary rocks in this area dip gently and uniformly to the northeast.

3.2.3 Unconsolidated Deposits

The Festus quadrangle geologic map (Whitfield and Middendorf 1992) shows Quaternary (Holocene) alluvium and terrace deposits to be closely associated with Joachim Creek and its tributaries

in the vicinity of Joachim Creek (Fig. 3.1b). The map also shows that the extent of alluvium and terrace deposits across Joachim Creek (in the vicinity of the private wells, e.g., PW-19) is very limited, consistent with the thin overburden thickness (~3ft) that was encountered in that area (at BR-07, refer to Sect. 3.2.4 and Fig. 3.11).

Whitfield and Middendorf (1992) describe the Holocene alluvium as clay, silt, sand, and gravel chiefly derived from local loess and colluvium. Colluvium is described as a mixture of residuum, from fines to cobbles, and loess that is moving down slope as a result of slope wash and gravity. Colluvium accumulates at the base of valley slopes and in large valleys washes onto the floodplain, blending with the alluvium. Terraces typically contain lenticular beds of sand and gravel interbedded with silt and clay (Section 2.4.2, page 10 of LBG 2003).

The soil survey for Jefferson County conducted by the United States Department of Agriculture (USDA) indicates the presence of seven soil types within the Hematite Site area: (1) the Horsecreek silt loam directly under the Facility and BR-11 area, (2) the Haymond silt loam comprising the terrace deposits between theFacility and Joachim Creek, (3) the Kaintuck fine sandy loam along the immediate flood plain of Joachim Creek (BR-06, BR-08, and BR-10), (4) the Moko-Rock outcrop complex in the vicinity of the Tile Barn, (5) the Freeburg silt loam in the pasture area of BR-05, (6) the Bloomsdale silt loam in the areas of BR-09 and BR-12, and (7) the Useful silt loam in the area of BR-07 (USDA 2003).

Background surface and near-surface soil samples were collected from two locations (Fig. 2.7). The USDA soil survey for Jefferson County indicates that background soil samples collected from the location to the east of the Hematite Site (south of the National Guard Armory – Fig. 2.7) are linked to the occurrence of the Kaintuck, Horsecreek, and, possibly, the Wilbur soil series. These soils are coarse to silty alluvium associated with terrace and flood plain deposits. Although Wilbur soils are not found within the Hematite Site, they are similar to the Kaintuck, Horsecreek, and other terrace flood plain soils mapped on the Hematite Site.

Off-Site surface soil samples also were collected approximately 3 miles southwest of the Hematite Site adjacent to Highway P (Fig. 2.7). Soils in this area belong to the Useful and Freeburg soil series, both of which are found on the Hematite Site.

From this brief assessment, it is apparent that surface soil samples from both background locations are from a group of soil series also found on the Hematite Site or, in the case of Wilbur soils, closely related to soils found on the Hematite Site. Therefore, analytical results for contaminants in background soils should provide a valid basis for comparison with similar data obtained from Hematite Site soils.

3.2.4 Site-Specific Geology

As noted in Sect. 3.2.1, the Hematite Site lies in the northeastern portion of the Salem Plateau. The Ozark uplift took place in the early Paleozoic during a time associated with deposition of a thick sequence of strata that included the Roubidoux Formation and Jefferson City-Cotter Dolomite. As a result of the uplift (locally associated with the St. Francois Mountains to the south-southwest of the Hematite Site, Fig. 3.1a) and subsequent erosion, these sedimentary formations both dip gently and thicken in a northeasterly direction. The approximate strike and dip of the Jefferson City-Cotter strata are N45W and 2 to 5° northeast, respectively, at points closest to the Hematite Site, as indicated on field copies of the Festus quadrangle used by Whitfield and Middendorf (1992) to prepare the most recent geologic map of the area. However, notations on this map indicate that both the strike and dip of these strata are somewhat variable in the region.

The topography in the region of the Hematite Site is relatively deeply dissected by streams (refer to Fig. 1.1 for a topographic map). Downward cutting of Joachim Creek and other streams in the area (or their predecessors) was in response to the Ozark uplift. In the immediate vicinity of the Hematite Site, Joachim Creek is at an elevation of approximately 412 ft above mean sea level (AMSL) and occupies a relatively narrow valley (approximately 2000 ft wide) that generally trends east-northeastward. The valley is bounded both to the north and south by uplands that reach elevations in excess of 600 ft AMSL. A number of intermittent streams are tributaries to Joachim Creek in the area and also are incised resulting in the distinctive dissected topography characteristic of this region. These tributaries flow generally southeastward or northwestward from the highlands to their points of confluence with Joachim Creek.

Figure 3.1b is a portion of the geologic map encompassing the Hematite Site (Whitfield and Middendorf 1992). The shallowest and most relevant components of the bedrock geology in the vicinity of the Facility are dominated by (in descending stratigraphic order) the Cotter Dolomite, Jefferson City Dolomite, and Roubidoux Formations. Figure 3.1b shows that the upland regions to the north and south of Joachim Creek are underlain by the Cotter Dolomite. The Jefferson City Dolomite is exposed in the valley walls of the tributaries to Joachim Creek. The nearest outcropping of the Roubidoux Formation is in the city of Desoto, Missouri, approximately 6 miles to the southwest of the Hematite Site.

The regional characteristics of the bedrock units were described in Sect. 3.2.2. Lithologic descriptions provided in Whitfield and Middendorf (1992) and examination of core materials and core logs obtained during the RI and previous investigations indicate that in the vicinity of the Hematite Site the Jefferson City-Cotter Dolomite is composed of dolostone and sandy dolostone with minor interbedded sandstone and cherty intervals. The Roubidoux Formation is composed of dolostone with chert intervals and relatively common sandstone interbeds. The Jefferson City Dolomite-Roubidoux Formation contact reportedly occurs approximately 10 to 15 ft above a recognizable sandstone layer in the upper Roubidoux Formation. Although this sandstone is not always present, many of the bedrock logs from the Hematite Site appear to confirm its presence. Therefore, this sandstone will be used as a basis for recognizing the Jefferson City-Roubidoux contact in this report.

The stream valleys in this region are characterized by deposits of alluvium that have their origin through local erosion in the upland regions and subsequent deposition in the relatively gently sloping valleys. The valley occupied by Joachim Creek has a zone of alluvium as much as 30 to 35 ft thick underlying and immediately adjacent to the creek that rests on top of the Jefferson City-Cotter bedrock surface. The soil cover in the upland regions is much thinner and observations made at BR-07 (borehole drilled in the upland region southeast of Joachim Creek, refer to Fig. 2.6a for location) indicate a thickness of only several ft.

It is apparent that Joachim Creek has responded to several episodes of uplift in the region evidenced by several different phases of alluvial deposition. For example, Whitfield and Middendorf (1992) mapped a terrace deposit in the valley of Joachim Creek that is found in discontinuous, narrow strips near the margins of the valley or as small, isolated pockets within the valley. The Hematite Site lies on terrace deposits that extend along the northern boundary of the Joachim Creek valley.

3.2.4.1 Overburden

The overall thickness of alluvium/terrace deposits underlying the Joachim Creek valley near the Facility varies from 20 to 35 ft and is comprised primarily of upper fine-grain silts and clay that overlie coarser-grain material (sands and gravels with some cobbles) near the bedrock surface. The thickness of the coarse-grain units is highly variable in this region and ranges from 0 to greater than 20 ft.

The details of the local subsurface geology can be described by a series of geologic cross-sections based on drilling logs obtained from cores associated with this RI, as well as from a number of logs from earlier investigations (LBG 1999, 2002b). Figures 2.5 (a and b) are maps showing the location of borings in the overburden obtained during this investigation. Boring logs were compiled for these locations and a complete inventory of these logs is included in Appendix C.

Three cross-sections were assembled to examine the overburden underlying and proximal to the Hematite Facility. The layout of these cross-sections is provided on Fig. 3.2. Cross-sections B-B' and C-C' are oriented approximately parallel to Joachim Creek. Cross-section A-A' is roughly perpendicular to both B-B' and C-C'. Figure 3.3 is the legend for the geologic units encountered in both the overburden and bedrock in this investigation.

Cross-section A-A' (Fig. 3.4) reveals a bedrock surface that is relatively flat, but slopes gently toward Joachim Creek. The bedrock surface illustrated in cross-sections B-B' and C-C' (Figs. 3.5 and 3.6, respectively) also is relatively flat with no indication of significant relief. The density of the borings represented on Fig. 2.5a supports this inference.

The correlation of lithologic units on Figs. 3.4 to 3.6 focus on the distinction between fine-grain and coarse-grain units. Alluvial depositional environments tend to be rather complex and heterogeneous with numerous examples of abrupt variations in lithologies from coarse to fine representing the complicated interplay between episodes of erosion and deposition as the stream channel migrates laterally within its flood plain. Detailed lithologic correlations can be difficult to make, but the interpretations illustrated in these cross-sections honor the boring logs and are realistic of what might be found in an alluvial depositional setting.

One notable feature revealed by cross-section A-A' (Fig. 3.4) is the change that occurs at the terrace-alluvium boundary that is manifested by a thickening of coarse-grain lithologies from less than 5 ft in the terrace deposits to more than 15 ft in the vicinity of Joachim Creek. The sediment in this area is associated with the most recent episodes of deposition from the stream. Underlying the terrace, there is evidence of variable thickness of coarse-grain materials, but nowhere are these zones as thick as those found in the alluvium. Examination of core material indicates that the pebbles and cobbles of the coarse-grain unit are angular to sub-rounded, suggestive of a local origin and little transportation prior to deposition.

The common occurrence of the coarse-grain material in the lower part of the overburden is significant because it is relatively permeable and appears to be a principal pathway for contaminant migration by groundwater in the overburden (see discussion in Chapter 5). The thickness of this zone has been mapped in the vicinity of the Hematite Site based on the core logs available in Appendix C and from earlier studies (LBG 1999, 2002b) by focusing on the subset of logs that demonstrably intersected the overburden-bedrock interface. These logs yield a reliable estimate of thickness for the coarse-grain units.

Figure 3.7 is an isopach map for the coarse-grain material in this area. Although some interpretation is required in constructing this map, the general configuration of the coarse deposits appears to define several thick, lenticular zones parallel to the stream that may represent old channel lag deposits.

Consistent with information in cross-section A-A' (Fig. 3.4), the subsurface interface between the terrace and alluvial deposits appears to be the zone where significant thickening of sands and gravels occurs near Joachim Creek. In the vicinity of BR-02 (refer to Fig. 2.6a for location), the thickness of the coarse alluvial zone is much less. This area corresponds to the outside of a meander loop of Joachim Creek, which represents a zone of northward, lateral migration and erosion. Recent erosional activity associated with Joachim Creek may have removed much of the coarse-grain material that had been present in this region.

3.2.4.2 Bedrock

Figure 3.8 illustrates the location of three cross-sections that focus on the bedrock underlying the Hematite Site. The cross-sections are presented on Figs. 3.9, 3.10, and 3.11. Overburden detail is purposely omitted, as it is not relevant to a discussion of bedrock. Cross-sections D-D' and E-E' are oriented approximately normal to the regional strike (N45W). Cross-section F-F' is oriented approximately strike-parallel.

The bedrock core logs (Appendix C) obtained during the RI contain few distinctive marker beds that can be used as an indication of location within the stratigraphic section. However, a thin (5 to 10 ft thick) and apparently laterally continuous sandstone interbed mentioned previously (introduction to Sect. 3.2.4) appears to represent a unit that has been described as occurring approximately 10 to 15 ft below the top of the Roubidoux Formation. Cross-section D-D' (Fig. 3.9) shows a correlation based on this marker bed. Because of the strike-normal orientation of the cross-section, this bed yields information about the dip of these strata. The dip represented by this sandstone bed ranges from 1.4 to 2.9° in this cross-section, a value consistent with results from field mapping of surface outcrops (Whitfield and Middendorf, 1992) and from regional studies of these strata. Note that boreholes BR-01-RB and BR-04-RB were drilled by LBG (2002b) and contain the interpreted contact between the Jefferson City Dolomite and the Roubidoux Formation.

Stratigraphic correlation on what is believed to be the same sandstone bed also is illustrated in cross-section E-E' for boreholes BR-06, BR-03, and BR-10 (Fig. 3.10). The location of the marker bed in BR-03 is based on an evaluation of the core from BR-06 and the conclusion that the interpreted contact between the Jefferson City Dolomite and Roubidoux Formation in BR-03-RB (LBG 2002b) appears to be too deep by approximately 50 ft. The original location of the contact may have been based on the incorrect sandstone bed. Shifting the contact upward by this amount puts it in association with the sandstone bed illustrated in the cross-section.

The projection of the sandstone marker bed to BR-02 is problematic because the core log for this borehole shows the presence of only several very thin (~ 1 ft thick) sandstone interbeds within 20 ft of the Jefferson City-Roubidoux contact. Assuming that the contact is properly identified, these thin interbeds are interpreted to be correlative with the more prominent sandstone marker bed observed in the other boreholes. Therefore, the marker bed is projected to a position approximately 15 to 20 ft below this contact in BR-02. The resultant apparent dip of the marker bed in this cross-section is about 3°, comparable to that observed on Fig. 3.9 and within the range of measured values provided by Whitfield and Middendorf (1992).

3.2.4.3 Local structural features

Cross-section F-F' is shown on Fig. 3.11. Based on a correlation of the same sandstone marker bed observed in D-D' and E-E', this bed appears to define a subtle warp in the strata, the axis of which is located close to Joachim Creek. This may be a depositional feature, but probably is not tectonic in origin. The limbs of this warp have an apparent dip on the order of 1 to 2°. As mentioned in Sect. 3.2.1, older geologic maps showed the Crystal City Anticline (Pike 1929, Schmitz 1965, McCracken 1966) passing through this area. More recent maps do not have this feature (Whitfield and Middendorf 1992).

The structural interpretation of bedrock for the Hematite Site based on cross-sections D-D', E-E', and F-F' and discussed above can be integrated into a consistent geologic framework for the area. Figure 3.12 is a cross-section that is coincident with cross-section E-E' and is oriented approximately perpendicular to the regional geologic strike. In this cross section, however, all boreholes associated with the RI and earlier studies (LBG 2002b) that penetrated the sandstone marker bed (and, by inference, the Jefferson City-

Roubidoux contact) have been included. Each borehole has been projected into the plane of the cross-section by correcting for the dip associated with the anticlinal-like structure (cross-section F-F' on Fig. 3.11). Therefore, the logs for boreholes located distant from the cross-section must be moved upward an amount equal to the distance from the plane multiplied by the tangent of the dip angle of the strata obtained from Fig. 3.11. This process has the effect of unfolding the structure into a planar feature, while faithfully retaining information about the regional northeasterly dip of bedding (Figs. 3.9 and 3.10). Because of the vertical adjustment of boreholes not lying in the plane of the cross-section, the vertical scale represents relative elevation.

The results of applying these corrections to the vertical orientation of boreholes (Fig. 3.12) demonstrates that the relative location of the sandstone marker bed identified in all of the cores defines an inclined plane dipping to the northeast at approximately 2.7°. The excellent alignment of the marker bed and the consistency of the apparent dip of this planar feature to the known regional dip of bedrock in this area provide strong support to the structural interpretations presented in this report.

Information regarding the identification of prominent bedrock fracture sets in outcrop or cores is limited, although the logs that describe core material obtained during the RI do mention the presence of fractures when observed. The LBG (2002b) investigation included construction of boreholes BR-01, BR-02, BR-03, and BR-04. Detailed core descriptions and a number of geophysical and hydrologic logging studies were associated with borehole construction. LBG (Section 5.2.1, page 21, and Section 5.3.1, page 26 of LBG 2002b) reports that the fracture density for the Jefferson City-Cotter Dolomite and Roubidoux Formation lies within the ranges of 0.5 to 3.4 and 0.7 to 4 fractures per ft, respectively. Furthermore, they indicate that fractures, joints, and bedding planes in the Roubidoux core appear to be widened by dissolution, whereas it is less apparent in the Jefferson City-Cotter core material. If such observations are generally true for the Hematite Site, they can have an impact on groundwater flow and contaminant transport. However, data obtained during this RI do not provide definitive information related to these earlier observations.

3.3 HYDROGEOLOGY AND HYDROLOGY

Regional hydrogeology is described in Sect. 3.3.1, while site-specific hydrology and hydrogeology based on data collected during the RI are presented in Sects. 3.3.2 and 3.3.3, respectively.

3.3.1 Regional Hydrogeology

As mentioned previously, the Hematite Site is located within the Salem Plateau of the Ozarks Physiographic Province. The Salem Plateau (Fig. 3.1a) roughly coincides with the outcrop area of the Ozark Aquifer, one of the major hydrogeologic units within the Ozark Plateaus Aquifer System (Imes and Emmet 1994). The aquifer consists of dolostone, limestone, and sandstone formations ranging in age from Late Cambrian to Middle Devonian, and is separated from the deeper, more-permeable St. Francois Aquifer by the St. Francois Confining Unit (refer to Sect. 3.2.1 for a list of stratigraphic units). Within the Salem Plateau, the younger formations of the Ozark Aquifer are not present and the outcrop area consists of Ordovician Gasconade, Roubidoux, and Jefferson City Dolomite. The surface of these carbonate rocks has been deeply eroded and dissected by surface drainage systems, forming a rugged topography that is clearly seen in the hills that bound Joachim Creek valley at the Hematite Site. The aquifer's permeability was developed by dissolution of the carbonate rocks along fractures and bedding planes, including karst development, although the latter does not appear to be significant in the region surrounding the Hematite Site (MDNR MEGA 2004). Sandstone is present as massive, clean, well-sorted bodies in some formations and, therefore, is relatively permeable where it is not cemented.

