STRATIGRAPHY OF THE PB-1 WELL, NOPAL I URANIUM DEPOSIT, SIERRA PEÑA BLANCA, CHIHUAHUA, MEXICO

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Abstract

The Nopal I site in the Peña Blanca uranium district has a number of geologic and hydrologic similarities to the proposed high-level radioactive waste repository at Yucca Mountain, making it a useful analogue to evaluate process models for radionuclide transport. The PB-1 well was drilled in 2003 at the Nopal I uranium deposit as part of a DOE-sponsored natural analogue study to constrain processes affecting radionuclide transport. The well penetrates through the Tertiary volcanic section down to Cretaceous limestone and intersects the regional aquifer system. The well, drilled along the margin of the Nopal I ore body, was continuously cored to a depth of 250 m, thus providing an opportunity to document the local stratigraphy. Detailed observations of these units were

afforded through petrographic description and rock-property measurements of the core, together with geophysical logs of the well. The uppermost unit encountered in the PB-1 well is the Nopal Formation, a densely welded, crystal-rich, rhyolitic ash-flow tuff. This cored section is highly altered and devitrified, with kaolinite, quartz, chlorite, and montmorillonite replacing feldspars and much of the groundmass. Breccia zones within the tuff contain fracture fillings of hematite, limonite, goethite, jarosite, and opal. A zone of intense clay alteration encountered in the depth interval 17.45–22.30 m was interpreted to represent the basal vitrophyre of this unit. Underlying the Nopal Formation is the Coloradas Formation, which consists of a welded lithic-rich rhyolitic ash-flow tuff. The cored section of this unit has undergone devitrification and oxidation, and has a similar alteration mineralogy to that observed in the Nopal tuff. A sharp contact between the Coloradas tuff and the underlying Pozos Formation was observed at a depth of 136.38 m. The Pozos Formation consists of poorly sorted conglomerate containing clasts of subangular to subrounded fragments of volcanic rocks, limestone, and chert. Three thin (2–6 m) intervals of intercalated pumiceous tuffs were observed within this unit. The contact between the Pozos Formation and the underlying Cretaceous limestone basement was observed at a depth of 244.40 m. The water table is located at a depth of ~223 m. Several zones with elevated radioactivity in the PB-1 core are located above the current water table. These zones may be associated with changes in redox conditions that could have resulted in the precipitation of uraninite from downward flowing waters transporting U from the overlying Nopal deposit. All of the intersected units have low (typically sub-millidarcy) matrix permeability, thus fluid flow in this area is dominated by fracture flow.

These stratigraphic and rock-property observations can be used to constrain flow and transport models for the Peña Blanca natural analogue.

Introduction

This stratigraphic study is part of an integrated research project examining the migration behavior of radionuclides at Peña Blanca. The Peña Blanca uranium mining district, located in the Sierra Peña Blanca, north of Chihuahua, Chihuahua, has been identified as a natural analogue for the proposed repository for high-level radioactive waste at Yucca Mountain (Pearcy et al., 1994). This site has a number of characteristics in common with Yucca Mountain, including the presence of fractured rhyolitic tuff overlying limestone basement, a Basin and Range extensional tectonic setting, an unsaturated zone > 200 m thick, and an arid climate.

The immediate objectives of this study include locating stratigraphic contacts in the third dimension, describing the lithologies of the different units, and measuring selected rock properties of the cored section. These observations serve as primary inputs to flow and transport models evaluating radionuclide mobility at the Peña Blanca site.

Previous Studies

The Sierra de Peña Blanca region has been the subject of numerous previous studies. Alba and Chavez (1974) presented a regional stratigraphic section that includes the following Tertiary volcanic and sedimentary units (in decreasing stratigraphic order): the Mesa Formation (trachyte), the Peña Blanca Formation (tuffs and conglomerate), the

Escuadra Formation (rhyolite and tuff), the Nopal Formation (rhyolite and tuff), the Corrales Formation (tuff and rhyolite), and the Pozos Formation (calcareous conglomerate); these all overlie Cretaceous limestone (interpreted to be correlative with the Edwards Formation of Texas). Alba and Chavez (1974) also reported K-Ar dates on sanidine for several of the Tertiary volcanic units, including one from the Nopal Formation; this age was recalculated as 44.8±0.9 Ma using the decay constants of Steiger and Jäger (1977). Rodríguez et al. (1976) provided a more detailed description of the stratigraphic units, and noted the presence of U mineralization associated with hydrothermally altered Nopal Formation rhyolitic tuff. Additional studies that examined the relation between altered volcanic rocks and the presence of uranium mineralization at the Nopal deposit include Calas (1977), Goodell (1981), Cárdenas-Flores (1985), Magonthier (1985), Leroy et al. (1987), Altamirano et al. (1988), George-Aniel et al. (1991), Leroy and George-Aniel (1992), and Reyes-Cortés (1997; 2002). Reyes-Cortés (1997; 2002) modified the earlier stratigraphic nomenclature for this area by subdividing the Nopal Formation into two different units: a basal series of lithic tuffs (the Coloradas Formation), and overlying rhyolitic ash flow tuffs (the Nopal Formation). A basal vitrophyre forms the contact between these two units. Pearcy et al. (1994, 1995), Prikryl et al. (1997), Pickett and Murphy (1999; 2002), Murrell et al. (2002), Goldstein et al. (2006), and Calas et al. (2008) evaluated processes affecting the mobility of radionuclides at the Nopal I site as a natural analogue for Yucca Mountain.

The Nopal I deposit is one of over 100 sites of U mineralization identified in the Sierra Peña Blanca uranium district of Central Chihuahua, Mexico (George-Aniel et al., 1991).