The stratigraphic units making up the Ozark Aquifer in the area are listed in Sect. 3.2.1. The basal formation is the Potosi Dolomite, which is the most permeable formation for this aquifer within the Salem Plateau region and is the most reliable source of groundwater for large-capacity wells. The overlying Eminence Dolomite has less secondary porosity and permeability. The Gasconade Dolomite and Roubidoux Formations are also important water-producing units in the region. The Gasconade Dolomite contains the permeable Gunter Sandstone Member, which is a loosely cemented sandstone along a line that extends from Cooper County, Missouri (approximately 140 miles west-northwest of Jefferson County), south into Boone County, Arkansas. The Roubidoux Formation overlies the Gasconade Dolomite. The Jefferson City and Cotter Dolomite, which serve as the top formations for the aquifer within the Festus quadrangle, consists predominantly of dolostone with small quantities of shale, chert, and sandstone; it is less permeable regionally than the stratigraphically lower rocks of the Ozark aquifer.

The estimated hydraulic conductivity of the Ozark aquifer varies from more than 1.0×10^{-3} ft/second (86 ft/day) to less than 1.0×10^{-8} ft/second (1×10^{-3} ft/day). The hydraulic conductivity north of the northernmost regional groundwater divide varies from about 1.0×10^{-5} ft/second (1 ft/day) to about 1.0×10^{-3} ft/second (86 ft/day). The regional groundwater divide trends east-west through St. Francois County, immediately south of Jefferson County, approximately 35 miles south of the town of Hematite.

Imes and Emmett (1994) report that the Ozark aquifer is unconfined within the Salem Plateau region, with regional and local groundwater movement strongly influenced by surface topography. Groundwater flows from the upland areas toward the valleys where water discharges as stream base flow. Regional flow is controlled by the larger rivers (e.g., Mississippi and Missouri rivers) and regional topography, while local shallower flow is controlled by smaller streams and local topography. Along the northern and eastern boundaries of the Salem Plateau, the aquifer is incised by the Missouri and Mississippi Rivers. The rivers are major discharge areas for groundwater moving north and east from the Salem Plateau.

In the vicinity of the Hematite Site, groundwater within the shallower bedrock units (e.g., Jefferson City – Cotter) appears to be unconfined. However, as discussed in Sect. 3.3.3, observations based on results of a variety of hydraulic testing and potentiometric measurements for the deeper, Roubidoux Formation suggest that in this region this aquifer is confined.

3.3.2 Site-Specific Hydrology

3.3.2.1 Stream characteristics

As noted previously, Jefferson County is characterized by an average of 38 in. of precipitation per year (USDA 2003). The majority of the precipitation will run off from the surface or return to the atmosphere as a result of evapotranspiration, whereas the remainder will infiltrate into the subsurface. Most of the infiltration will follow short, subsurface flow paths in soils and alluvial sediments and discharge into local streams. The remaining flow will enter the bedrock and recharge bedrock aquifers. Shallow groundwater in bedrock formations is influenced by local topography with short flow paths followed by discharge into seeps and springs or alluvium.

The *Missouri Water Atlas* (MDNR 1986) shows that Joachim Creek, located south of the Hematite Facility, is a permanent flowing stream. There are several other surface water features present on the Hematite Site, including a spring, intermittent perennial and ephemeral streams, a lake, and ponds (refer to Figs. 1.2 and 1.3 for the location of these features). Descriptions of these surface water features are summarized below (based on Section 2.5.2, pages 12 to 14 of LBG 2003).

- The Site Spring flows an estimated 1 to 10 gpm most of the year. The spring is likely a result of fracture flow in the Jefferson City-Cotter Dolomite, which receives its source water in the hills northwest of the Hematite Site.

- The Site Pond is a small concrete dam impoundment southwest of the Plant. It receives flow from the Site Spring and the stormwater runoff from the area of the Hematite Facility (see Fig. 1.2 for the outfall location).

- The Site Creek is the effluent from below the dam of the Site Pond. It receives discharge from the Hematite Facility's sanitary water system (see Fig. 1.2 for the outfall location). It flows through a culvert beneath the railroad track and joins the effluent from the Lake Virginia drainage basin.

- The combined Lake Virginia/Site Creek tributary flows east to Joachim Creek.

- The Northeast Site Creek east of the Burial Pits flows southeast, then east to its confluence with the effluent of East Lake tributary, and then to Joachim Creek.

- East Lake, located east of the Hematite Facility, is an earth impoundment lake used as a water supply for cattle. It is reported to never have been used in conjunction with Hematite Facility operations.

- North Lake Tributary is the effluent drainage from North Lake and North Tributary. This tributary crosses the terrace, west of East Lake.

- North Tributary is an intermittent stream west of North Lake.

MDNR (1970) estimated the base flow recession, which is the amount of water that will flow in a stream after a 30-day rainless period. The base flow recession from 1961 through 1965 on the Joachim Creek is 0.2 ft^3/second. These data indicate that Joachim Creek is a gaining stream, and therefore, a recipient of shallow groundwater discharge (LBG 1999). This observation is consistent with the discussion in Chapter 5 that suggests that groundwater in the overburden at the Hematite Site migrates from the vicinity of the Hematite Facility toward Joachim Creek where it discharges.

Water levels at the surface water gauging stations (refer Fig. 2.1 for locations) were measured monthly from June 2004 through January 2005 (Table 3.1). Average, minimum and maximum water levels for this measurement period are shown in the following table:

Gauging Station	**Surface Water Elevation[a] (ft AMSL)**		
	Average	**Min**	**Max**
Site Pond	424.9	424.7	425.1
Site Pond Creek	423.0	422.7	423.6
Northeast Site Creek	427.6	dry	429.0
East Lake	428.5	427.7	429.7
Joachim Creek (at bridge)	412.7	412.5	413.2[b]

[a] Statistics for surface water elevation measurements taken monthly from June 2004 through January 2005.

[b] Water level at the Joachim Creek gauging station was above the surface water gauge in January 2005. The maximum water level elevation shown is the highest measured value when the surface water gauge was not flooded.

The water levels at all the surface water gauging stations (Table 3.1) exhibited similar seasonal trends, with water levels decreasing in the summer (July through September 2004) and increasing in the winter (November through January 2005). Immediately before the measurement event in January 2005, significant precipitation occurred which resulted in elevated water levels at all the surface water gauging stations (Joachim Creek was flooded). The surface water data also shows that the Northeast Site Creek is an intermittent stream, based on observed dry bed conditions in July, September and October 2004.

Surface water levels were also measured through survey methods at points along Joachim Creek downstream of the bridge and closer to the Hematite Site. These surface water measurements were made in conjunction with water level measurements at nearby wells to determine whether groundwater discharges into Joachim Creek. These surveyed surface water measurements are presented and discussed in Sect. 3.3.3.2.

3.3.2.2 Water supply

There are no public water supply intakes on Joachim Creek. According to an early report regarding the Hematite Site prepared for EPA (Ecology and Environment 1990), most of the residents of Hematite receive their drinking water from a public water supply well (in Public Water Supply District #5) located approximately 2.5 miles south-southeast of the town (near the intersection of Sunnyside and Carron roads). Previous reports also state that surface water is not used for drinking within a 4-mile radius of the Hematite Site (Section 2.5.3, page 14 of LBG 2003).

An industrial high-capacity well (125 gallon per minute capacity) is located within the Hematite Facility (LBG 2002a). The well has a total depth of 600 ft BGS (Plate 6 of LBG 2002b), and is open from the Roubidoux Formation through the Eminence Dolomite Formation (refer to Sect. 3.2.1 for bedrock formations underlying the Hematite Site).

Domestic and industrial water wells in the regional area produce water from the Powell-Gasconade aquifer group of the Ozark Aquifer, which includes the Jefferson City and the Roubidoux Formations (MDNR 1974). Note that the Powell Dolomite stratigraphically overlies the Cotter Dolomite, but is absent within the immediate area surrounding the Hematite Site (Whitfield and Middendorf 1992). LBG (2002a) conducted a survey of water-producing wells within a 2-mile radius of the Hematite Facility. A majority of the wells surveyed were open boreholes with casing depths 80 ft or greater, although the older wells tended to have shallower casings (e.g., 40 ft). Out of more than 200 mostly private wells included in the survey, only 6 wells penetrated the deeper Gasconade and Eminence Dolomite. Although the Jefferson City Dolomite is generally not capable of sustained water production because of its low storage capacity and is subject to failure during drought or sustained pumping (MDNR 1974), it appears to be adequate for individual/private-use wells, several of which were completed in this formation (LBG 2002a). However, most of the wells included in the survey intersected both the Jefferson City and the Roubidoux Formations.

3.3.3 Site-Specific Hydrogeology

The components of the hydrogeologic system near the Hematite Site that are relevant to this RI include the following:

- Overburden (see Sect. 3.2.4.1)
- Jefferson City-Cotter Formation (see Sect. 3.2.4.2)
- Roubidoux Formation (see Sect. 3.2.4.2)

Flow within the overburden generally is from areas of high elevation toward lower elevation, with local streams being the zone of discharge. Within this general framework, the principal groundwater flow paths in overburden are dictated by the occurrence of porous and permeable lithologies such as sands and gravels. For this reason, the basal coarse-grain unit in the overburden (occurring in both the terrace and alluvial zones; refer to Fig. 3.4) is expected to be an important pathway for groundwater flow and transport of dissolved contaminants.

Surface topography also appears to be a strong driver that influences groundwater flow directions in the shallow bedrock on the Salem Plateau (refer to Sect. 3.3.1). The impact of topography on flow direction tends to decrease with increasing depth where the influence of regional flow patterns dominated by major rivers to the north and east is the controlling factor. In this region of the Salem Plateau, deep groundwater in these formations generally flows to the northeast (Imes and Emmett 1994).

3.3.3.1 Identification of HSUs in bedrock

Before proceeding with construction of potentiometric maps for bedrock or an assessment of groundwater flow directions, it is important to determine how the screened intervals in the bedrock wells are related to one another. The goal is to identify the HSUs present at the Site and those wells that intercept each one. The cross-section illustrated on Fig. 3.12 forms the basis for this analysis.

Figure 3.13 is an expansion of Fig. 3.12 that includes all bedrock boreholes at the Hematite Site and illustrates the screened intervals in each (or the open intervals for the private wells, portrayed by dashed lines). Although the wells were labeled as either "Jefferson City (JC)" or "Roubidoux (RB)," it is apparent that some completion zones probably were not in the designated formation. The patterned zones delineate three tentatively identified HSUs: Jefferson City-Cotter, Jefferson City-Roubidoux contact zone, and Roubidoux Formation. These HSUs were selected based on geology (e.g., they are strata-bound and parallel to the regional dip). The identification of these HSUs is based on historical and RI data, and should be considered as a working conceptual model that honors available data.

Additional insight into the hydrologic properties of these HSUs is available through estimates of hydraulic conductivity from slug testing conducted during previous investigations (GEA 1996, LGB 1998 and 2002b) and as part of this RI (see Sect. 2.5 for a description of the test method; analyses of the slug test data are in Appendix G of this report). In addition, injection tests were conducted by LBG (2002b, Section 4.2, page 10), which provided estimates of relative transmissivity. Table 3.2 gives the results of the slug tests from a number of well locations in the overburden, Jefferson City-Cotter Dolomite, and Roubidoux Formation obtained during the RI. A re-examination of the LBG 1999 and 2002b data yields results comparable to those obtained in Table 3.2 for the same tested intervals.

As seen in Table 3.2, the K_h values are variable in each formation, but are generally higher in the overburden (3.8 to >155 ft/day) and the Jefferson City-Cotter (<0.2 to 103.9 ft/day) than in the Roubidoux Formation (0.8 to >15 ft/day).

LBG (2002b, Section 4.2, page 10, and associated boring logs) also reported some additional borehole testing information that they refer to as "Permeability Test" data. This information is related to the maximum rate of water injection that could be achieved from isolated 20-ft intervals in boreholes BR-01, BR-02, BR-03, and BR-04 along most of their length. The results are reported in units of "gpm" and are assumed to represent a qualitative measure of permeability; details of the injection test protocol can be found in Section 4.2 (page 10) of LBG 2002b.

Figure 3.14 shows all of the K_h results on cross-section G-G' (refer to Fig. 3.8 for the cross-section location). The injection test results are presented on Fig. 3.15, in which each borehole is represented in its

proper orientation relative to the sandstone below the Jefferson City-Roubidoux contact identified in lithologic cross-sections (i.e., Figs. 3.9 through 3.13). The vertical blue line segments on Fig. 3.15 represent the location in each borehole of those zones with high injection rates (i.e., apparent transmissivity). These boreholes were originally drilled into the Gasconade Formation that underlies the Roubidoux Formation. The injection tests were performed before these boreholes were grouted back to their current completion depths, which account for the length of the test records.

The hydraulic conductivity results on Figs. 3.14 and 3.15 are combined on Fig. 3.16. The patterned areas identify those zones with relatively high conductivity and/or transmissivity. By comparing Fig. 3.16 with Fig. 3.13, where three HSUs have tentatively been identified, the following conclusions can be reached:

- There is an upper transmissive zone that lies within the Jefferson City-Cotter HSU and appears to be most closely associated with those boreholes completed within about 50 ft of the overburden-Jefferson City-Cotter interface (e.g., PZ-03, PZ-04, WS-31, BR-08-JC, and BR-10-JC).

- The Jefferson City-Roubidoux contact zone is a region of variable, but typically low, transmissivity.

- There is a deeper, second zone of high transmissivity (Roubidoux HSU) defined by the injection test results of LBG (2002b, data shown in associated boring logs) that lies immediately below the relatively low transmissivity Jefferson City-Roubidoux contact zone.

In summary, it is reasonable to conclude that observations regarding hydraulic conductivity measurements of the Jefferson City-Cotter and Roubidoux Formations that have emerged from this RI are of local significance and particularly important for understanding the fate and transport of contaminants in bedrock associated with the Hematite Facility. However, the observations may incorrectly suggest hydraulic properties that are regional in scope and apply to the entire thicknesses of these formations. For example, regionally transmissive stratigraphic intervals in the lower part of the Roubidoux Formation are known to support very productive, community-scale water wells. The completion intervals in the upper part of the Roubidoux for the deep wells included in this RI typically are not highly transmissive in comparison to the deeper, more productive units in the formation. Furthermore, the hydraulic conductivity values measured in the upper Roubidoux Formation generally are lower than what was observed in many wells completed in the Jefferson City-Cotter (Table 3.2). However, the high conductivity zone identified within the Jefferson City-Cotter appears to be locally limited to a region extending southeast from the Hematite Facility and probably corresponds to a specific stratigraphic interval in the formation, but is not representative of the formation as a whole.

3.3.3.2 Potentiometric surface

Figures 3.17 through 3.21 illustrate the potentiometric surfaces for the major HSUs defined in this investigation based on water level measurements made during December 2004 (data tabulated in Appendix D). Figure 3.17 shows a number of wells in the immediate vicinity of the Hematite Facility that are completed in the fine-grain sediments in the shallow overburden. These wells typically are screened from 5 to 15 ft BGS, approximately 10 to 15 ft above the overburden-bedrock interface. Although the number of data points is not large, it is apparent that under the main part of the Hematite Facility, head elevations are greater than 430 ft AMSL, whereas heads are 4 to 10 ft lower further to the east and all are less than 430 ft AMSL. The cause of this lateral decline in heads may reflect a shallow flow pathway leading to discharge into the Northeast Site Creek that flows intermittently through this region. Alternatively, it is possible that the Burial Pits on the eastern side of the Hematite Facility (Fig. 1.3)

influence shallow groundwater flow. The burial trenches were excavated to a depth of about 12 ft (LBG 1999) and are expected to contain relatively more permeable fill material than the native sediments. It is possible that a hydraulic connection exists between the Burial Pits and the permeable lower sands and gravels such that shallow groundwater entering the trench area is able to migrate downward to the deep overburden. Figure 3.17 is similar to the potentiometric surface for the NSSSC as defined and reported by LBG (1999, Section 5.2.5, page 21), which suggests that hydrologic conditions in this shallow unit have not changed significantly since 1999.

Figure 3.18 is a potentiometric surface map based on those wells completed in the lower part of the overburden. Many of these wells were installed by DPT to the depth of refusal and some of them may not have fully penetrated the overburden if large cobbles were encountered in the coarse material. Nearly all of these wells are screened at a depth that includes some of the coarse-grain material, but many also incorporate some finer-grain units in the screened interval. However, the wells appear to be hydraulically connected to the coarse-grain basal layer. The potentiometric surface defined by these wells on Fig. 3.18 clearly defines a southeasterly groundwater flow direction toward Joachim Creek. The region of highest hydraulic heads on this map corresponds to the location of the Hematite Facility.

LBG (1999, Section 5.2.5, pages 21-22) also presented a potentiometric map for the DSCC, a unit they identified that lies below the NSSSC and above the coarse-grain material at the base of the overburden. The map was limited in extent to the immediate vicinity of the Hematite Facility. During fieldwork for the RI, geologists were unable to distinguish this subunit in core material. As a consequence, this Report combines water level and contaminant data for the DSCC wells of LBG (1999) and the deep overburden wells of the RI. The water level results illustrated in Fig. 3.18 and related discussion of contaminant distributions in the deeper overburden (Chaps. 4 and 5) suggest that this approach is valid.

In Sect. 3.3.2.1 it was noted that Joachim Creek is a gaining stream in the vicinity of the Hematite Site. Additional information is available that supports this interpretation. As part of the RI, water levels were measured for Joachim Creek at several points near the Facility in association with water level determinations in neighboring overburden monitoring wells in February 2005. The results are summarized as follows (refer to Fig. 3.18 for well locations):

Location	Water Level (ft AMSL)
BR-06-OB	409.7
Joachim Creek near BR-06	409.7
BR-10-OB	408.1
Joachim Creek near BR-10	407.4

These measurements, coupled with the observed hydraulic gradient in the direction of Joachim Creek as illustrated on Fig. 3.18, suggest discharge from the overburden into the stream. During periods of flooding of the stream, there may be temporary reversal of flow proximal to Joachim Creek, but this condition will not persist once the stream water level returns to normal.

Comparison of the hydraulic heads in shallow (Fig. 3.17) and deep (Fig. 3.18) overburden underlying the Hematite Facility illustrates a downward vertical gradient (details are discussed in Sect. 3.3.3.3). Head differences of 10 ft or more are common in the region of the Facility. This fact suggests that the shallow groundwater represents a perched water table. The fact that the hydraulic heads are highest in the vicinity of the Hematite Facility may result from several different mechanisms. For example, a possible source of increased recharge in this area may be related to operation of the Facility. Leaks in stormwater, domestic and process water, and waste transfer piping could be a factor in these

observations. Alternatively, shallow subsurface groundwater flow from the topographically elevated region northwest of the Facility may be important. Likewise, storm runoff from the adjacent Highway P could contribute to this observation.

The potentiometric surface maps for bedrock are presented as a sequence of separate illustrations based on the three HSUs defined in the previous section. Figure 3.19 represents the potentiometric surface for the Jefferson City-Cotter HSU. In general, the potentiometric surface on Fig. 3.19 appears to define a zone of high heads in bedrock under the Hematite Facility. The region of high heads roughly corresponds to similar regions observed in both the shallow and deep overburden wells (Figs. 3.17 and 3.18, respectively) and suggests that the overburden and shallow Jefferson City-Cotter HSU may be hydraulically interconnected.

There is evidence for declining heads in the direction of Joachim Creek, as defined by wells close to the Hematite Facility (i.e., PZ-04, PZ-03, WS-30, and WS-31) and those located further toward the southeast (i.e., BR-08, BR-10, and BR-03). All of these wells are screened in a shallow zone within approximately 50 ft of the overburden-bedrock interface. Evidence, to be presented in Chapter 5, based on contaminant distributions in the Jefferson City-Cotter Dolomite supports an interpretation of flow and transport toward the southeast. Other wells to the north of Joachim Creek and lying on its flood plain (i.e., BR-04, BR-05, BR-09, BR-11, and BR-02) appear to define a potentiometrically flat surface, suggesting little potential for lateral groundwater flow except in close proximity to the Hematite Facility. Contaminant data discussed in Chapter 5 will help refine the details of groundwater flow in this region.

The cluster of wells on the topographically elevated region to the south of Joachim Creek also appears to define a region of high heads, and contours have been drawn in a way that may reflect a topographic influence, with heads declining northwestward in the direction of Joachim Creek. This gradient suggests a zone of groundwater convergence or discharge from the Jefferson City-Cotter HSU to the overburden near to the location of the creek. This inference is consistent with the vertical groundwater gradients observed between the overburden and Jefferson City-Cotter in this area (Sect. 3.3.3.3). However, the water levels measured in PW-19 and PW-06 on December 3, 2004 (Fig. 3.19) appear to be low in comparison to their nearest neighbors and relative to another set of water levels that were obtained less than 2 weeks later. This latter data set was obtained in association with site-wide groundwater sample collection (described in Sect. 2.6) that occurred in late December 2004 and early January 2005. The differences between these two data sets may be associated with slow re-equilibration of water levels in the Jefferson City-Cotter HSU following conversion of PW-06, PW-16, and PW-19 from open holes to dual completion wells in mid-November 2004.

There also is uncertainty in attributing water levels observed in PW-05, PW-10, PW-24, and PW-25 to the Jefferson City-Cotter HSU. These private wells are all completed as open holes (refer to Fig. 3.19 for well locations and Fig. 3.13 for open depth intervals): PW-24 and PW-25 wells are completed in the Jefferson City-Cotter Dolomite and the others reach the Jefferson City-Roubidoux contact zone. It is not possible, given existing information regarding these private wells, to identify which hydrologic zone intersected by these open boreholes has a controlling influence on the observed heads. Thus, it is questionable that they are representative of the Jefferson City-Cotter HSU, as defined by other wells that are isolated within this zone (e.g., PW-06-JC, PW-16-JC, and PW-19-JC). For that reason, water levels for these wells are not included in the potentiometric map in Fig. 3.19.

Figure 3.20 shows a potentiometric surface for the Jefferson City-Roubidoux contact zone HSU that differs significantly from that for the Jefferson City-Cotter HSU that was illustrated in Fig. 3.19. Borehole BR-12-JC has a head value that is elevated with respect to the others, but the more dominant feature is the indication of a significant northeasterly component to the gradient (and to groundwater flow). As already noted, the regional potentiometric gradient declines towards the northeast and Fig. 3.20 appears to be part

of this regional hydraulic regime. As for Fig. 3.19, water levels for the open boreholes/private wells to the south of Joachim Creek have not been included in drawing the potentiometric surface shown on Fig. 3.20 because it is not possible to determine what HSU controls the water levels.

Water levels were measured in BR-12-RB on December 3, 2004 (427.31 ft AMSL) and again on December 8, 2004 (417.9 ft AMSL). The latter measurement was associated with a groundwater sample collection activity (Sect. 2.6). Well BR-12-RB is the only well that showed this magnitude of difference between water levels measured only five days apart and a measurement error is suspected. Other water level measurements in BR-12-RB made during 2005 suggest that the 417.9 ft AMSL value is more likely to be correct and, consequently, this value is used in Fig. 3.20.

Water levels for wells in the Roubidoux HSU (Fig. 3.21) define a potentiometric surface roughly similar to that observed on Fig. 3.20, and appear to reflect the regional influences (i.e., a northeasterly trending gradient). Artesian conditions in BR-03-RB prevented an accurate determination of the head on December 3, 2004, and an additional riser was added to the well before December 9, 2004. The water level in BR-03-RB was re-measured on December 9 as part of groundwater sampling and an elevation of 423.1 ft AMSL was obtained.

The HSUs illustrated in Fig. 3.13 were defined primarily from compelling stratigraphic and structural lines of evidence. The HSUs represent narrow stratigraphic windows, approximately 20-30 ft thick, that are inclined at an angle similar to the regional dip (~2.7º; Fig. 3.12). The wells shown in Fig. 3.13 all are projected into a cross section that represents the axial plane of the subtle warp shown in Fig. 3.11. The relative vertical positions of the wells have been adjusted to compensate for the dipping strata on the flanks of the warp feature (1-2º). Given the thin package of strata that define a HSU it is reasonable to acknowledge that hydraulic integration probably exists within that geologic interval. Therefore, the HSU becomes the key unit from which to construct potentiometric maps for the region and overlay groundwater geochemical relationships.

As illustrated in Fig. 3.13, the stratigraphic window represented by the Jefferson City-Cotter HSU is approximately 20-25 ft thick and encompasses the screened intervals of 16 wells located in the vicinity of the Hematite site. Therefore, this HSU is a data-rich resource and the resulting potentiometric surface (Fig. 3.19) is a convincing representation of integrated water level information and not a random collection of data that bear no relationship to one another. Each of the other HSUs yield unique potentiometric surface maps that emphasize the progressive change in the potentiometric environment from shallow groundwater that is impacted by near surface factors to deeper HSUs where regional potentiometric properties dominate. There is essentially no evidence suggesting the existence of natural hydraulic linkages between vertically adjacent HSUs.

It is possible to combine information from potentiometric surface maps (Figs. 3.17 through 3.21) and slug test results (Table 3.2) to compute estimates of groundwater flow velocities based on Darcy's Law:

$$\text{Linear Velocity} = - K_h \, (dh/dl)/\rho \text{ (where } \rho = \text{porosity).}$$

However, one must assume that the two points used to calculate velocity actually lie on a flow path. Estimates have been made of Darcy flow velocities for a variety of potential flow paths, and the results obtained for overburden range between approximately 20 and 300 ft/year; estimated velocity values in bedrock range from 2 to >300 ft/year. These results, and other estimates based on the assumed rate of advance of contaminant plumes, are discussed in more detail in the groundwater modeling report (Appendix A of this Report and SAIC 2005).

In unconsolidated porous media such as the overburden, there is a reasonable level of confidence that the potentiometric surface provides a good indication of the direction of groundwater flow and contaminant transport. This inference is testable by referring to the distribution of contaminants in overburden groundwater and will be discussed in Chapter 5. In contrast, the relationship between groundwater flow and contaminant transport and the configuration of the potentiometric surface for bedrock formations is more difficult to interpret. Groundwater flow directions in fractured media are dependent on the orientation of transmissive fracture sets. The transmissivity of individual fractures depends on the interconnectivity of a network of fractures. Lithologic features, such as the presence of transmissive interbeds, also will influence flow directions.

Both the Jefferson City-Cotter Dolomite and the Roubidoux Formation are dominated by dolostone, although sandstone interbeds are known to occur in the geologic section underlying this area (see Figs. 3.9 through 3.11). Groundwater flow in the dolostone primarily should follow laterally continuous, permeable interbeds, such as sandstone, and fractures, some of which may have been widened by dissolution. The core logs reveal the presence of the interbeds. The drilling log entries also note that fractures were occasionally encountered in recovered core, but details about the role of fractures in groundwater flow in the vicinity of the Hematite Site are not available because comprehensive information on fracture frequency, orientation, and apertures are not available. As noted in Sect. 3.2.4.3, there is no information on the dominant fracture sets and their orientation in this region.

Preferential flow in bedrock also may be associated with zones of weathering that widen fractures and increase permeability. Some parts of the Jefferson City-Cotter Dolomite near the overburden-bedrock interface in the valley of Joachim Creek may be an example of this process. Consequently, the potentiometric surfaces for the Jefferson City-Cotter Dolomite and Roubidoux Formation should be regarded only as providing information on the potential directions of groundwater flow. A better understanding of the connection between head gradients and groundwater flow will emerge in Chapter 5 when the distribution of contaminants in groundwater from these formations is considered.

3.3.3.3 Vertical head gradients

Whereas the previous discussion examines the potential for lateral groundwater flow (and contaminant transport), it is also important to understand the evidence relating to the potential for vertical groundwater flow at the Hematite Site. Figures 3.22 through 3.24 present vertical gradient results between the shallow and deep overburden, the deep overburden and Jefferson City-Cotter Dolomite, and the Jefferson City-Cotter Dolomite and Roubidoux Formation, respectively. Note that these gradients were calculated based on water level measurements made in December 2004. The vertical gradient is defined as follows:

Vertical Gradient = - dh/dZ = - (shallow head – deep head)/vertical separation of monitored zones
(negative values of –dh/dZ indicate a downward gradient)

Figure 3.22 shows that the vertical gradient between the shallow and deep overburden layers underlying the Hematite Facility is strongly downward, except at WS-26/WS-27 next to Northeast Site Creek where an upward gradient is observed. The general observation of a downward head gradient in this area is consistent with the earlier discussion related to Figs. 3.17 and 3.18. A region of downward gradients under the Hematite Facility also is observed when water levels in the deep overburden are compared to the Jefferson City-Cotter Dolomite, as illustrated on Fig. 3.23. However, the magnitude of the gradient is less than that on Fig. 3.22. The overburden-Jefferson City-Cotter gradient near Joachim Creek is upward, which coincides with the interpretation of this region as a zone of groundwater convergence (i.e., discharge), as seen on Fig. 3.19. As illustrated on Fig. 3.2.4, the gradient between the Jefferson City and Roubidoux Formation is upward throughout most of the area, except to the east for wells BR-02 and BR-05 where the gradient is slightly downward.

3.3.3.4 Interconnectivity of geologic units: time series water level measurements

It is important to assess the degree of interconnectivity of the main hydrologic units in the vicinity of the Hematite Site, because this information will help explain the vertical distribution of contaminants. Furthermore, it is an essential piece of information for the CSM that will support numerical modeling and the F&T evaluation in Chapter 5.

Figures 3.25 through 3.27 are time-series plots of water levels in selected wells with at least quarterly measurements that extend over a period of from one to several years. Comparison of these water level results focuses on the relative shapes of the time-series patterns and not on absolute values of water level elevations. The data show that for the common period of water level records (March to December 2004) the overburden and shallow Jefferson City-Cotter HSU (Fig. 3.25) well hydrographs appear to be very similar. In addition, from August 2004 to August 2005 the hydrographs for BR-04-JC (Jefferson City-Cotter HSU) and BR-08-RB (Jefferson City-Roubidoux Contact Zone HSU) also mimic one another (Fig. 3.26). One possible explanation for these observations is that these geologic units are hydraulically interconnected. Alternatively, the similar hydrographs may reflect the fact that the Jefferson City-Cotter Dolomite outcrops in the vicinity of the Hematite Site and water levels are responding independently to seasonal changes in precipitation and recharge (i.e., elevated water levels in winter-spring and lower during the drier summer months). The Jefferson City-Cotter well shown on Fig. 3.26 is BR-04-JC, which is located northeast of the Facility and completed at a depth of approximately 100 ft BGS. BR-08-RB is located southeast of the Facility and screened at a depth of approximately 110-150 ft BGS.

The discussion in Chapter 5 establishes that VOC contamination originating at the Hematite Facility has migrated downward into parts of the Jefferson City-Cotter HSU. This observation supports the inference of a hydraulic connection between the overburden and shallow bedrock in at least some parts of the Site. In contrast, no VOC contamination exists in the Jefferson City-Roubidoux Contact Zone HSU on the Hematite Site. In addition, information presented in Sect. 3.3.3.1 tends not to support an intimate hydraulic connection between the Jefferson City-Cotter and Jefferson City-Roubidoux Contact Zone HSUs.

Water level data for Roubidoux HSU wells (Fig. 3.27, this figure has the same vertical scale as Fig. 3.26) suggest a somewhat different response over time. The most significant difference is that these wells have experienced an overall rapid rise in water levels that appears to have begun in 2003. Head increases of 30 to 40 ft have taken place by the end of 2004. The magnitude of the increase appears to increase with increasing distance from the Hematite Site, such that BR-02 has the greatest head rise and BR-01 the least over the same period of time. There are two events that most likely have contributed either individually or in concert with one another to cause this dramatic rise.

First, in late summer 2003, the city of Festus, located approximately 5 miles to the east of the Hematite Site (refer to Fig. 1.1 for the location of Festus relative to the Site), brought online a new water-production facility located on the floodplain of the Mississippi River about 1 mile from the river. This “collector” well draws water from the sediments marginal to and underlying the Mississippi River using horizontal wells and now provides nearly all of the water needs for the area. Startup of this well permitted the city to place its four production wells located on the west side of Festus (i.e., closer to the Hematite Site) on standby. These wells had been pumping approximately 1 gpd from the lower Roubidoux Formation. Currently, they are used only during periods of peak demand in mid- to late summer, or when the collector well is off-line. When supplementing production from the collector well, the pumping rate on these wells is much less than before August 2003.

Secondly, once contamination was discovered in private wells located southeast of the Hematite Site across Joachim Creek, the local public water supply system was extended to the residents and all wells in

this area were shut down (between November 2003 and March 2004). The U.S. Geological Survey (USGS) reports that in Missouri, residential, self-supplied water usage is approximately 65 gpd/person (http://water.usgs.gov/pubs/circ/2004/circ1268/htdocs/table06.html). Therefore, the total daily withdrawal of groundwater by the more than 20 families in this area probably was on the order of 5000 GPD. Although this amount is much less than for the city of Festus, there may have been a local impact on drawdown in the Roubidoux Formation until these wells were shut down.

Both of these events relieved a source of hydraulic stress to the Roubidoux Formation. The magnitude of the impact of the shut down of the Festus production wells is regional in scale, while the impact of the shut down of the private wells was probably only of local extent.

Further support for the magnitude of regional impact of the Festus production wells comes from a well located within 1 mile of one of the original Festus production wells that is monitored by USGS and has continuous water level data over the time period of interest (USGS 2005). This USGS well is located ~3 miles northeast of the Hematite Facility, is 1048 ft deep, and is completed in the lower Roubidoux/Potosi Formation. Since mid-2003, this well has experienced a rise in water level of approximately 150 ft (Fig. 3.28).

On July 6, 2005, the city of Festus temporarily resumed pumping three of its deep production wells. Coincident with this event, the water levels in the USGS monitoring well and wells BR-02-RB and BR-03-RB began to decline rapidly. This result adds support to the proposed cause and effect relationship between large-scale pumping (or shutdown) of the Festus wells and observed changes in water levels in monitoring wells penetrating into the Roubidoux HSU on the Hematite Site.

In addition to the overall rise in water levels throughout 2004 in Roubidoux HSU wells located near the Hematite Site, comparison of the shapes of the hydrograph trends for Roubidoux, Jefferson City-Cotter, and overburden wells (Figs. 3.25 through 3.27) shows general similarity over the past 1 to 2 years. However, the amplitude of changes in the Roubidoux water level data appears to be damped in comparison to the other wells. The fine structure to the water level curves on Figs. 3.25 through 3.27 appears to be persistent among wells completed in the three geologic units and, as noted above, probably represents a response to seasonal changes in the amount of precipitation and recharge. The water level records are too short to provide a detailed comparison to local precipitation records.

Whereas information discussed earlier in this section suggests hydraulic interconnection between overburden and at least parts of the Jefferson City-Cotter HSU, deeper bedrock units appear to be more isolated from one another. The contrast between hydrographs for the Jefferson City-Cotter and Roubidoux wells since mid-2002 (Figs. 3.26 and 3.27) suggests that significant hydraulic interconnections do not occur between these two geologic units. This observation supports an interpretation that contamination of the Roubidoux Formation by downward migration of groundwater is unlikely (discussed further in Chapter 5). Rebound of water levels of 20 to 40 ft in the Roubidoux wells (especially BR-04-RB) during this period of time is not reflected to any significant degree in the hydrograph of BR-04-JC. It is more likely that the superficial similarities of the fine structure of these hydrographs are related to their response to seasonal precipitation and recharge factors transmitted to the formations from areas of surface outcrops on a regional scale.

Another example of information supporting the lack of hydraulic interconnectivity between the Jefferson City-Cotter Dolomite and Roubidoux Formation is illustrated by the results of integrity testing in wells PW-06, PW-16, and PW-19. Following their shut down, these private wells were reconfigured as dual-completion monitoring wells with deep and shallow screened intervals isolated by a thick grouted zone. In November 2004, the lower intervals in these wells were pumped at a sustained rate of 2 to 4 gpm for 1 hour, as water levels in the upper zones were monitored. The purpose of the testing was to confirm

the integrity of the grout seal. The shallow zones in PW-06 and PW-19 showed no changes in water level during the test. Not only do these results establish that the grout seal is intact, but they also show that the lower and upper screened intervals of bedrock are not significant in hydraulic communication. Water levels in the upper zone at PW-16 rose slightly (1.09 ft) during the pumping of the deep zone, an observation that is difficult to reconcile with the nature of the testing.