The Nopal I mine was active between 1969 to 1983, when all U mining activity in the region ceased (Murphy et al., 1997). The Nopal I deposit consists mostly of uranyl silicate and uranyl oxyhydroxide minerals such as uranophane, soddyite, weeksite, and schoepite, with minor amounts of primary uraninite (Pearcy et al., 1994). The original size of the Nopal I ore body was ~333 t U_3O_8 (Leroy et al., 1987), with around 320 t estimated to still be in place (Murphy and Codell, 1999).

Stratigraphy of the PB-1 Well

The PB-1 well was one of three wells drilled at the Nopal I site by the Comisión Federal de Electricidad under contract to the Universidad Autónoma de Chihuahua in 2003 through funding provided by the US Department of Energy (Figure 1). The other two wells were sited ~50 m to the NE (PB-3) and SW (PB-2) of the PB-1 well, and were drilled to provide access to the water table to check for chemical gradients in groundwater compositions that might indicate the influence of the overlying ore deposit.

The PB-1 well head is located on the margin of the Nopal I ore deposit on the +10 level of the abandoned uranium mine, with UTM coordinates of 3220793 N, 399275 E (NAD83 datum) and a surface elevation of 1463 masl (S. Harder, pers. comm.). This well location corresponds to a grid coordinate of 12.15 E, 9.1 N for the field grid system installed by Southwest Research Institute (Figure 2) for detailed fracture mapping at the Nopal I site (Pearcy et al., 1995; Prikryl et al., 1997).

The PB-1 well was drilled to a depth of 250 m using a Christensen CS-1000 wireline coring rig. NQ core (4.76 cm diameter) was obtainedthroughout the entire drilled section, with an overall core recovery of 86.2%. Due to drilling problems encountered during coring, the drilling was done in three phases. The initial well was cored from 0–111.0 m, where the drill string was stuck. A portable rotary rig (Prospector model TKT-1000) was used to drill a 6" diameter hole immediately adjacent to the first hole down to 111 m, where NQ coring resumed from 111.45 m down to 212.85 m, where the core barrel was lost in the hole. After several failed attempts to retrieve the core barrel out of the hole, the rotary rig was again moved to the location, and a 6" diameter hole was drilled down to 213 m, where coring was continued down to a final depth of 250 m. The upper 2 m of the well was enlarged so that a surface casing of 12" diameter could be installed over this interval, and the borehole was then reamed out using the rotary rig with an 8 ½" diameter bit to a depth of 253.5 m.

A series of geophysical logs were run in the hole (caliper, natural gamma, neutron, temperature, deviation, density, resistivity, and video), and the well was completed using 4" diameter PVC casing, with slotted liner over the bottom ten meters of the well. A quartz sand filter capped with a bentonite seal was emplaced around the annulus of the slotted liner section. The rest of the annulus was backfilled using a cement-bentonite mixture. The well has been used for collection of groundwater samples and for monitoring the elevation of the regional water table.

Initial core descriptions were made at the rig site, and more detailed observation of the cores was conducted at the Facultad de Ingeniería of the Universidad Autónoma de Chihuahua, where the PB-1 core is stored. Each of the 60 core boxes was photographed and described in detail, and selected core samples were set aside for additional petrographic and geochemical studies. Hand measurements of radioactivity were made on the core samples on a ~20 cm interval to complement the natural gamma log run in the reamed PB-1 borehole. A total of 28 thin sections from the PB-1 core were prepared and described petrographically.

Four main stratigraphic units were observed in the PB-1 core: the Nopal Formation, the Coloradas Formation, the Pozos Formation, and the underlying Cretaceous limestone basement (Figure 3). Several thin (2-6 m) intervals of pumiceous tuff were found within the Pozos conglomerate. Each of these units is described in greater detail below.

Nopal Formation

The uppermost portion of the core consists of densely welded, crystal-rich rhyolitic ash-flow tuff from the Nopal Formation. The cored section of this formation (0–22.30 m) is highly altered, with devitrification of the glassy matrix and kaolinite commonly replacing both feldspars and groundmass (Figure 4). Relict flattened pumice fragments and volcanic lithic fragments were also observed. Zeolites have been observed locally in the

Nopal Formation (Reyes-Cortes, 2002), but were not identified in thin sections of core. Other alteration minerals encountered in the Nopal tuff core samples included quartz, chlorite, and montmorillonite. Much of the core (located immediately adjacent to the U ore body) is highly brecciated, with hematite, limonite and goethite fracture fillings. The lowermost portion of this formation consists of an intensely argillically altered basal vitrophyre (17.45–22.30 m); the altered vitrophyre is more easily identified in outcrops exposed near the PB-1 well head.

Coloradas Formation

The cored interval (22.30–136.38 m) of the Coloradas Formation consists of welded, lithic-rich rhyolitic ash-flow tuff. The altered tuff contains ~10–20% volcanic lithic fragments with some pumice-rich intervals (up to 30%). The flattened pumice (fiamme) often exhibit good flow foliation (Figure 5). Like the Nopal tuff, the PB-1 core samples of this unit are quite altered. Much of the tuff is devitrified, oxidized (hematite, limonite, goethite) and altered to kaolinite and montmorillonite (argillic alteration). Secondary quartz is also abundant, occurring as a devitrification product as well as a low temperature phase found in veins and pores. Many of the alteration minerals replace primary minerals and the devitrified matrix, and fill voids and fractures within the altered tuff. There are numerous zones of fracturing and brecciation within the cored section of the Coloradas tuff, as 23 distinct fracture zones were identified in the video log for the Coloradas section of the PB-1 borehole. There is a sharp contact between the Coloradas tuff and the underlying Pozos conglomerate in the PB-1 core at a depth of 136.38 m.