The rebound in water levels observed in the Roubidoux wells on Fig. 3.27 is significant for another important reason. Prior to the shut down of the Festus production wells in 2003 and the private wells near the Hematite Site in 2004, water levels within these Roubidoux wells were 20 to 40 ft lower than results from the most recent measurements made in December 2004. The potentiometric surface for the Roubidoux Formation (Fig. 3.21) and the vertical gradients between this formation and the Jefferson City-Cotter Dolomite (Fig. 3.24) for this RI were measured after a significant period of recovery had occurred and apparently are approaching a new, higher, static potentiometric level. Had similar data been obtained prior to 2003 for all of the new wells shown in these figures, the resultant patterns of head distributions would have been dramatically different. Specifically, there would have been a strong easterly gradient in the Roubidoux Formation (i.e., greater drawdown for wells closer to the city of Festus production wells), and the vertical gradients between the Jefferson City-Cotter Dolomite and Roubidoux Formation would have been consistently downward rather than upward. A potentiometric map for the Roubidoux Formation based on water level data obtained from four wells in August 2002 emphasizes some of these relationships and is presented in Fig. 5.20 with a related discussion.

This observation is critically important because groundwater flow and contaminant migration in the vicinity of the Hematite Facility probably occurred over a period of years prior to 2003 during which hydraulic conditions (at least for the Roubidoux Formation) were very different than today. The distribution of contamination currently observed in the Roubidoux Formation in the private wells southeast of the Facility appears to be related to the lower heads prevailing in that formation prior to 2003. F&T modeling accounts for these recent changes in water levels in the Roubidoux Formation and addresses how the changes will impact future contaminant migration patterns (Chapter 5).

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CHAPTER 3 FIGURES

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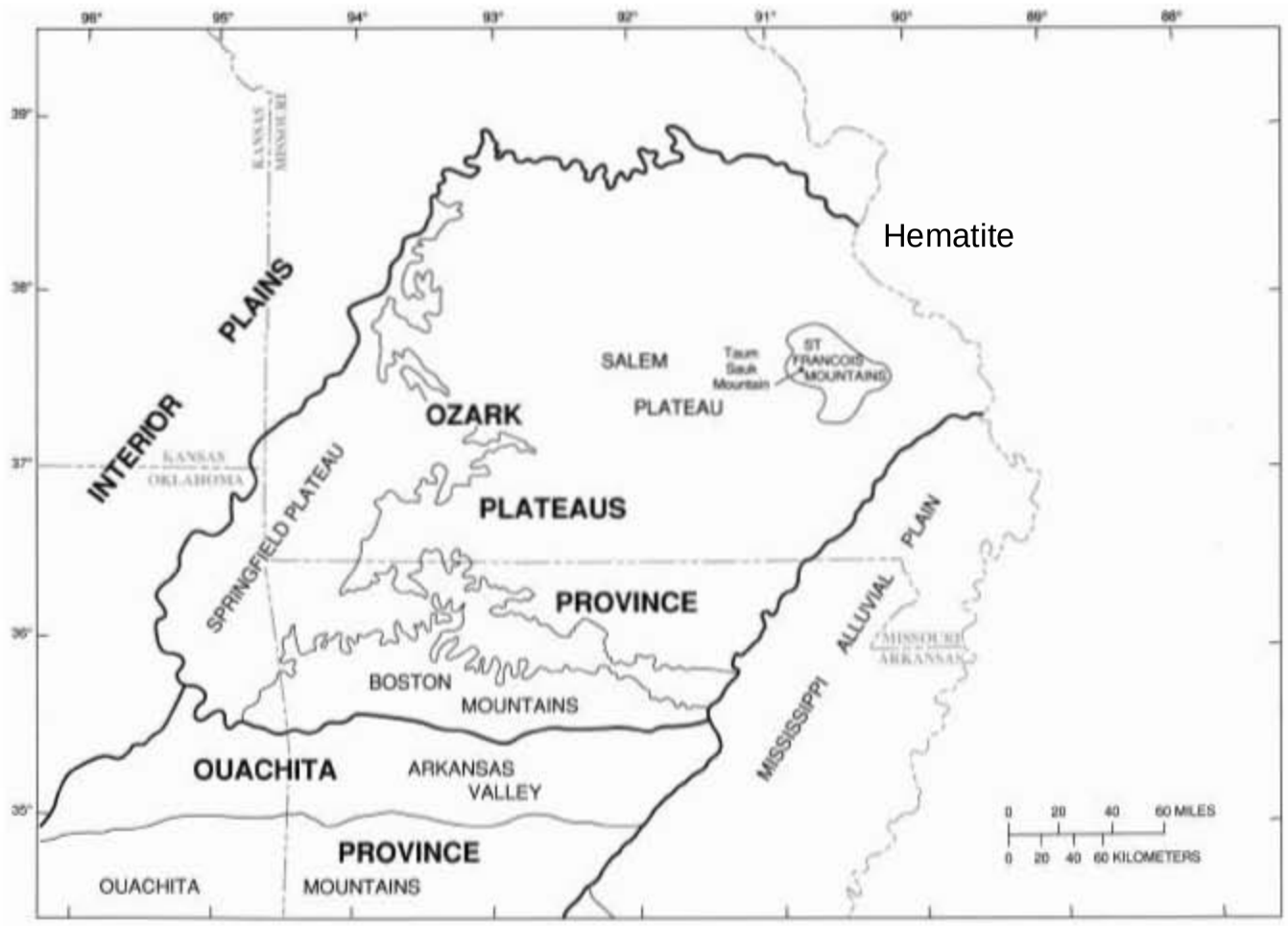


Fig. 3.1a. Location of Hematite in Salem Plateau, Ozarks Plateaus Physiographic Province.

Fig. 3.1b. Geologic map of Hematite Site area.

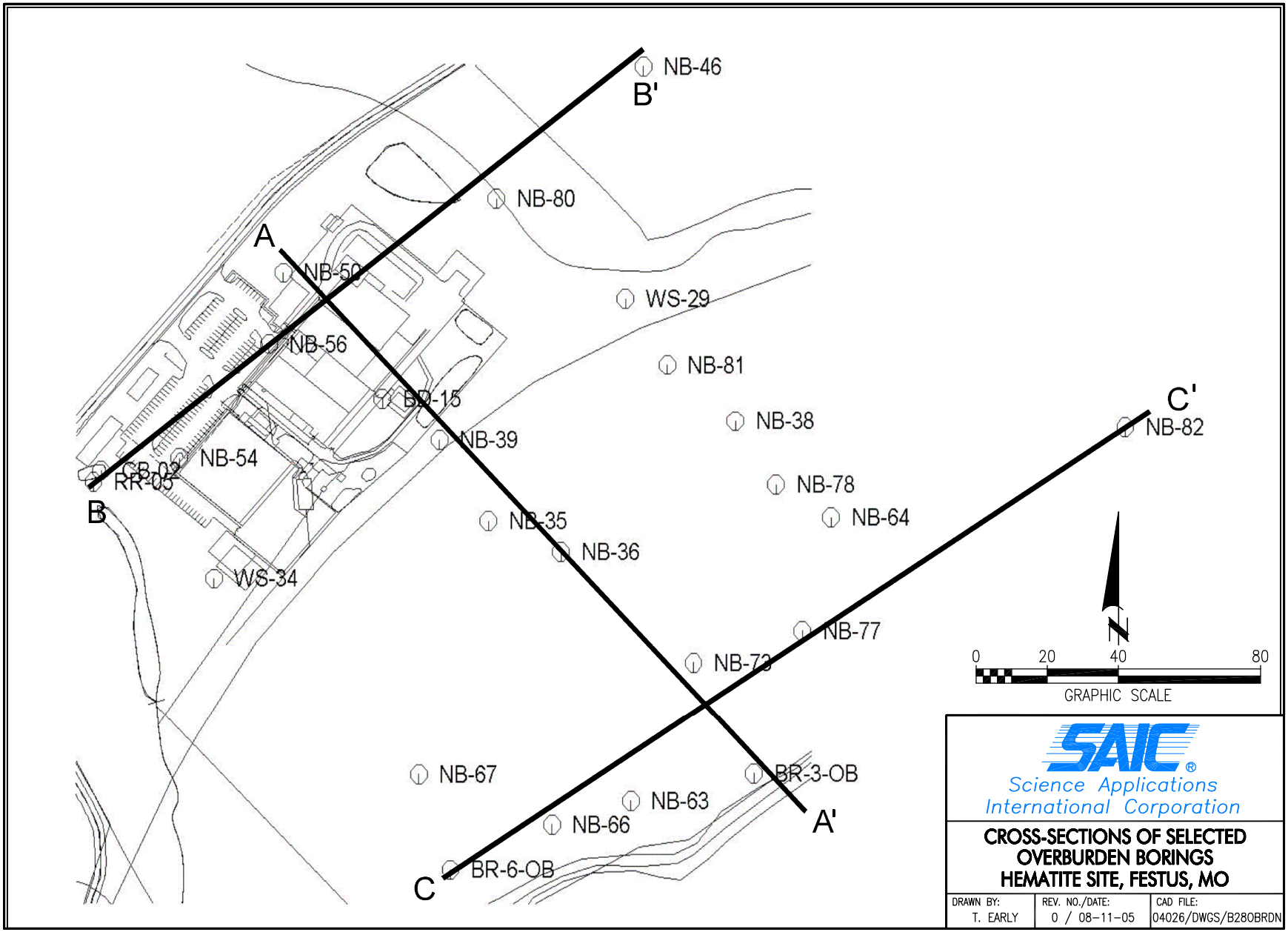


Fig. 3.2. Cross-sections of selected overburden borings.

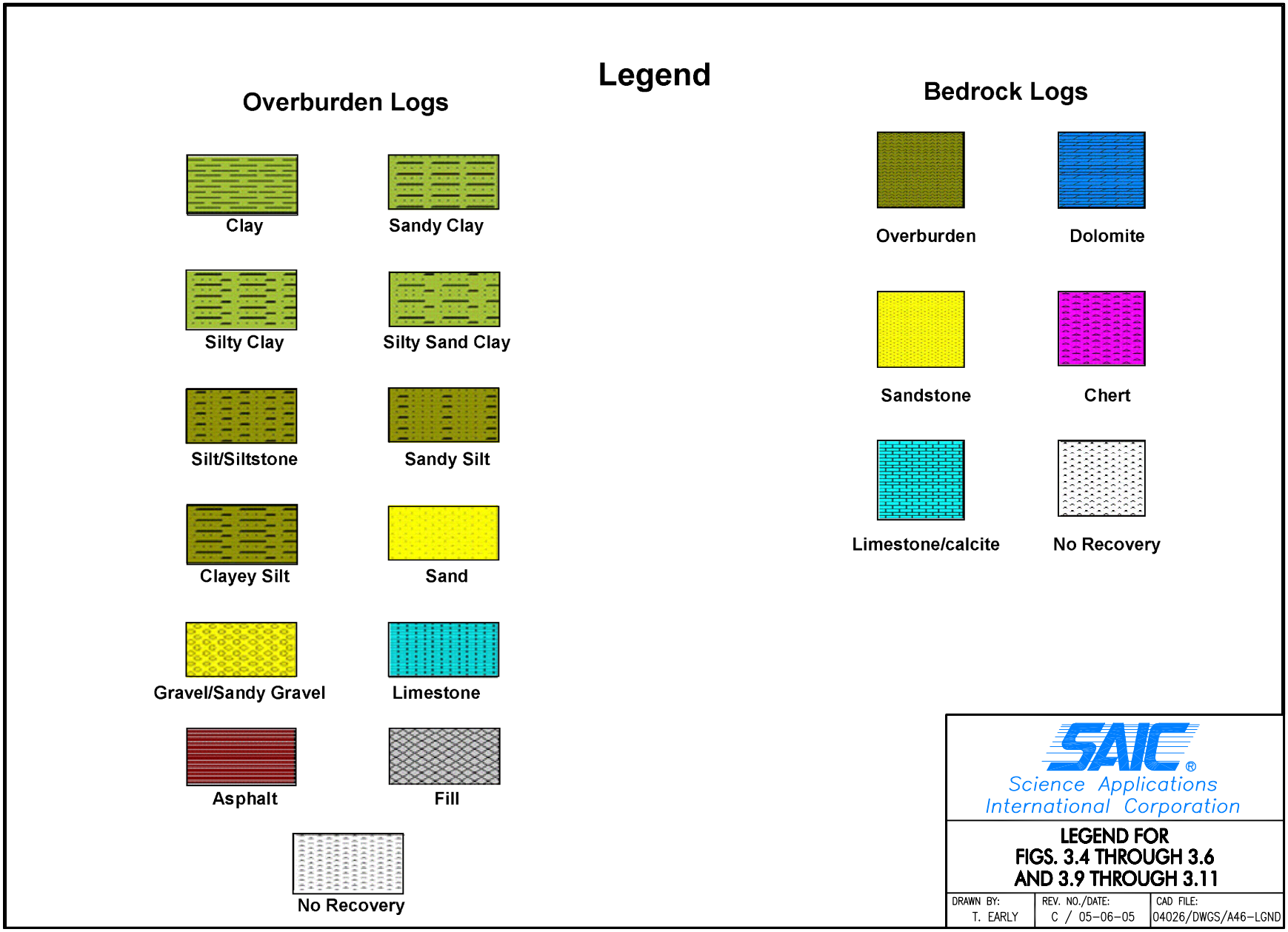


Fig. 3.3. Legend for Figs. 3.4 through 3.6 and 3.9 through 3.11.

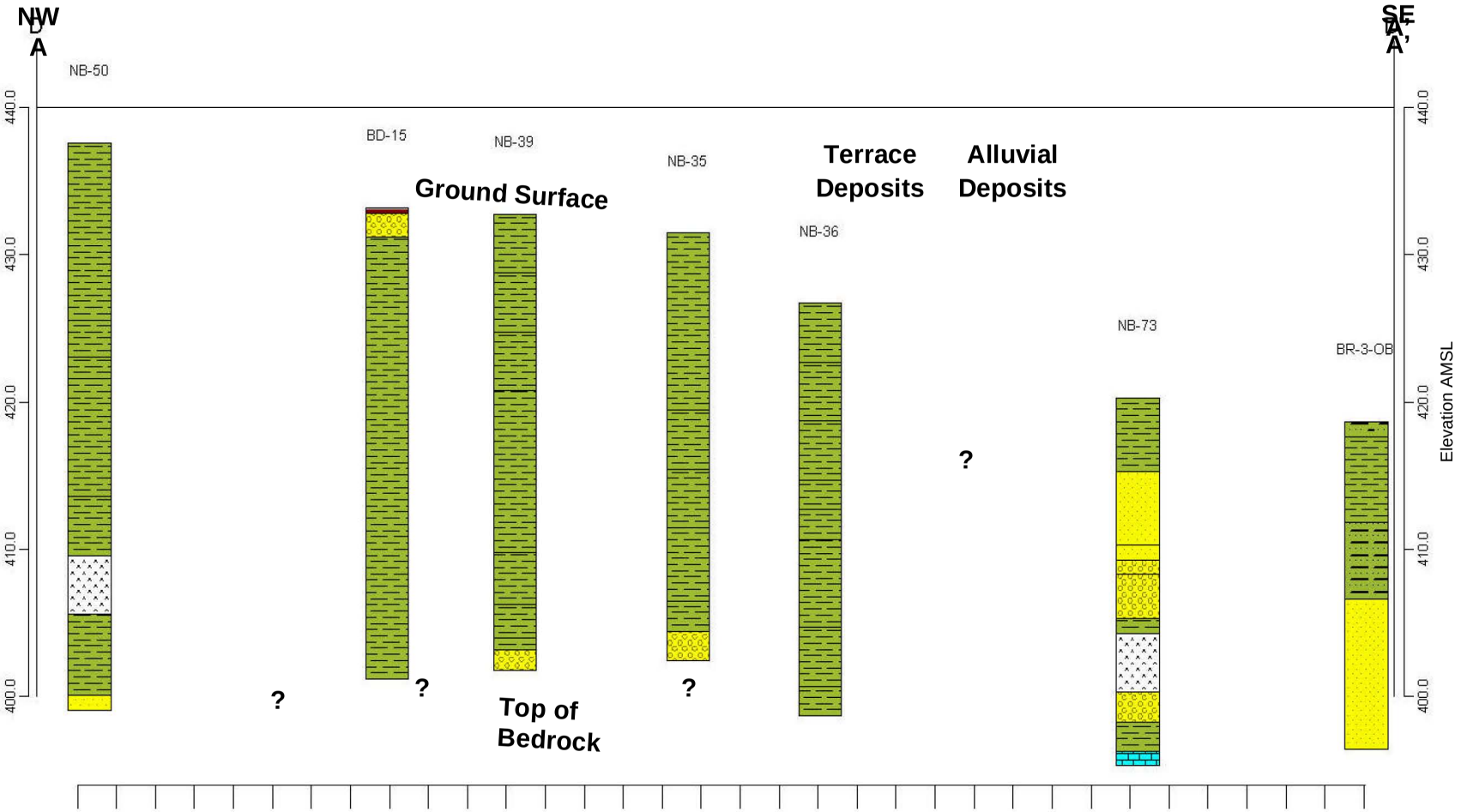


Fig. 3.4. Cross-section A-A'; overburden wells.