Pozos Formation

The Pozos Formation (136.38–244.40 m) intersected by the PB-1 well consists of poorly sorted conglomerate with minor sandstone interbeds. The conglomeratic clasts consist of subangular to subrounded fragments of volcanic rocks, limestone, and chert, with clasts ranging in size from 1 mm (Figure 6) to over 10 cm in diameter. Three thin (2–6 m) intervals of intercalated pumiceous tuffs were observed within this unit in the PB-1 core (Figure 7); these may be correlative to the Corrales Formation tuffs. Bleached and oxidized zones were observed within the sediments, and have been interpreted to represent changes in oxidation state. Within the cored interval of this formation, there are a number of fractured and brecciated zones that are associated with secondary mineralization, most often consisting of limonite, hematite, silica, calcite, kaolinite, and clays. The contact between the Pozos Formation and the underlying Cretaceous limestone was observed in the PB-1 core at a depth of 244.40 m.

Cretaceous Limestone

A fine-grained massive limestone was encountered at the base of PB-1 (244.40–250.00 m); this unit is considered to be Cretaceous in age (Reyes-Cortes 2002), corresponding with either the uppermost Tamaulipas Formation or Cuesta del Cura Formation. This limestone contains microfossils (foraminifera, ostrocods, bryozoans, and gastropods) set in a fine-grained, micritic matrix (Figure 8). Minor thin veins of calcite cut the limestone, especially in zones with brecciation.

The measured formation thicknesses from the PB-1 well represent apparent thicknesses; slightly dipping beds result in measured thicknesses that are slightly greater than actual thickness of unit. Measured dips in the vicinity of the Nopal I deposit (Reyes, 1997) range from 9 to 20 degrees, with an average value of 13 degrees. The thickness of the Coloradas Formation in the PB-1 core (114 m measured → 111 m dip corrected) is slightly greater than average thickness (90 m) reported by Reyes (1997). The thickness of the Pozos Formation (108 m in core → 105 m dip corrected) is very similar (111.8 m) to the Nopal questa outcrop section measured by Reyes (1997), which is located ~1 km NW of PB-1.

Geophysical Logs

A series of geophysical logs were run in PB-1 prior to installation of the PVC liner. The results of the natural gamma, neutron, and temperature logs are presented in Figure 3; also included are the results of radiation measurements of the PB-1 core conducted in the field. Five other logs (density, video, resistivity, caliper, and deviation) were also run. Interpretive summaries of the logs are presented below.

Natural Gamma: The range of natural gamma values from the borehole logging of PB-1 (Figure 3) varies from 160 to 144,490 counts per second (cps). The highest values (> 50,000 cps) are encountered in the upper 15 m of the borehole and correspond to a zone of intense alteration. Below this zone, values remain high down to the base of the ore body, which extends to a depth of ~110 m below the +10 level (Fig. 1 of Ildefonse et al., 1990), but there is a general trend towards lower gamma values with depth, with some occasional hot spots. Log gamma values from 110 m to 165 m depth are generally between 300 to 600 cps; below this depth, natural gamma values begin to increase. Near the water table (located at a depth of ~222.6 m), there is a narrow zone (216.6–225.1 m) with distinctly higher gamma values (all above 2,500 cps, with a maximum value of 7,927 cps). Below this zone, gamma values drop rapidly, and at depths greater than 227.1 m, all log gamma values are below 400 cps.

Measurements on the core samples were made using a hand-held radiometer at the time of core retrieval at the rig site (with a measurement interval of ~20 cm), and were repeated at a coarser scale at the Universidad Autónoma de Chihuahua campus. Radiation readings made on core samples obtained from the PB-1 well (Figure 3) yielded much lower readings than the natural gamma log measurements. The core sample measurements made at the rig site were ≤ 1,200 cps, with most values < 200 cps. The most striking difference between the natural gamma log and the core field measurements was the absence of the extremely high values detected by the geophysical log within the upper 15 m of PB-1. The highest value obtained from the core samples within this depth interval is 280 cps from the field measurements; this value is dwarfed by the natural gamma log values of 7,370–144,490 cps for the same interval. This discrepancy is most likely caused by the location of PB-1 at the margins of the Nopal I uranium ore body (Figure 2). The core samples do not have significant uranium mineralization, thus supporting the relatively low core radiation levels. The proximity of the upper portion of the PB-1 borehole to the Nopal I uranium ore body is most likely the cause for the extremely high gamma log values registered in theupper 110 m of the logging run. Below this depth, the log gamma values are still higher than the corresponding core measurements; this may be a result of differences in instrument sensitivity and the larger amount of rock mass sampled by the downhole logging tool.

The highest PB-1 gamma values for the field-based core measurements were obtained within a section of highly altered and fractured conglomerate at a depth of 190 m, where a value of 1,200 cps was obtained. The corresponding natural gamma log value for this depth was 1,590 cps, which is not significantly different from the surrounding borehole values. It appears that this core's hot spot was not extensive enough to be resolved by the downhole logging tool. Detailed investigation of core from this depth interval revealed the presence of very small grains of uraninite (Fayek et al., 2006) associated with reduced phases such as pyrite and anatase within the Pozos sediments. This uranium phase appears to be much younger than the primary ore mineralization for the Nopal I deposit located above this region. The zone of elevated natural gamma values observed near the water table in the geophysical log was also encountered in the core measurements, where hot spots were encountered with values ranging up to 420 cps for the field core measurements.

Neutron: There is a fairly restricted range of neutron log values throughout the unsaturated zone of PB-1 (Figure 3), with most values ranging between 2,000 and 3,000 American Petroleum Institute (API) units. The sudden drop in the neutron log at 222.7 m, where values drop from above 2,000 down to around 100 API units, is associated with the location of the water table. There is a small shift in values occurring at 246.2 m, where values increase from around 100 API units (for the region above this depth and within the saturated zone) to values typically between 250–600 API units. This depth is very close to the contact between the Pozos conglomerate and the Cretaceous limestone (244.4 m) observed in the PB-1 core.

Density: The values of two different gamma-gamma density logs, short spacing (SS) and long spacing (LS), were reported for PB-1 by Comisión Federal de Electricidad (these are not displayed in Figure 3). In general, the density log values are not in good agreement with the actual bulk and grain density laboratory measurements of the core samples (Table 1), as most of the log density values obtained from the depth interval above the water table are lower than the core bulk density values. The lowest log density values were recorded in the upper 15 m of the borehole (within the highly altered Nopal tuff), where the SS and LS density values range from 0.05 to 1.7 and 0.03 to 1.2 g/cm^3, respectively. Density values for both logs between the depths of 15 and 145 m increase gradually with depth and exhibit little variability, with values typically ranging between 1.4 to 2.4 g/cm^3. Density values for both logs exhibit greater variability between 145 m and the top of the water table (222.6 m), as would be expected for this interval within the lithologically diverse Pozos conglomerate; most log density values within this interval range from 1.8 to 2.4 g/cm^3, with the LS density values higher than the SS values by about 0.2 to 0.3 g/cm^3. At the water table, there is an abrupt increase in the log density values, with log values below this depth registering around 2.2 g/cm^3 and 3.4 g/cm^3 for the SS and LS logs, respectively.

Temperature: There is a steady increase in measured temperature values with depth, going from 28.5°C near the surface down to 32.3°C at the base of the borehole. This increase in temperature is equivalent to a thermal gradient of 15°C/km. Temperatures appear to increase more rapidly within the saturated portion of the wellbore, resulting in a higher thermal gradient of 31°C/km for the well section below the water table (222.7–253.8 m). Stabilized temperatures measured at the bottom of the borehole in 2006 (33.0–33.4°C) are slightly higher than those recorded after the conclusion of drilling in 2003.

Video: The wellbore video log provides the opportunity to visually identify fractures and other features within the uncased borehole. A detailed surface fracture study by Pearcy et al. (1995) noted the key role of fractures for U transport at the Nopal I deposit. Fractures and cavities within the borehole were identified in over 30 intervals within PB-1. Most of the fractures are located within the Coloradas tuff, whereas most of the cavities are located within the Pozos conglomerate. Most of the fractures are steeply dipping (> 60°) and mineralized, consistent with observations recorded for fractures exposed on vertical faces at the Nopal I mine (Reyes-Cortés, 1997). An example of one of the mineralized fractures in the Coloradas Formation, along with its interpreted core counterpart, is shown in Figure 9. The appearance of a zone with abundant clasts within the PB-1 video log at a depth of around 136.6 m is interpreted to represent the contact between the tuff and conglomerate units and is in good agreement with the contact identified in the PB-1 core at 136.4 m. The static water level was visually detected at a depth of 218.5 m, which is 4.2 m shallower than the depth indicated by the neutron log (222.7 m). The turbid conditions of the drilling fluid in the well bore precluded observing features below this depth. The difference between these two water table level measurements is most likely indicative of the relative error in the depth measurement between these two logging runs. Subsequent measurements of the static water level at PB-1 using a Solinst water-level meter yielded a depth of ~222.6 m (relative to the wellhead ground surface elevation), very similar to the value obtained with the neutron log.

Resistivity: Three different resistivity logs were run in the depth interval below the water table (logs not displayed in Figure 3). The log responses of the normal short (16N) and lateral resistivity logs are very similar, with most values in the SZ ranging from 50 to 250 ohm-m. Higher values (up to 790 ohm-m) were recorded by the normal long (64N) resistivity log. The lowest resistivity values for all three logs (48.5 and 41.0 ohm-m for the 16N log and lateral log, respectively, at a depth of 245.5 m and 56.5 ohm-m for the 64N log at a depth of 244.2 m) were recorded close to the contact between the Pozos conglomerate and the underlying Cretaceous limestone (244.4 m).

Caliper: The nominal diameter of PB-1 is 8.5" (21.6 cm). Most of the caliper log measurements range from 20 to 24 cm (7.9–9.4"). There are some slightly smaller wellbore diameters measured in the bottom meter of the borehole, as well as a few zones with larger diameters resulting from caving occurring during drilling.

Deviation: The deviation log measures the deviation from vertical of the wellbore. The maximum deviation from vertical in PB-1 is reported to be 0.62 m.

Rock-Property Measurements

The collection of continuous core samples in the PB-1 drill hole provides the opportunity to measure key rock properties throughout the geologic section needed to constrain flow and transport models for the Nopal I site, including porosity and permeability. Eighteen 1" (2.54 cm) diameter core plugs were drilled from selected PB-1 core samples, with an effort made to avoid areas with open fractures. Helium porosity, air permeability, and rock density measurements were conducted on these samples by Core Laboratories (Englewood, CO). The results of the rock-matrix porosity, density, and permeability measurements are listed in Table 1. Reported standard deviations for core plug analysis measurements are ±0.5% for porosity, ±0.01 g/cm^3 for grain density, and ±30% for permeability.

Porosity: The variation of porosity with stratigraphic depth is plotted in Figure 10. The Nopal and Coloradas ash-flow tuff samples have porosity values ranging from 11.9 to 33.6%. This range of porosity values is similar to those measured by Meyer (1995) for five outcrop samples of Nopal tuff (7.8 to 25.5%) collected near the Nopal I deposit. Meyer (1995) observed a positive correlation between alteration intensity and porosity. The Pozos conglomerate samples have a smaller range of porosities, from 13.2 to 17.4%, and the two intercalated tuff samples have porosities of 15.7 and 18.7%. The basement limestone samples have the lowest porosity values (1.9 and 0.3%).