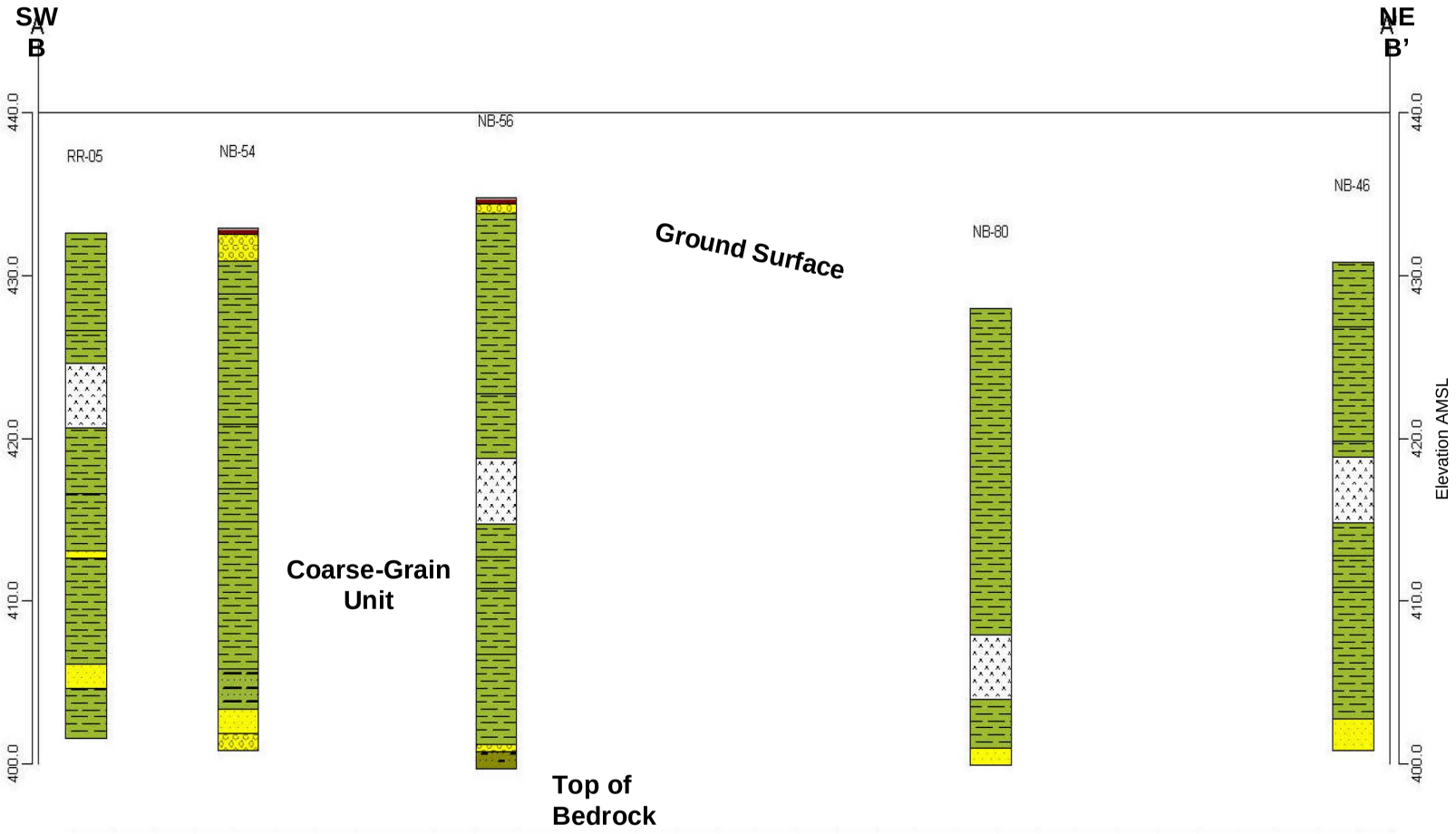


Fig. 3.5. Cross-section B-B'; overburden wells.

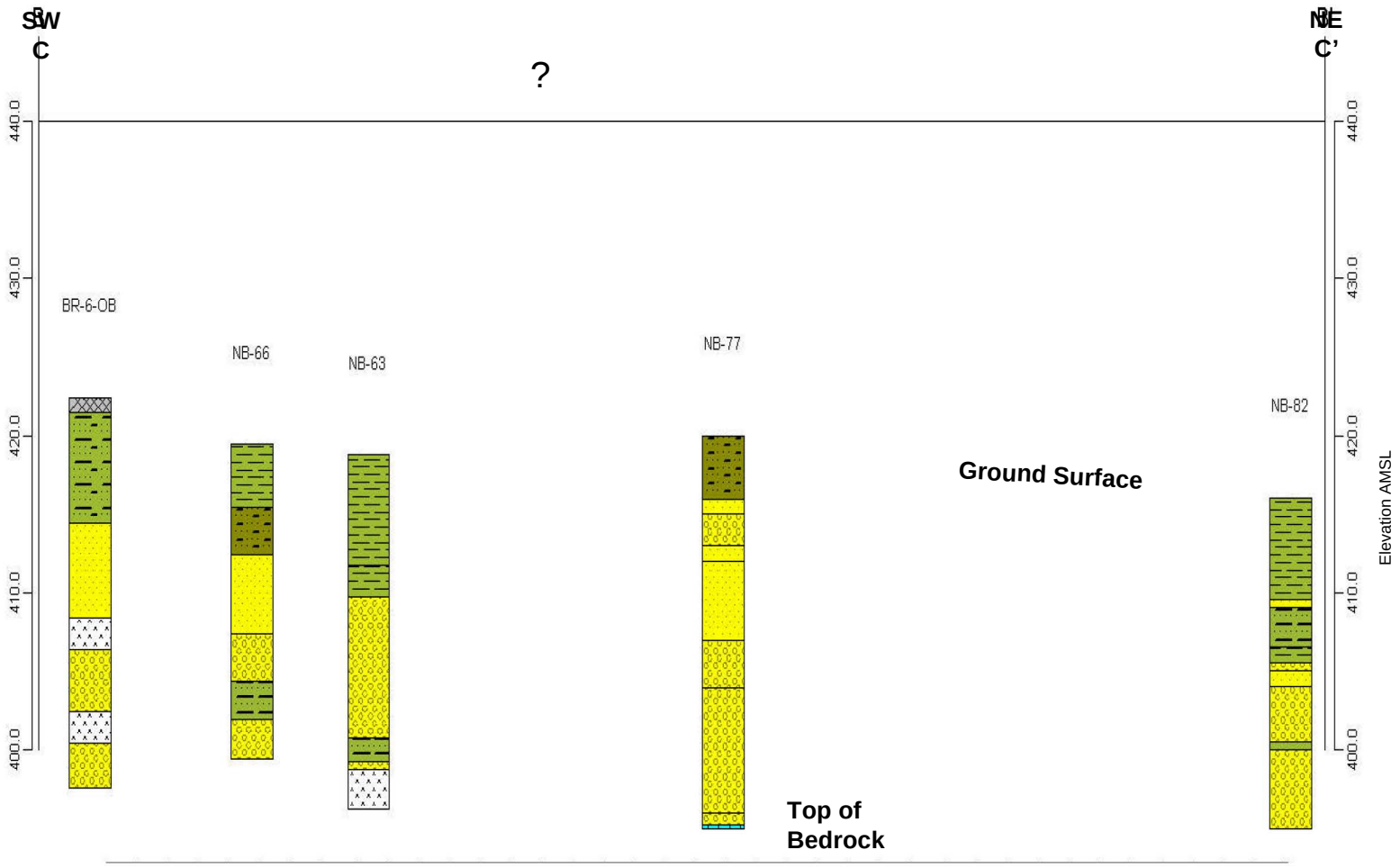


Fig. 3.6. Cross-section C-C'; overburden wells.

Fig. 3.7. Isopach map of coarse-grain-based deposits.

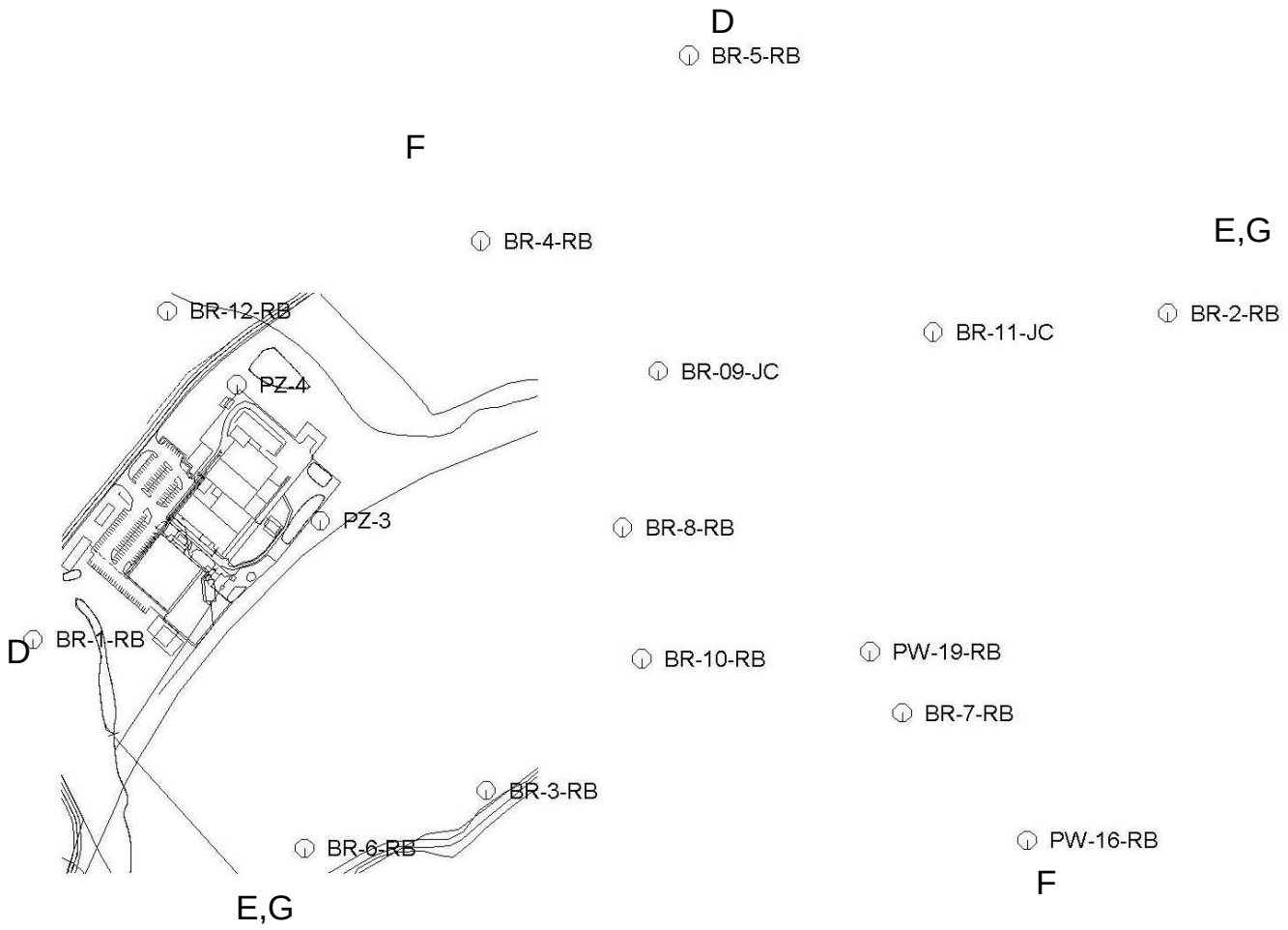


Fig. 3.8. Cross-sections of bedrock wells.

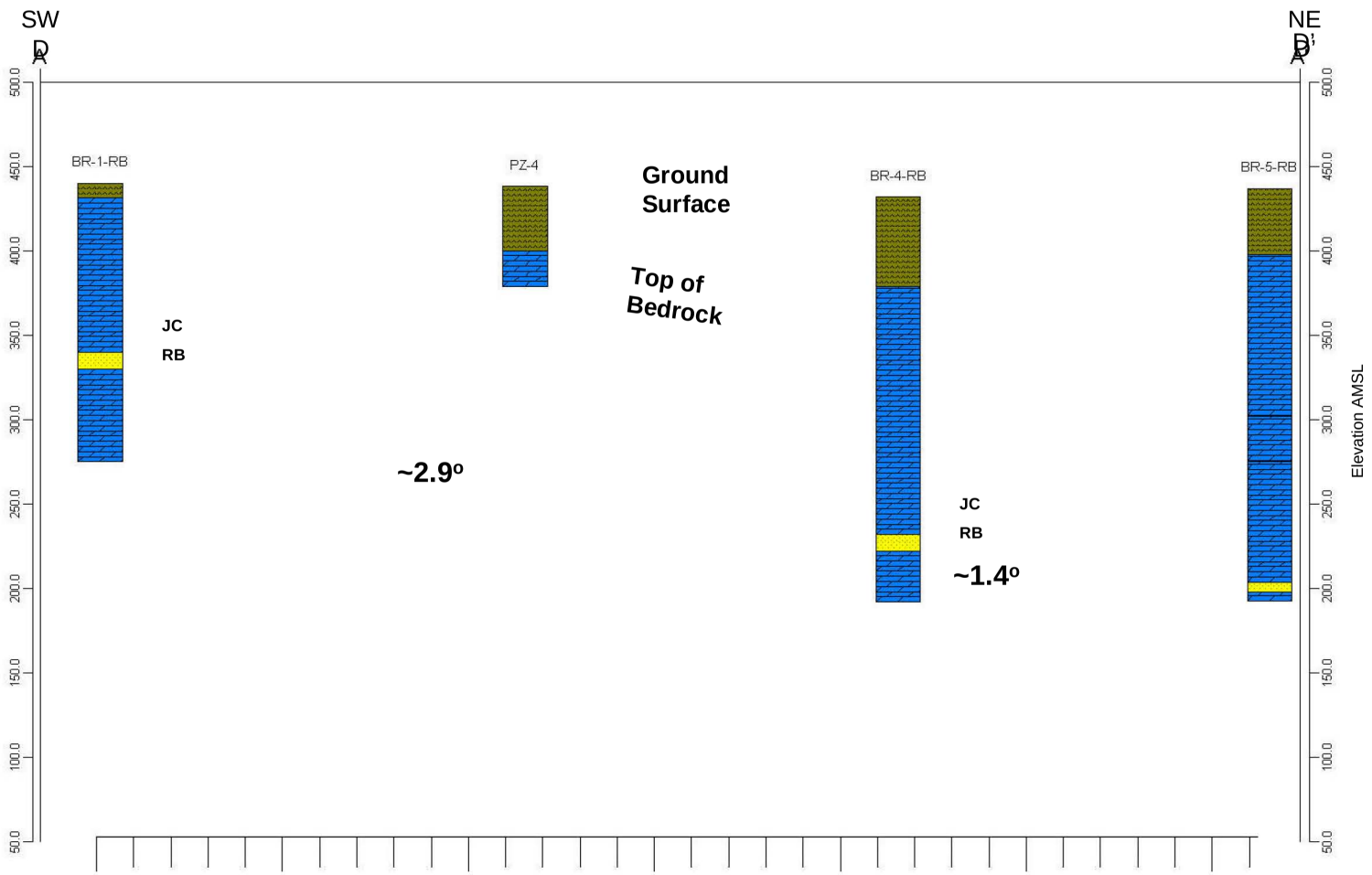


Figure 3.9. Cross-section D-D'; bedrock wells.

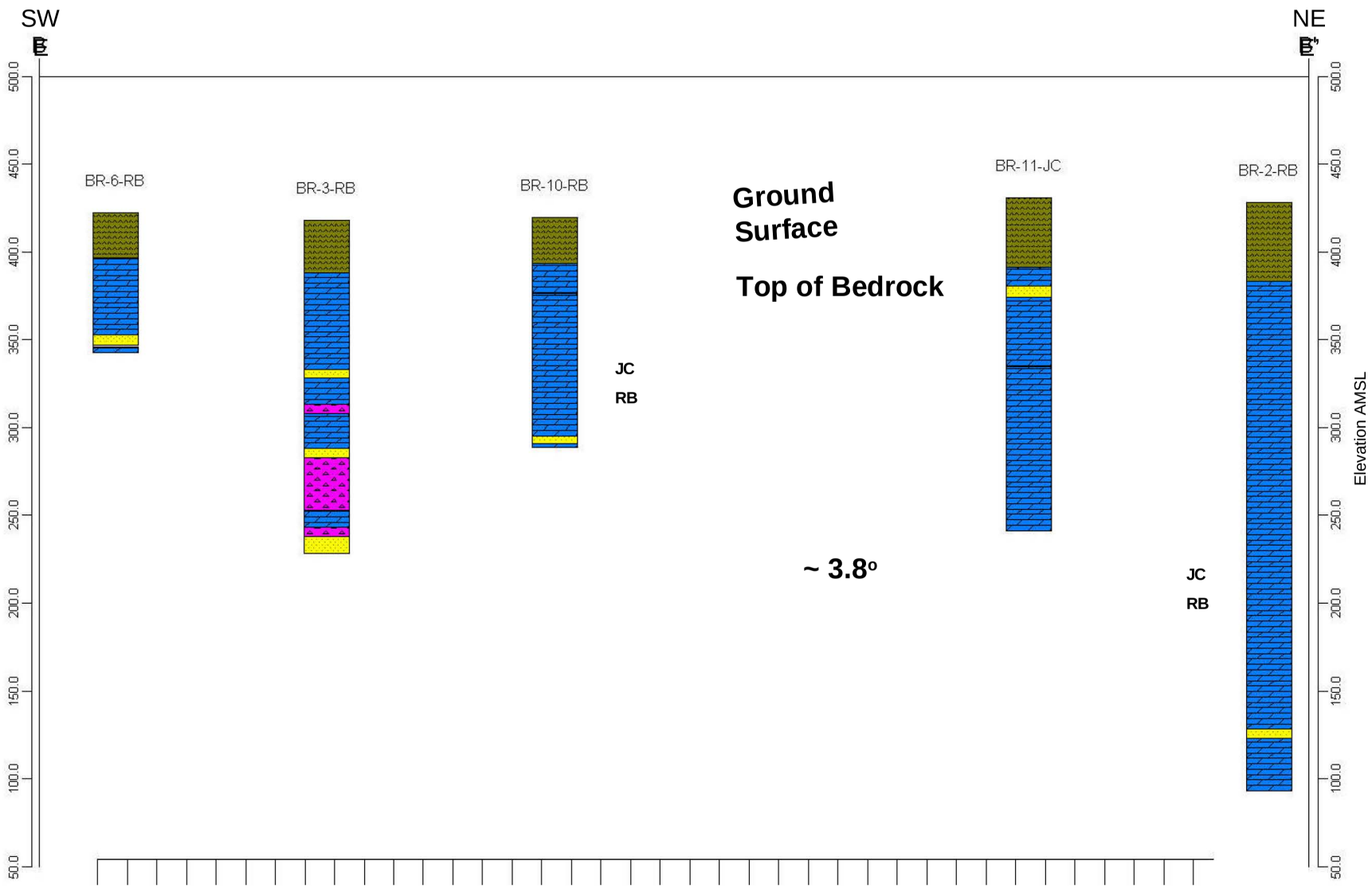


Fig. 3.10. Cross-section E-E'; bedrock wells.

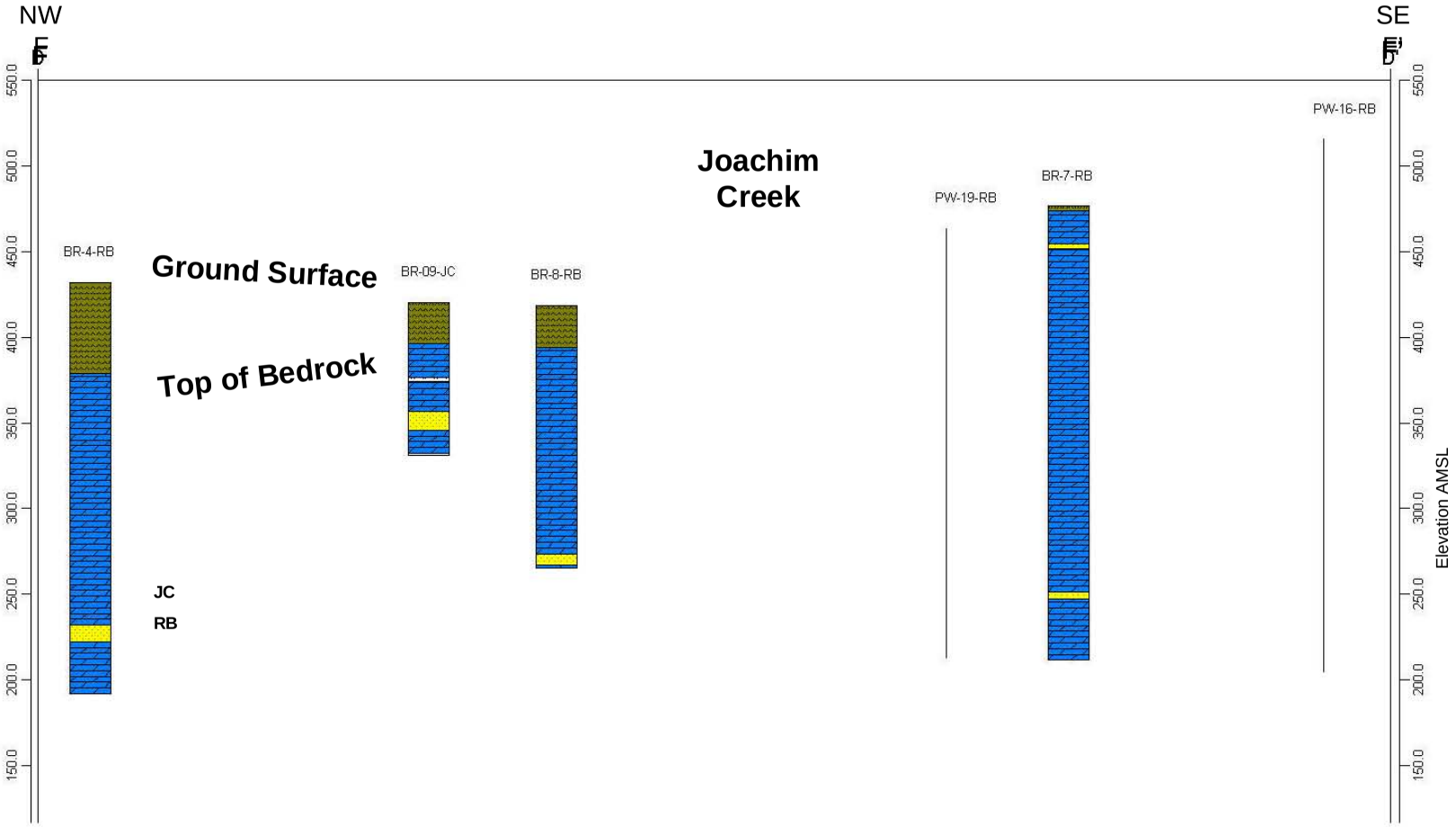


Fig. 3.11. Cross-section F-F'; bedrock wells.

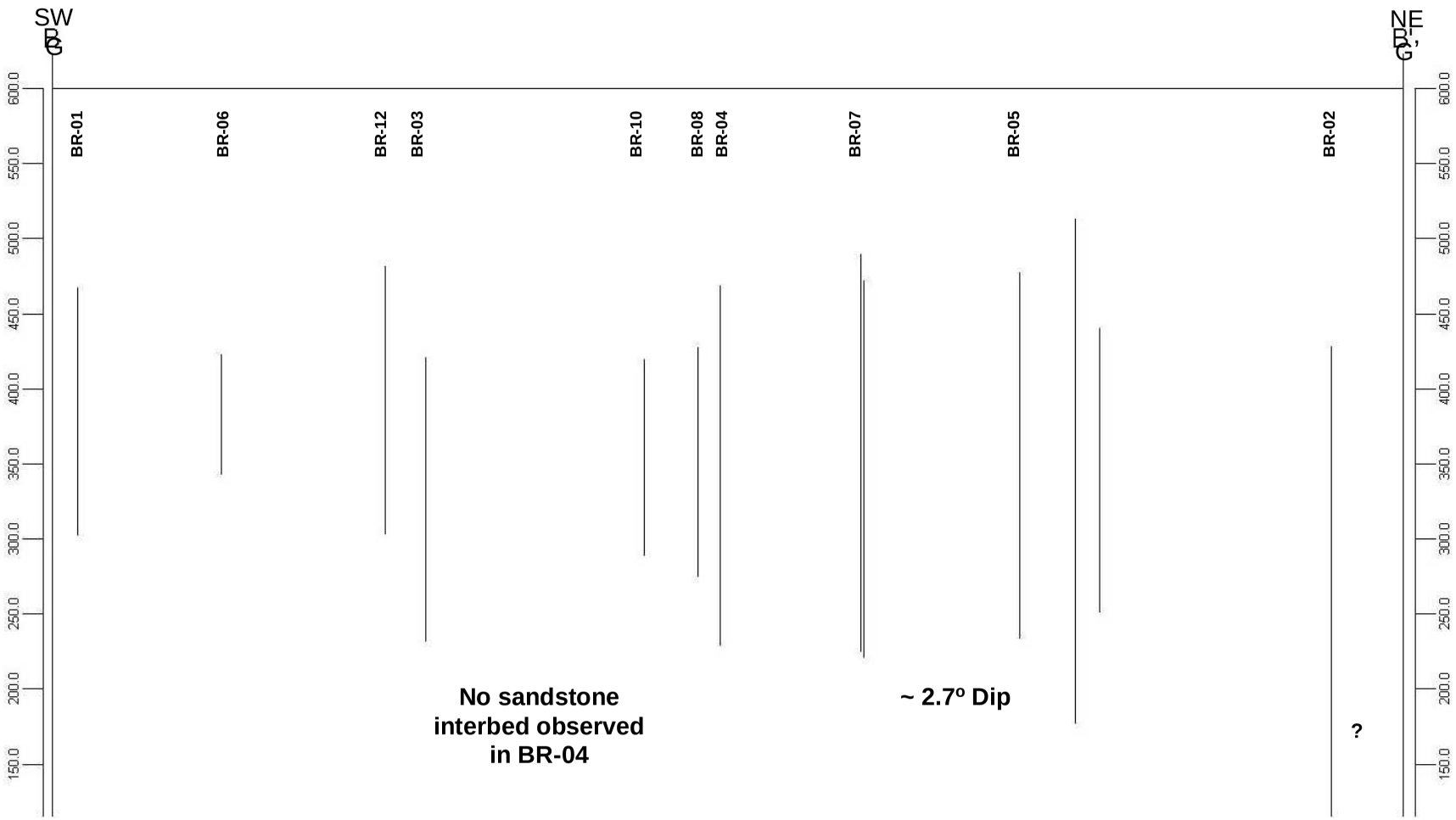
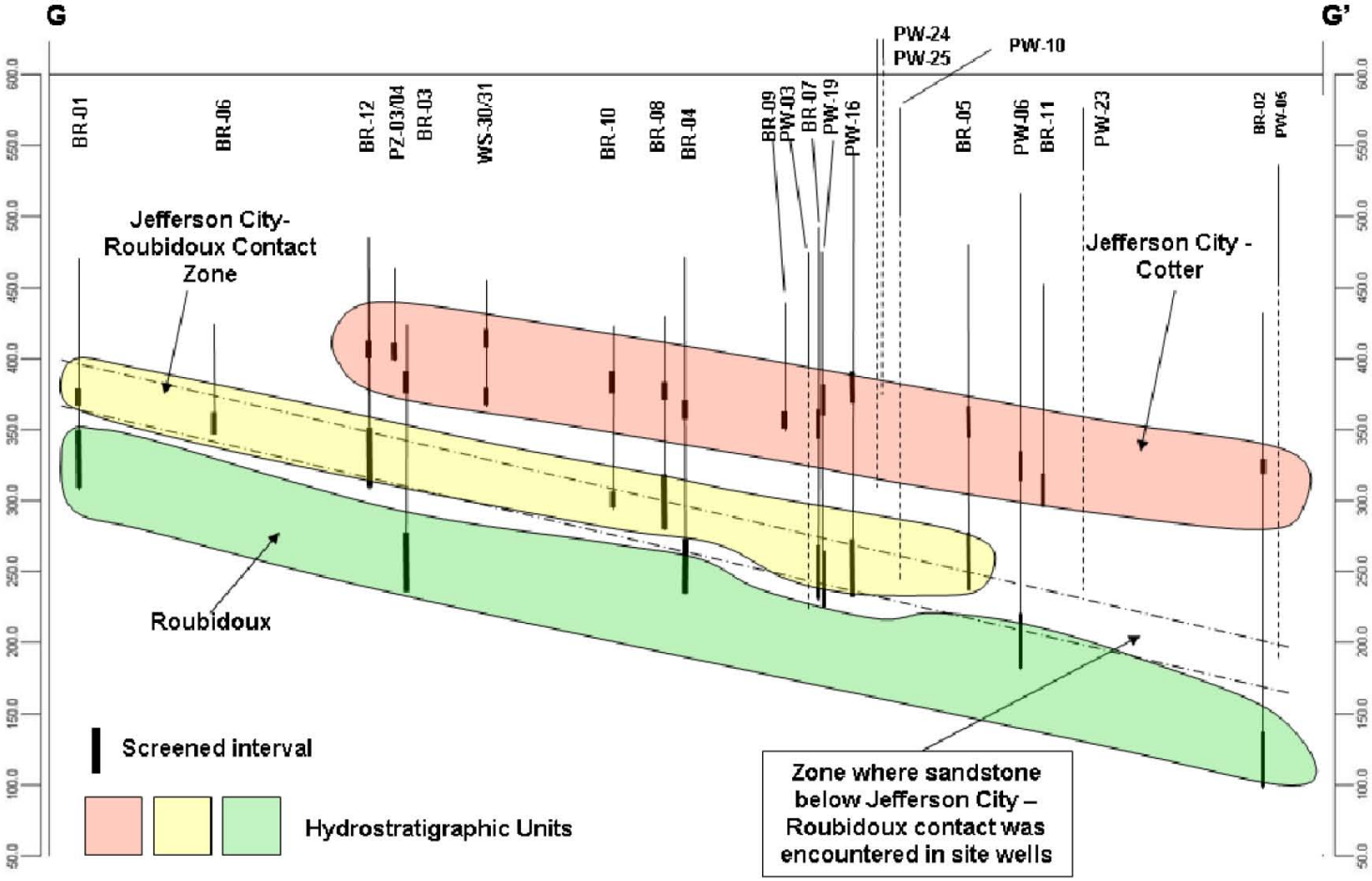


Fig. 3.12. Cross-section G-G'; bedrock wells corrected for geologic dip.


G
G'
PW-24
PW-25
PW-10
BR-01
BR-06
BR-12
PZ-03/04
BR-03
WS-30/31
BR-10
BR-08
BR-04
BR-09
PW-03
BR-07
PW-19
PW-16
BR-05
PW-06
BR-11
PW-23
BR-02
PW-05
Jefferson City-
Roubidoux Contact
Zone
Jefferson City -
Cotter
Roubidoux
Screened interval
Hydrostratigraphic Units
Zone where sandstone
below Jefferson City –
Roubidoux contact was
encountered in site wells
600.0
550.0
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0

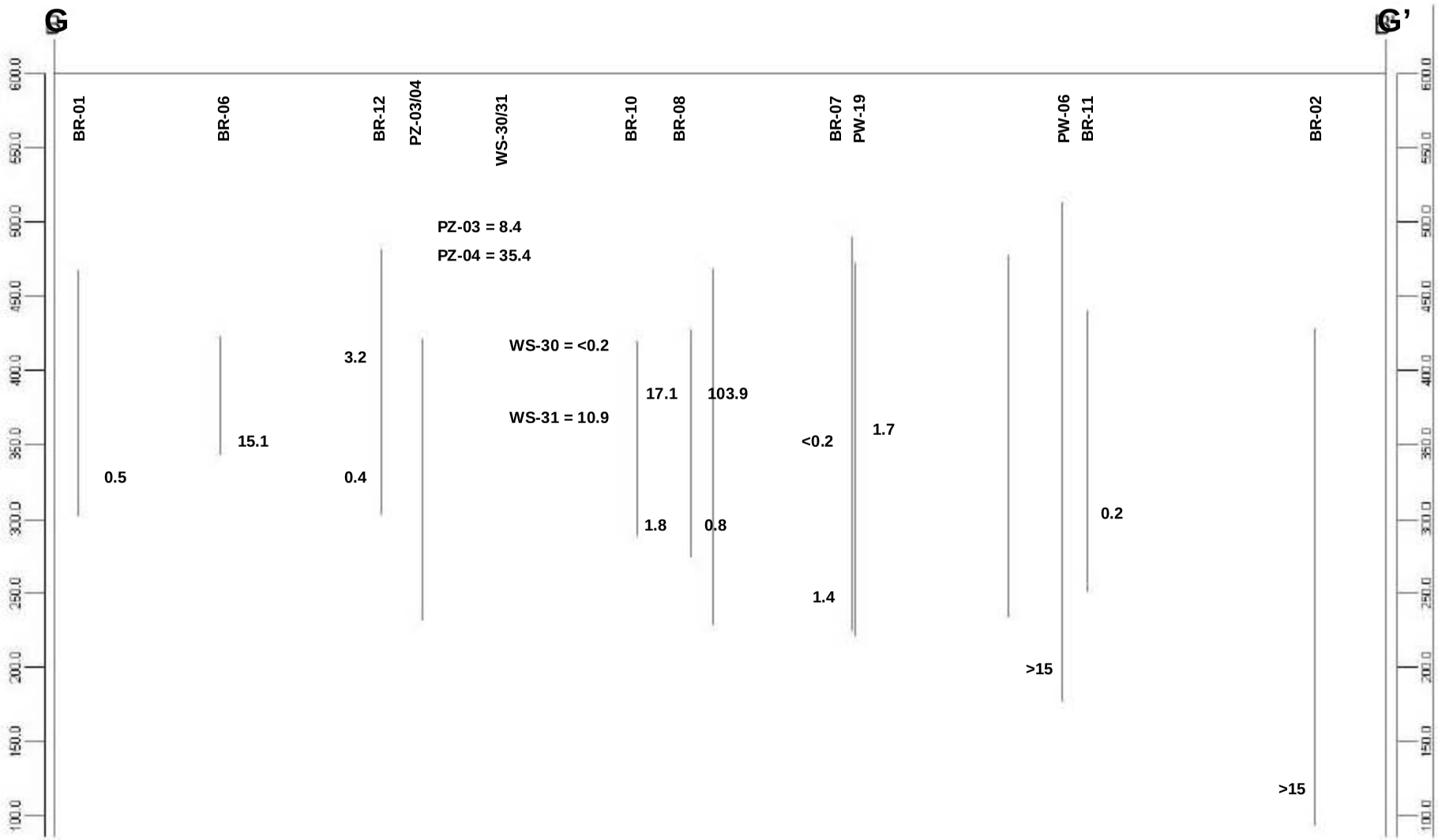


Fig. 3.14. Hydraulic conductivity from slug tests.