Grain Density: The grain density values vary primarily as a function of lithology. The grain density values of the Nopal and Coloradas welded tuffs range from 2.58 to 2.66 g/cm^3, and the tuff layers with the Pozos Formation have grain densities of 2.63 and 2.67 g/cm^3. These values are slightly higher than the range of grain density values (2.52 to 2.58 g/cm^3) for Nopal Formation outcrop samples reported by Meyer (1995). The Pozos conglomerate samples (which contain a mixture of volcanic and limestone fragments) have slightly higher grain densities (2.64 to 2.69 g/cm^3), and the basal limestone samples have the highest grain densities, with measured values of 2.69 and 2.70 g/cm^3 (essentially the same value, given the precision (±0.01 g/cm^3) of the measurements)

Permeability: The variation of permeability with stratigraphic depth is plotted in Figure 11. All of the measured matrix permeability values are low. The Nopal and Coloradas ash-flow tuff samples have matrix permeability values (Klinkenberg corrected) ranging from 0.003 to 2.45 md. These permeabilities are generally higher than those obtained by Meyer (1995) for the Nopal tuff outcrop samples (0.0001 to 0.098 md). The Pozos conglomerate samples have a similar range in matrix permeability (0.003 to 6.30 md), and the two intercalated tuffs have values of 0.055 and 0.132 md. The basement limestone samples have the lowest matrix permeabilities, with one sample having a Klinkenberg corrected value of 0.001 md, and the other below detection.

Because all of the rocks in this sequence have low matrix permeabilities, fluid flow within the thick unsaturated zone at the Nopal I site is likely dominated by fracture flow. The presence of fracture-filling minerals attests to previous episodes of fluid flow and transport. Most fractures observed in the two welded tuff units are steeply dipping, and probably originated as cooling joints. As commonly observed in welded tuffs (Winograd, 1971), the primary conduits for fluid flow in these units is through joints, fractures, and faults. A study of seepage in a mine adit at the Nopal I site (Levy et al., 2008) indicates that fluid flow in fractures is highly heterogeneous, with a limited number of fractures serving as fast flow paths within the unsaturated zone.

Conclusions

The Nopal I site has many similarities to the proposed radioactive waste repository site at Yucca Mountain, making it a useful analogue for testing flow and transport models for radionuclide migration (Table 2). Previous studies that have used the Nopal I site as an analogue (e.g., Ildefonse et al., 1990; Murphy and Codell, 1999; Murphy, 2000; Rechard et al., 2003) have focused on the uranium mineralogy of the Nopal I deposit as an analogue for the source term, and only address flow and transport of radionuclides in general terms. However, detailed stratigraphic and rock-property information is required to constrain such models (Figure 12).

The PB-1 well was drilled for the purpose of collecting geologic, geochemical, and hydrologic data that were not obtained in previous investigations of the Nopal I area. Four main stratigraphic units were intersected by PB-1 well; the Nopal Formation, the Coloradas Formation, the Pozos Formation, and the Cretaceous limestone. The measured stratigraphic thicknesses of the Coloradas and Pozos Formations are similar to those reported by Reyes (1997). The ash flow tuffs encountered in the upper two formations are highly altered, but do not have the abundant uranium mineralization found in the adjacent ore deposit. Natural gamma measurements obtained from geophysical logs and core measurements suggest that U may have been transported down from the Nopal I ore body to a region above the current water table. The tuffs have low matrix permeabilities; thus fluid flow and radionuclide transport through these formations is most likely controlled by the fracture network. Preliminary models for fluid flow at Nopal I (Ghezzehei et al., 2006) can be updated using these observations.

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Figure Captions

Figure 1: Location map for the PB-1 and neighboring wells in the Sierra Peña Blanca, Chihuahua, México.

Figure 2: Detailed plan view of Nopal I uranium deposit, with surface exposure of ore body outlined in pink. Local grid units and contour intervals are in m. Map adapted from Pearcy et al. (1995).

Figure 3: Stratigraphic column and selected geophysical logs for PB-1. Borehole gamma and core gamma values are given in counts per second (plotted on a log scale), neutron measurements are in API units, and temperature values are in °C.

Figure 4: Photomicrograph (crossed nicols) of altered Nopal tuff collected from a depth of 7.54 m. The matrix has been devitrified, and contains abundant secondary quartz (qz) and kaolinite (cao) along with subangular lithic fragments. Base of photo = 1.9 mm.

Figure 5: Photomicrograph (crossed nicols) of altered Coloradas ash flow tuff collected from a depth of 79.77 m. Tuff contains flattened and aligned fiamme (pmz) in a devitrified matrix (mtx). Base of photo = 4.35 mm.

Figure 6: Photomicrograph (crossed nicols) of the Pozos conglomerate at 148.65 m. Conglomerate contains fragments of rhyolite (frr) and limestone (frc). Base of photo = 4.35 mm.

Figure 7: Photomicrograph (uncrossed nicols) of pumiceous tuff interval within the Pozos conglomerate collected at 187.05 m. Tuff contains flattened pumice (pmz) and rock fragments (fr) in an altered glassy matrix (mtx). Base of photo = 4.35 mm.

Figure 8: Photomicrograph (uncrossed nicols) of micritic, fossiliferous Cretaceous limestone with a calcite vein (cta) collected from 247.72 m. Base of photo = 4.35 mm.

Figure 9: Video log image and corresponding core sample of Coloradas ash flow tuff with mineralized fracture at a depth of ~127 m. The nominal well bore diameter for video log is 8.5” (21.6 cm). Core sample consists of pervasively altered lithic vitric tuff, with lithic fragments of andesite no larger than 0.4 cm (15–20%), minor pumice (~5%), and minor altered phenocrysts. White, waxy kaolinite material fills the few altered feldspars. Groundmass of sample altered to clay. Fracture fill is limonite and/or jarosite, followed by late-stage calcite. Scale bars in lower photo are 1 cm.

Figure 10: Porosity versus depth for PB-1 core samples.

Figure 11: Matrix permeability (Klinkenberg-corrected) versus depth for PB-1 core samples.

Figure 12: Cross section (NE-SW) through the Nopal I deposit, providing the stratigraphic and hydrologic framework for flow and transport models. Figure modified from Pearcy et al. (1994).

Figures

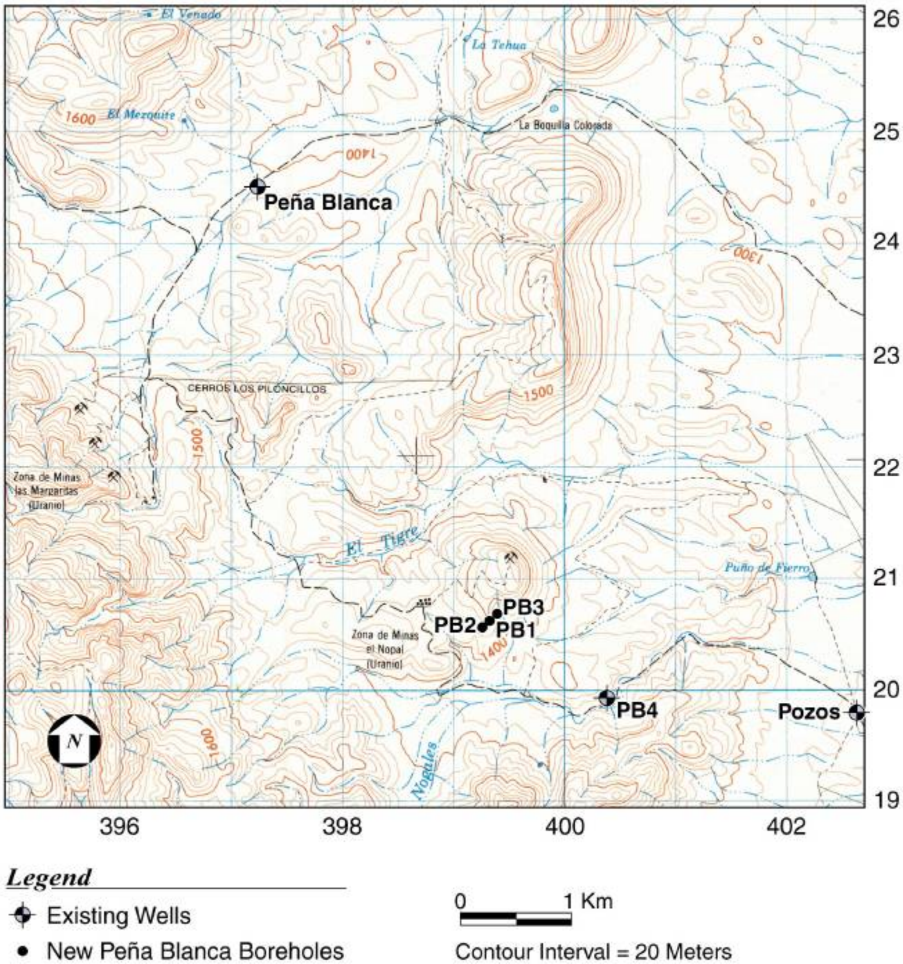
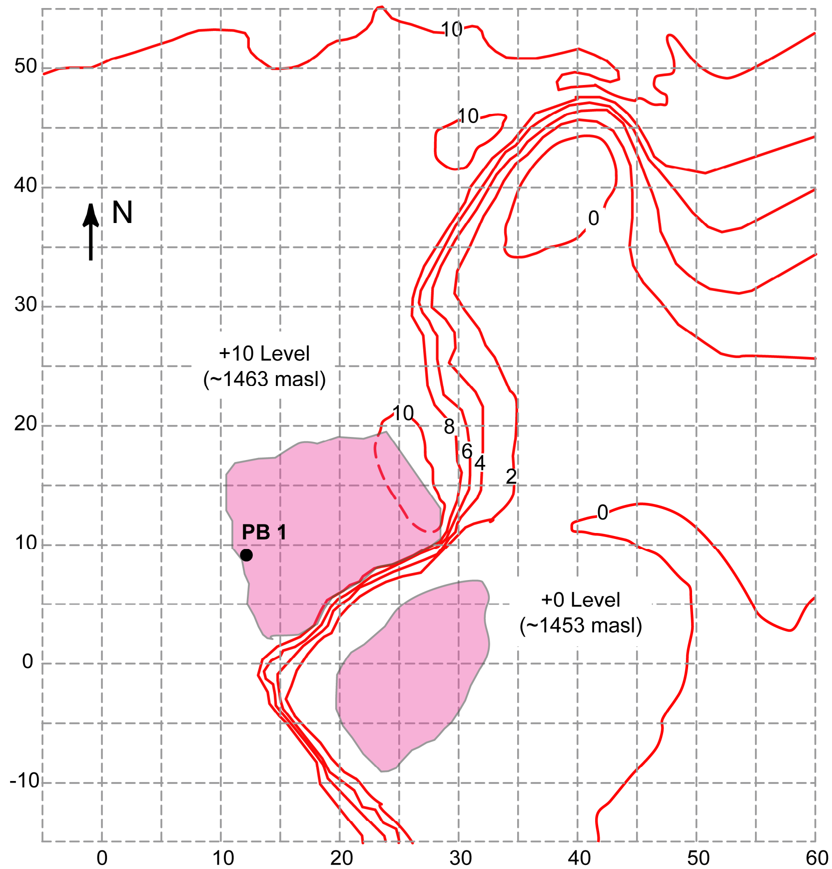


Figure 1



50
40
30
20
10
0
-10
0
10
20
30
40
50
60
N
10
10
0
+10 Level
(~1463 masl)
10
8
6
4
2
0
PB 1
+0 Level
(~1453 masl)