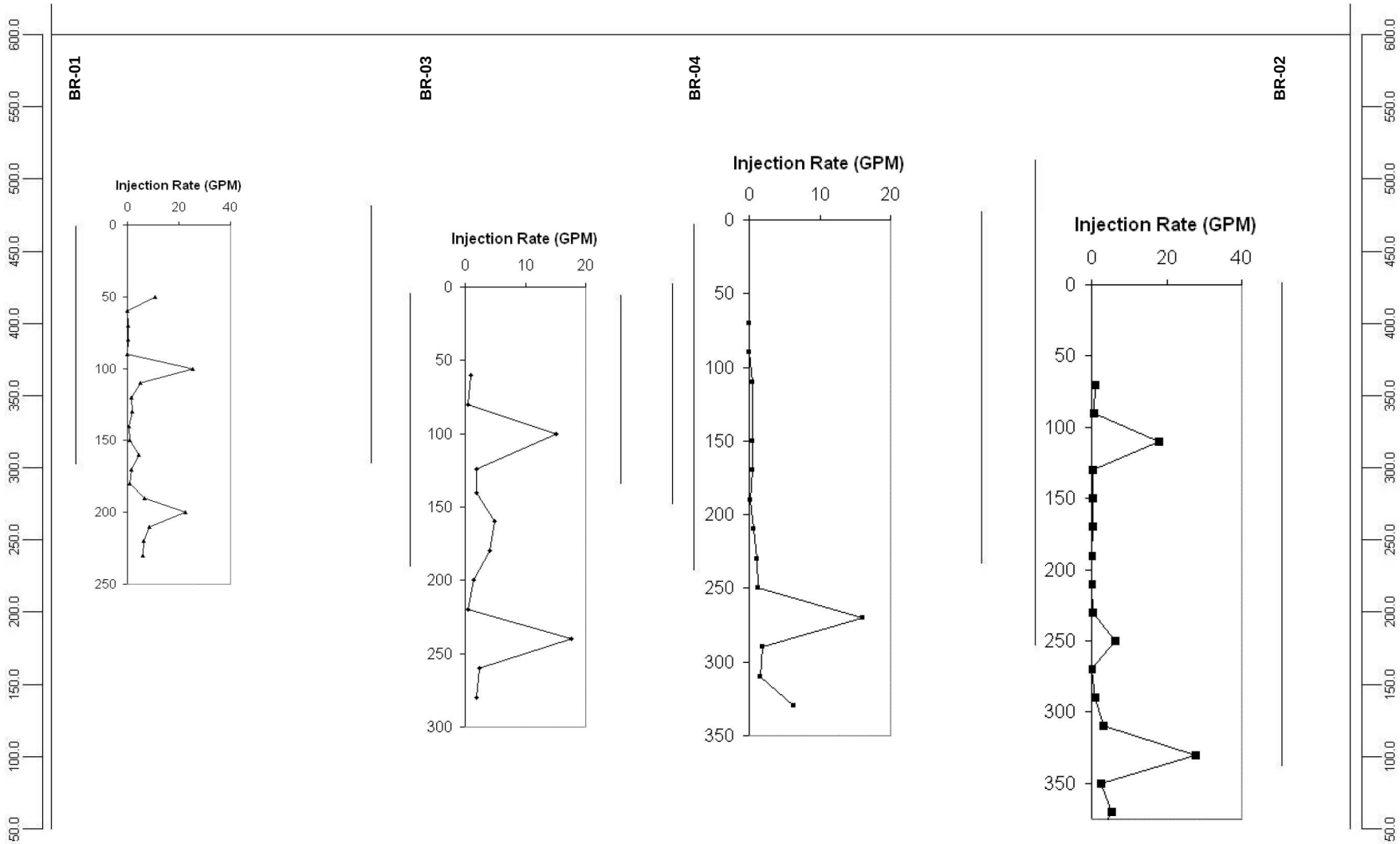


Fig. 3.15. Injection test data.

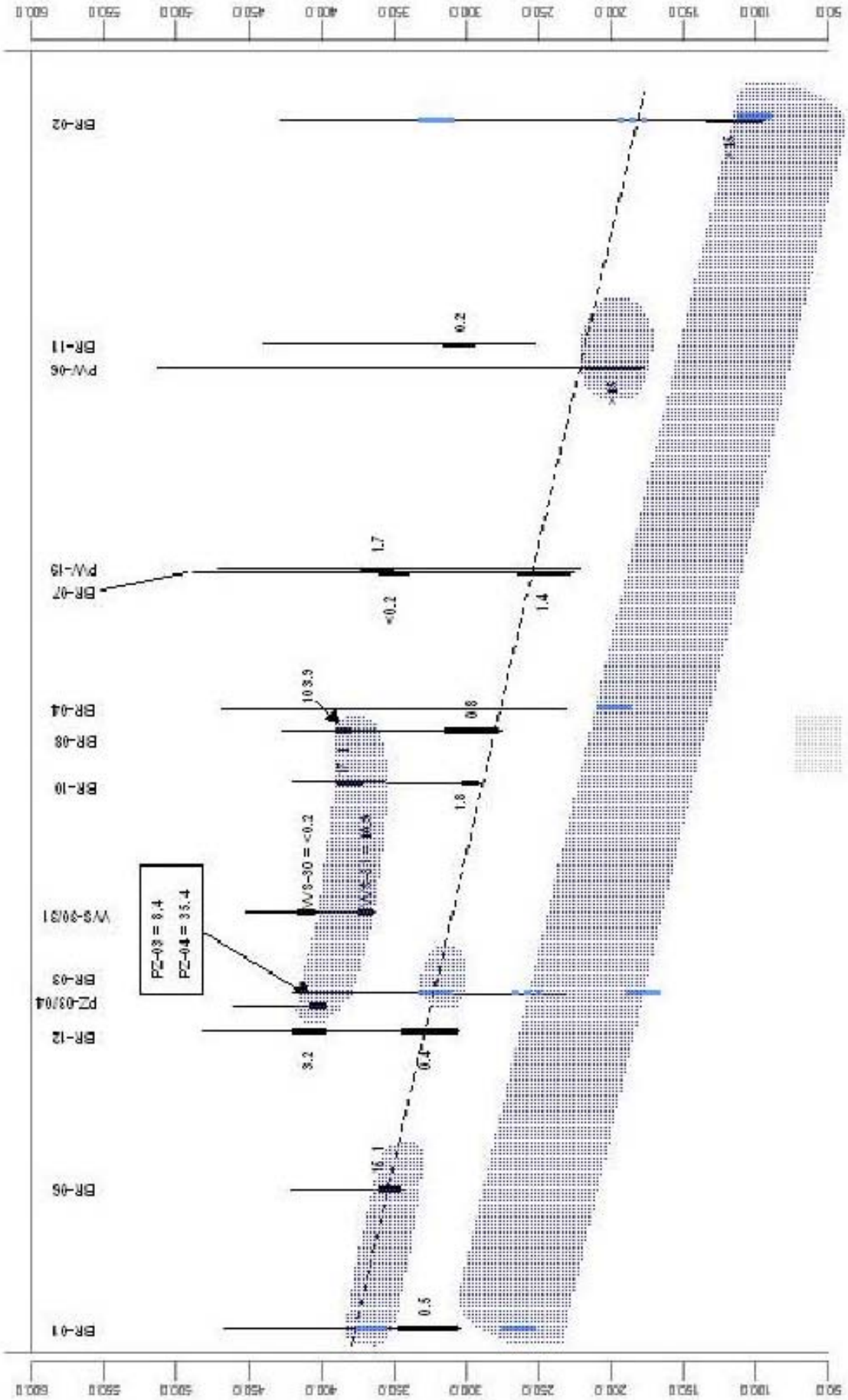


Fig. 3.16. Hydraulic summary.

PROPERTY BOUNDARY

<430 FT

>430 FT

Fig. 3.17. Potentiometric surface of shallow (fine-grained) overburden wells (December 2004).

Fig. 3.18. Potentiometric surface of deeper overburden wells (December 2004).

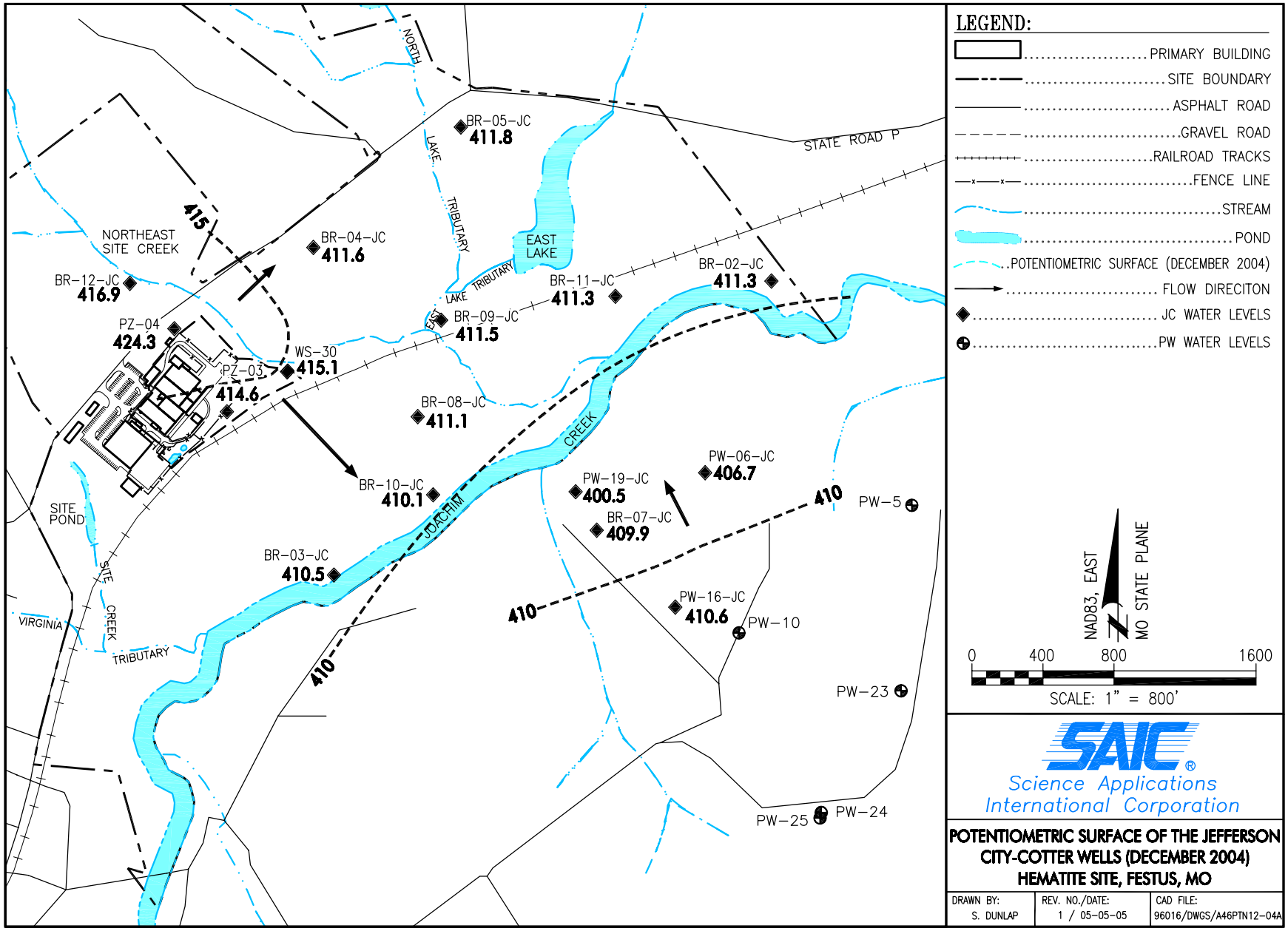


Fig. 3.19. Potentiometric surface of the Jefferson City-Cotter wells (December 2004).

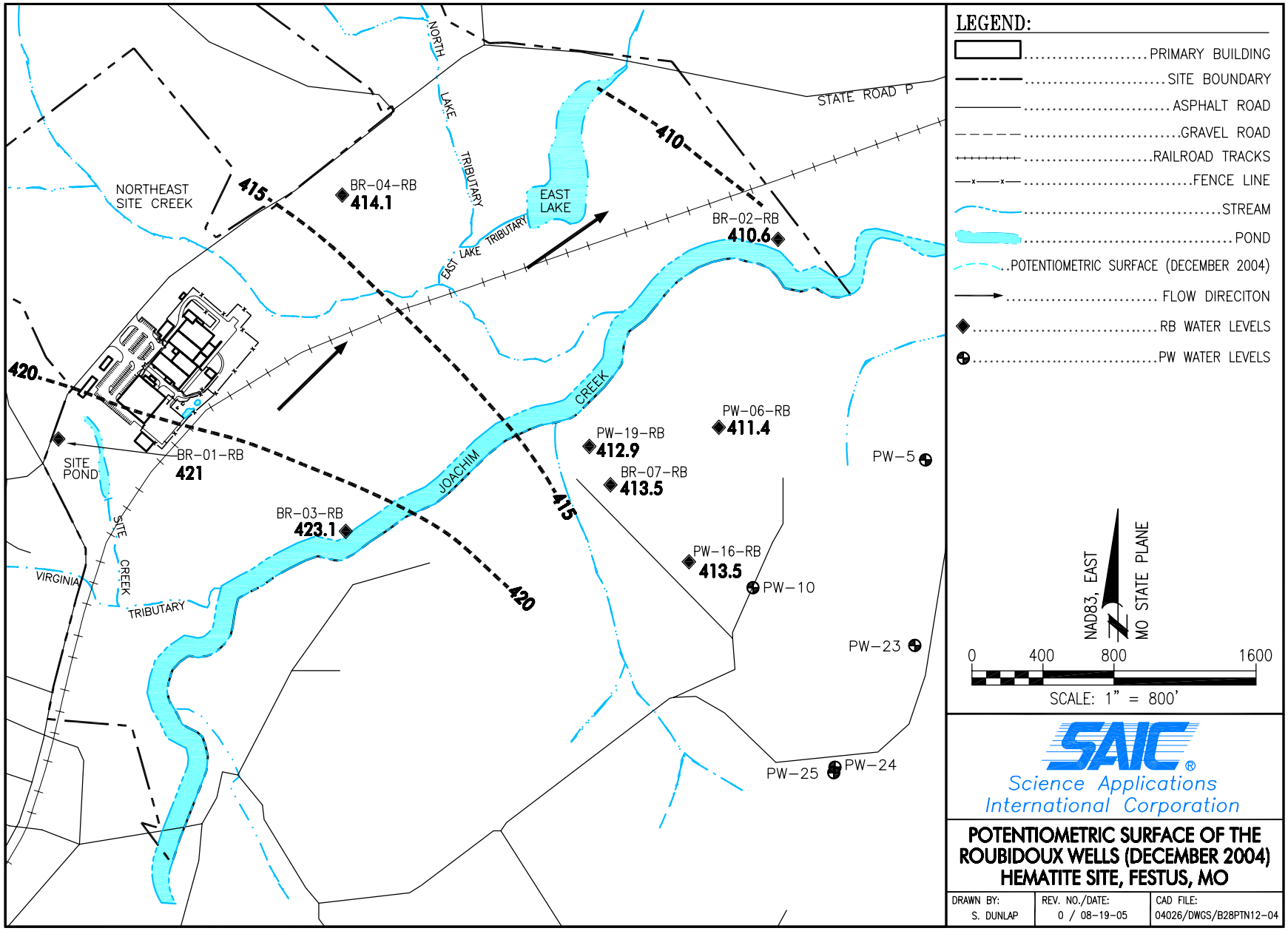


Fig. 3.21. Potentiometric surface of the Roubidoux sells (December 2004).

PROPERTY BOUNDARY

Fig. 3.22. Hydraulic gradient (-dh/dz) between shallow and deep overburden wells (December 2004).

PROPERTY BOUNDARY

Fig. 3.23. Hydraulic gradient (-dh/dz) between deep overburden and Jefferson City wells (December 2004).

PROPERTY BOUNDARY

Fig. 3.24. Hydraulic gradient (-dh/dz) between Jefferson City and Roubidoux wells (December 2004).

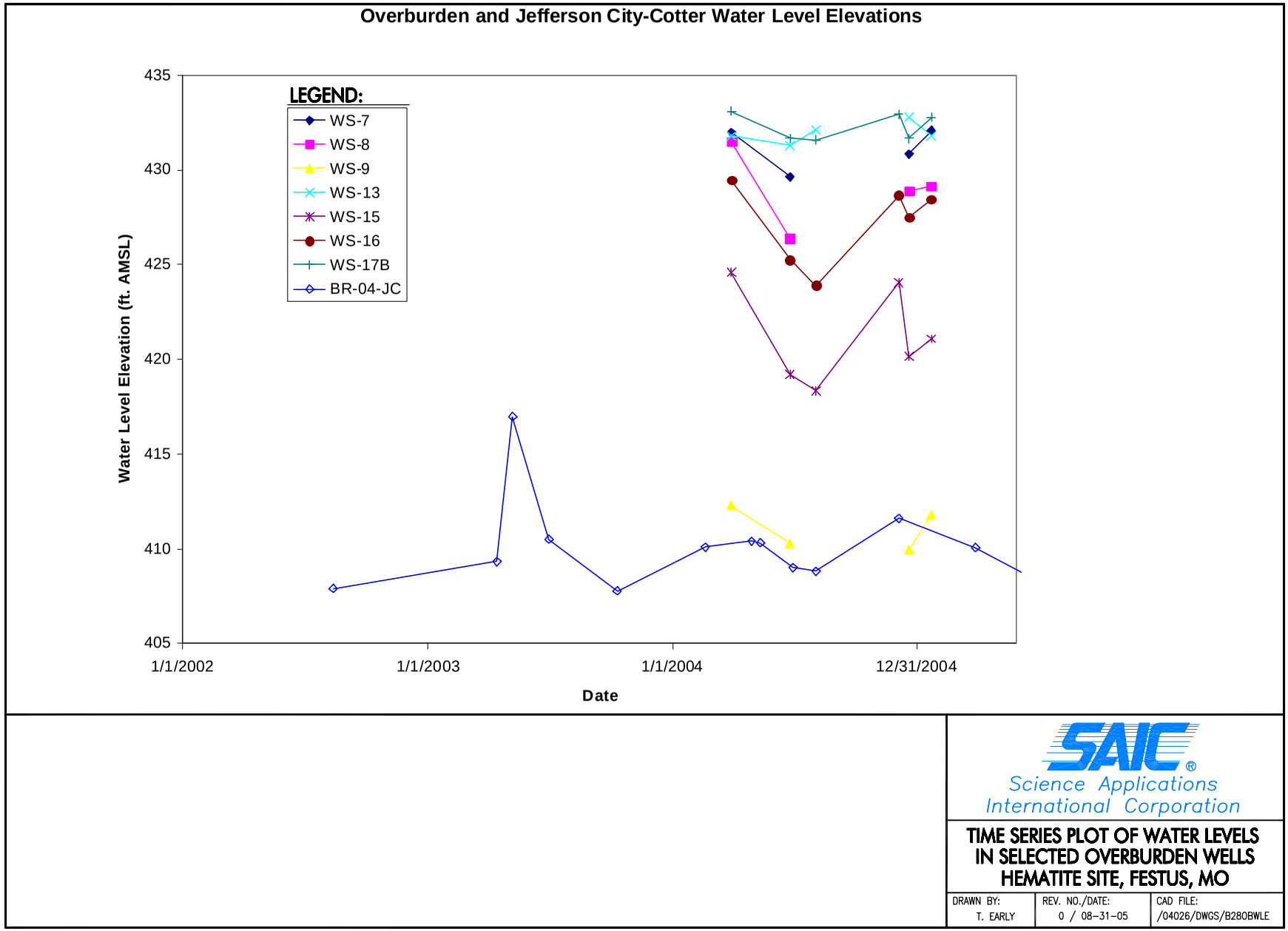
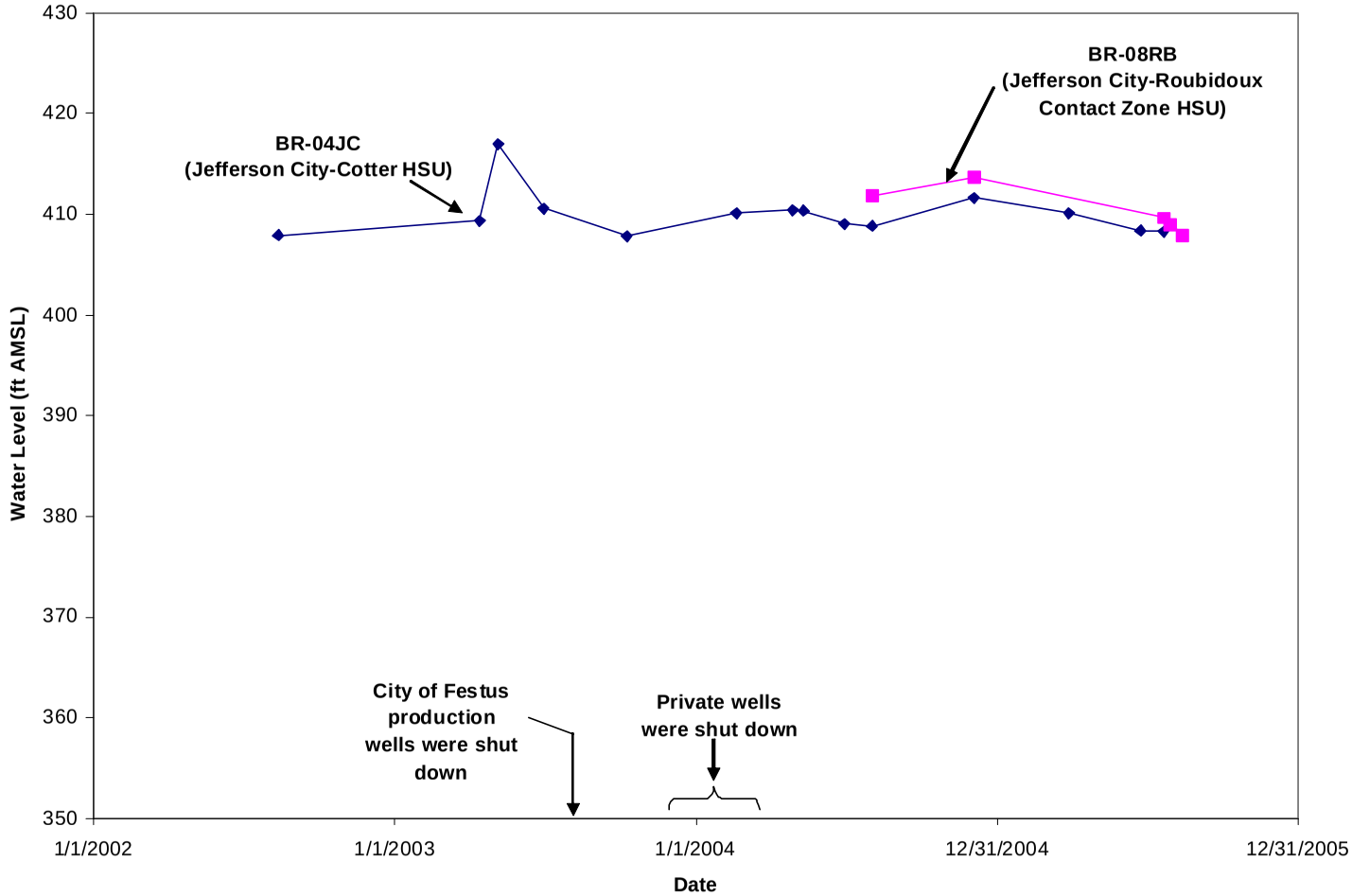


Fig. 3.25. Time series plot of water levels in selected overburden and Jefferson City-Cotter wells.

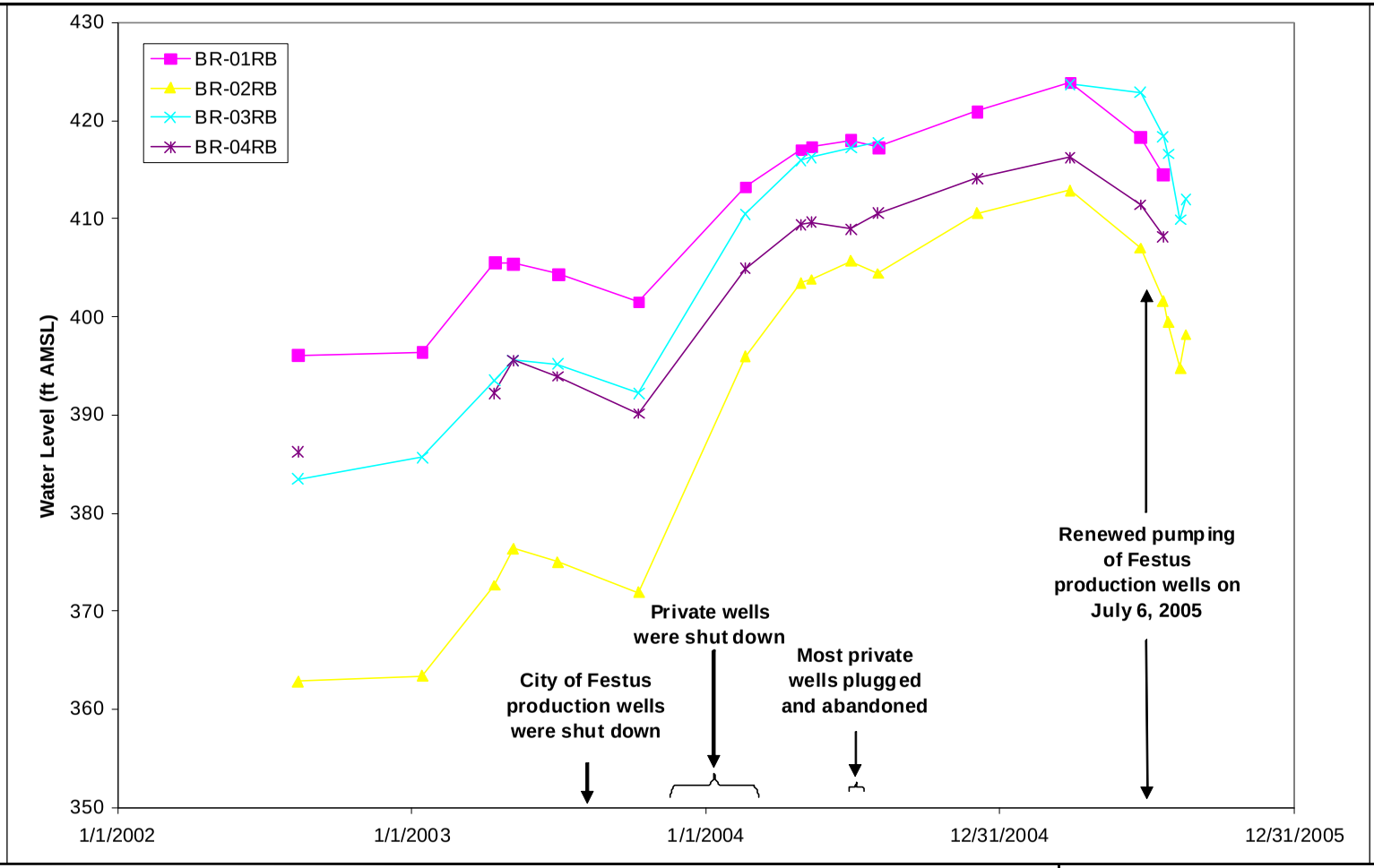


Science Applications International Corporation

TIME SERIES PLOT OF WATER LEVELS IN SELECTED JEFFERSON CITY WELLS HEMATITE SITE, FESTUS, MO

DRAWN BY:	REV. NO./DATE:	CAD FILE:
T. EARLY	0 / 08-31-05	/04026/DWGS/B28JCWLE

Fig. 3.26. Time series plot of water levels in selected Jefferson City-Cotter wells.
Note: The data for BR-04-JC are also shown in Fig. 3.25 but on a different scale for the y-axis.



Science Applications International Corporation

TIME SERIES PLOT OF WATER LEVELS IN SELECTED ROUBIDOUX WELLS HEMATITE SITE, FESTUS, MO

DRAWN BY:	REV. NO./DATE:	CAD FILE:
T. EARLY	1 / 10-11-05	/04026/DWGS/B28RBWLE

Fig. 3.27. Time series plot of water levels in selected Roubidoux wells.

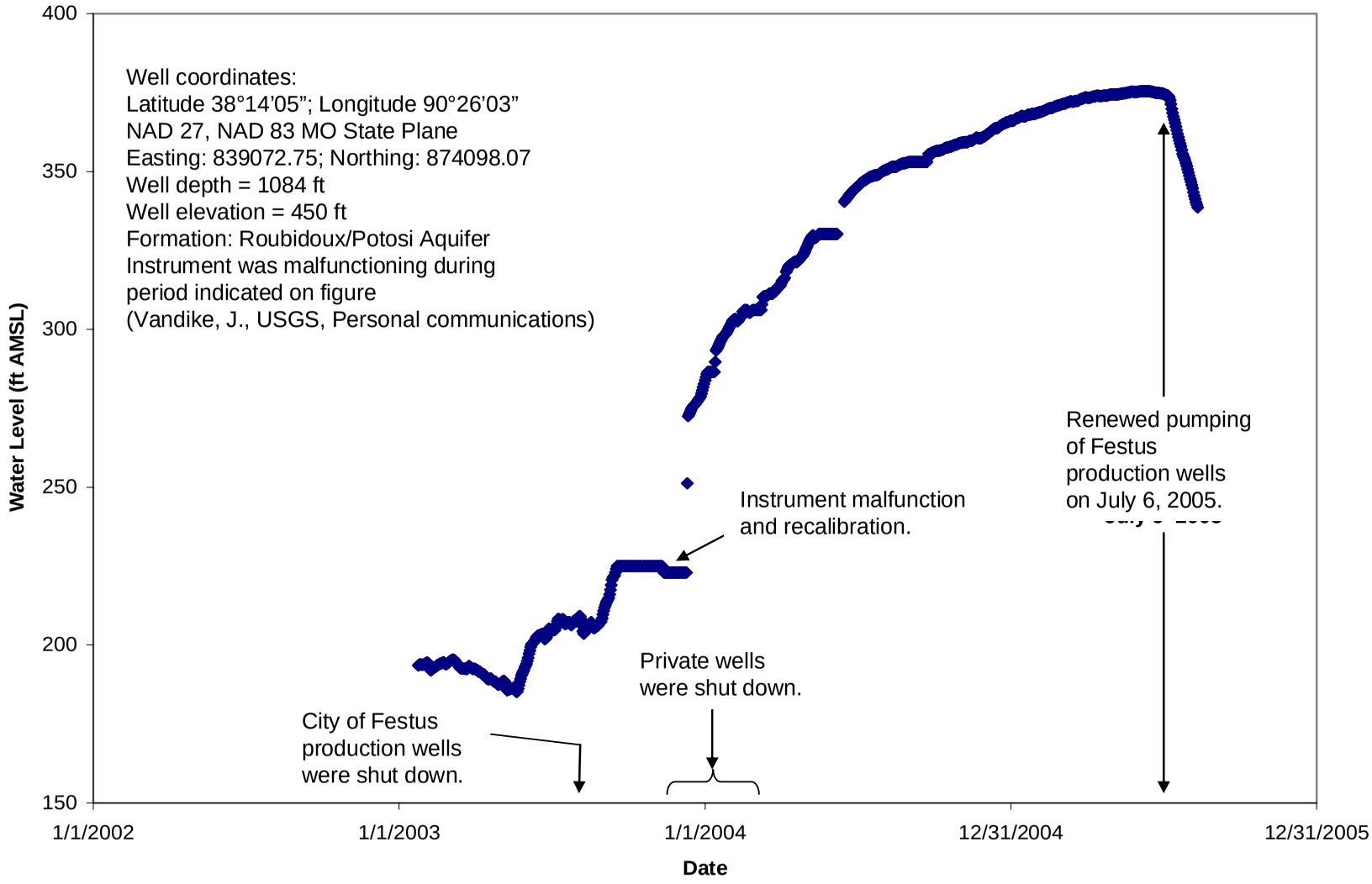


Fig. 3.28. Water level versus time data from USGS well 381405090260301 in Festus, MO.

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CHAPTER 3 TABLE

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Table 3.1. Surface water level measurements

Date	Site Pond		Site Pond Creek		Northeast Site Creek		East Lake		Joachim Creek (at bridge)	
	Gauge Reading of Water Level (ft)	Water Level Elevation (ft AMSL)	Gauge Reading of Water Level (ft)	Water Level Elevation (ft AMSL)	Gauge Reading of Water Level (ft)	Water Level Elevation (ft AMSL)	Gauge Reading of Water Level (ft)l	Water Level Elevation (ft AMSL)	Gauge Reading of Water Level (ft)	Water Level Elevation (ft AMSL)
5/27/2004	--	--	--	--	--	--	--	--	>>6.66	>>416.18
6/1/2004	--	--	--	--	--	--	--	--	3.50	413.02
6/4/2004	1.93	424.98	2.04	423.18	1.30	427.29	1.36	428.65	3.07	412.59
7/2/2004	1.68	424.73	1.55	422.69	dry bed		1.01	428.30	3.03	412.55
8/2/2004	1.75	424.80	1.70	422.84	1.03	427.02	1.16	428.45	3.1	412.62
9/7/2004	1.68	424.73	1.56	422.70	dry bed		0.84	428.13	3.02	412.54
10/14/2004	1.74	424.79	1.70	422.84	dry bed		0.38	427.67	3.26	412.78
11/23/2004	1.80	424.85	1.79	422.93	1.42	427.41	1.31	428.60	3.30	412.82
12/3/2004	1.96	425.01	2.10	423.24	1.46	427.45	1.46	428.75	3.64	413.16
1/5/2005	2.08	425.13	2.42	423.56	3.00	428.99	2.42	429.71	Flooding Condition	

Table 3.2. Summary of Slug Tests, December 2004

Well ID	Formation	Test Date	Description of Recovery Curve on Log Plot	K (ft/s) Rep 1	K (ft/s) Rep 1	K (ft/s) Rep 1	K (ft/s) Rep 1	Average (ft/sec)	Average K (ft/day)
BR-08-OB	COB	12/7/2004	Linear	1.232E-03	1.058E-03			1.145E-03	**98.9**
BR-10-OB	COB	12/6/2004	Linear	2.268E-03	1.315E-03			1.791E-03	**154.8**
BR-06-OB	COB	12/7/2004	Underdamped/Oscillating						**>155**
NB-73	COB	12/8/2004	Slightly underdamped/Oscillating	2.449E-04	2.795E-04			2.622E-04	**22.7**
NB-84	COB	12/14/2004	Linear w/ Slight oscillation	4.451E-05	4.434E-05			4.443E-05	**3.8**
BR-08-JC	JC	12/7/2004	Underdamped/Oscillating	1.363E-03	1.042E-03			1.203E-03	**103.9**
BR-10-JC	JC	12/7/2004	Slight underdamping/Oscillation	1.917E-04	2.030E-04			1.974E-04	**17.1**
BR-11-JC	JC	12/9/2004	Linear	2.045E-06	1.824E-06			1.935E-06	**0.2**
BR-12-JC	JC	12/9/2004	Linear	3.831E-05	3.548E-05			3.689E-05	**3.2**
PZ-04	JC	12/14/2004	Underdamped/Oscillating	4.078E-04	4.108E-04			4.093E-04	**35.4**
BR-07-JC	JC	12/14/2004	Very slow response to intro of slug, did not return to levels before intro of slug in 4 hours.						**<0.2**
PW-19-JC	JC	12/15/2004	Linear w/ Slight curvature	1.836E-05	2.128E-05			1.982E-05	**1.7**
WS-31	JC	12/15/2004	Linear	1.322E-04	1.211E-04			1.267E-04	**10.9**
PZ-03	JC	12/16/2004	Linear w/ Slight curvature	1.174E-04	7.790E-05			9.765E-05	**8.4**
WS-30	JC	12/16/2004	Very slow response to intro of slug, took 1 hour for transducer to drop 2 inches after slug intro						**<0.2**
BR-08-RB	RB	12/7/2004 a	l Concave up	1.261E-05	1.009E-05		5.950E-06	9.550E-06	**0.8**
BR-10-RB	RB	12/7/2004	Concave up	2.659E-05	3.994E-05	1.129E-05	6.030E-06	2.096E-05	**1.8**
BR-06-RB	RB	12/8/2004	Linear	1.748E-04				1.748E-04	**15.1**
BR-12-RB	RB	12/9/2004	Slightly Concave up	5.329E-06	4.765E-06	2.792E-06	4.440E-06	4.332E-06	**0.4**
BR-02-RB	RB	12/10/2004	Underdamped/Oscillating						**>15**
BR-01-RB	RB	12/13/2004	Linear	6.024E-06				6.024E-06	**0.5**
BR-07-RB	RB	12/13/2004	Concave up	too coarse	too coarse	1.582E-05		1.582E-05	**1.4**
PW-06-RB	RB	12/13/2004	Underdamped/Oscillating						**>15**

* The value set for the underdamped wells corresponds to the maximum measured hydraulic conductivity in the other wells within the same formation. For example, the maximum K measured in the RB wells is 15 ft/day in BR-06-RB The slug test data was well behaved for this well (monotonically change in water levels after release of slug). Thus, it is assumed that the lower limit for oscillatory response is 15 ft/day. A similar approach is used for setting the upper limit for slowly responding wells in very tight formation (e.g., wells in the JC and COB formations).