Figure 2

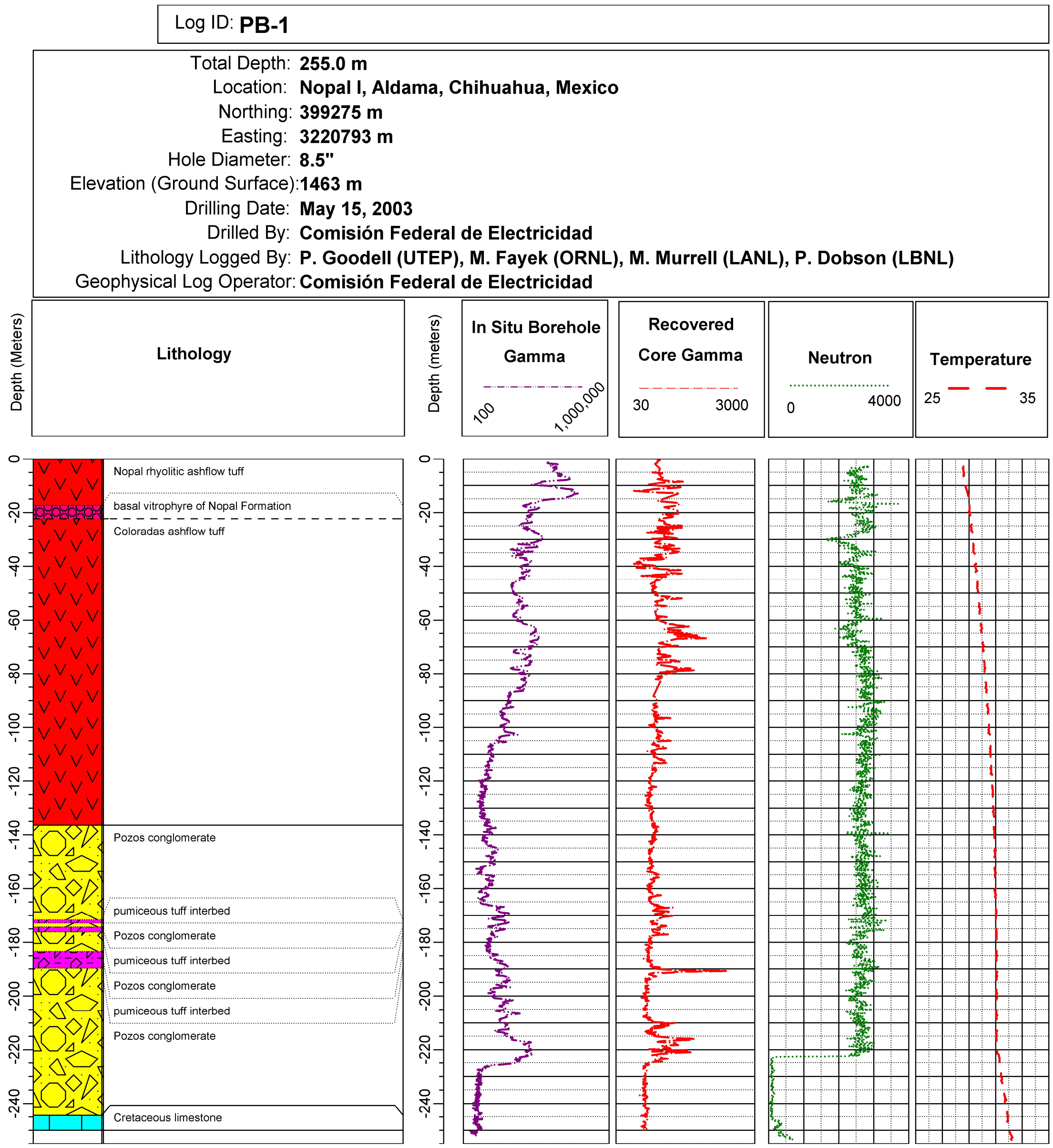

Log ID: PB-1
Total Depth: 255.0 m
Location: Nopal I, Aldama, Chihuahua, Mexico
Northing: 399275 m
Easting: 3220793 m
Hole Diameter: 8.5"
Elevation (Ground Surface): 1463 m
Drilling Date: May 15, 2003
Drilled By: Comisión Federal de Electricidad
Lithology Logged By: P. Goodell (UTEP), M. Fayek (ORNL), M. Murrell (LANL), P. Dobson (LBNL)
Geophysical Log Operator: Comisión Federal de Electricidad
Depth (Meters)
Lithology
Depth (meters)
In Situ Borehole Gamma
100
1,000,000
Recovered Core Gamma
30
3000
Neutron
0
4000
Temperature
25
35
Nopal rhyolitic ashflow tuff
basal vitrophyre of Nopal Formation
Coloradas ashflow tuff
Pozos conglomerate
pumiceous tuff interbed
Pozos conglomerate
pumiceous tuff interbed
Pozos conglomerate
pumiceous tuff interbed
Pozos conglomerate
Cretaceous limestone
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240

Figure 3

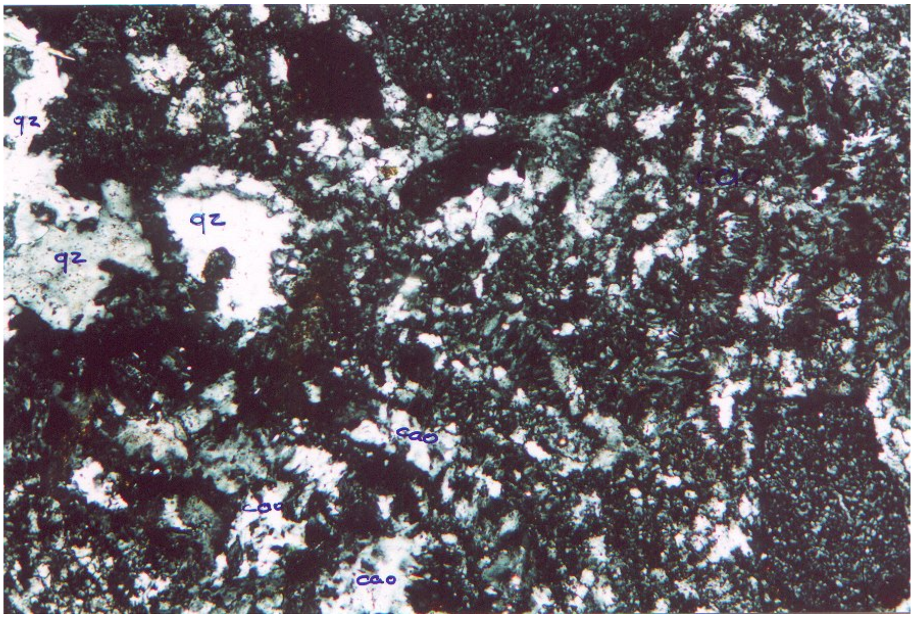


Figure 4

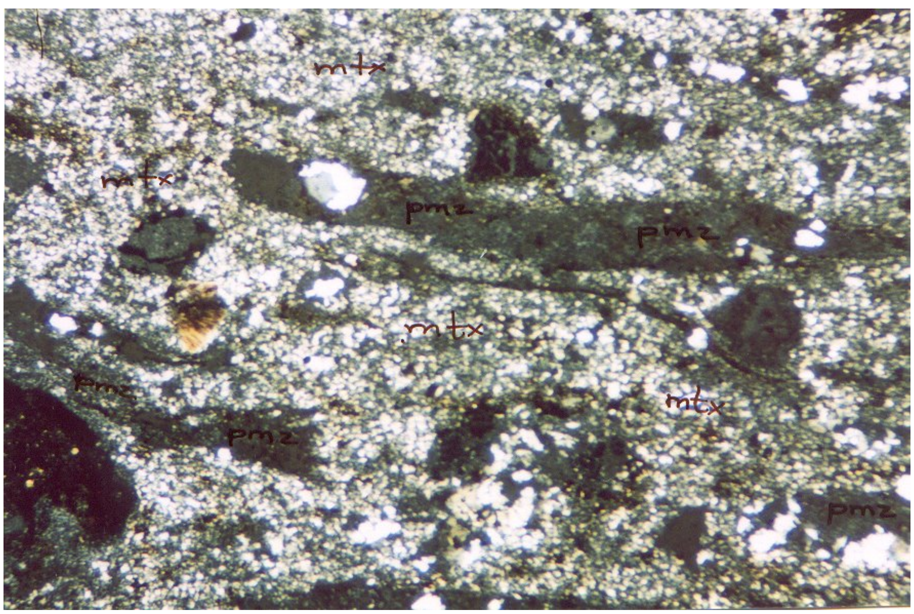


Figure 5

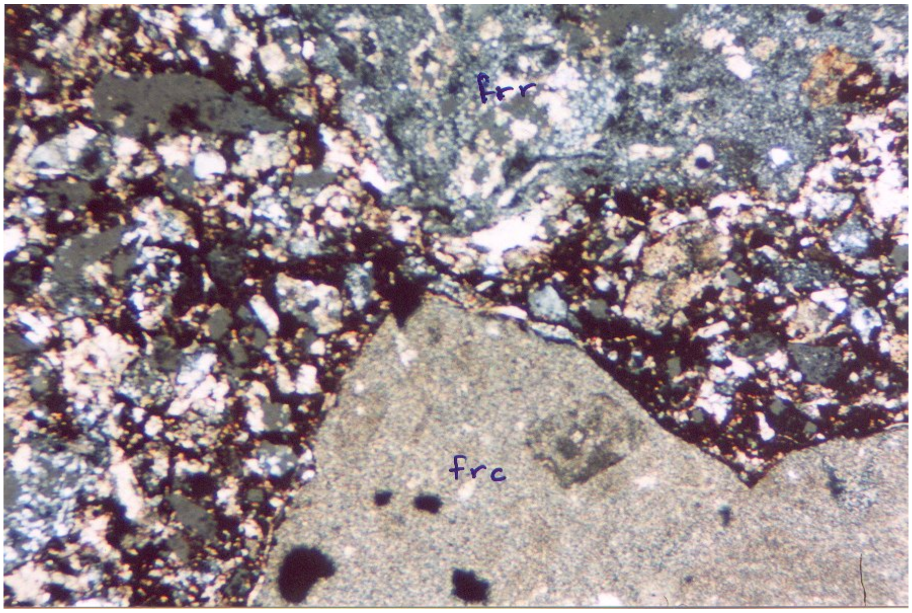


Figure 6

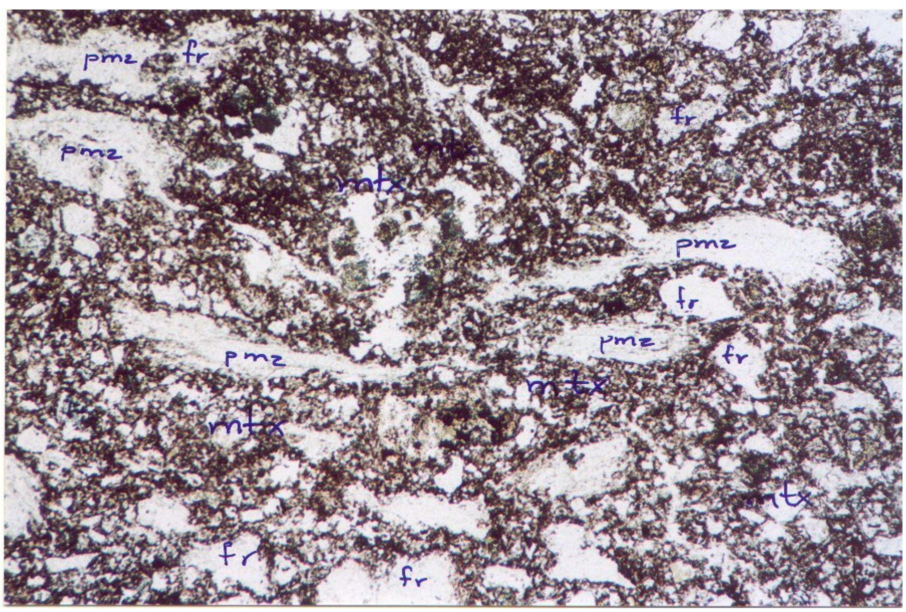


Figure 7

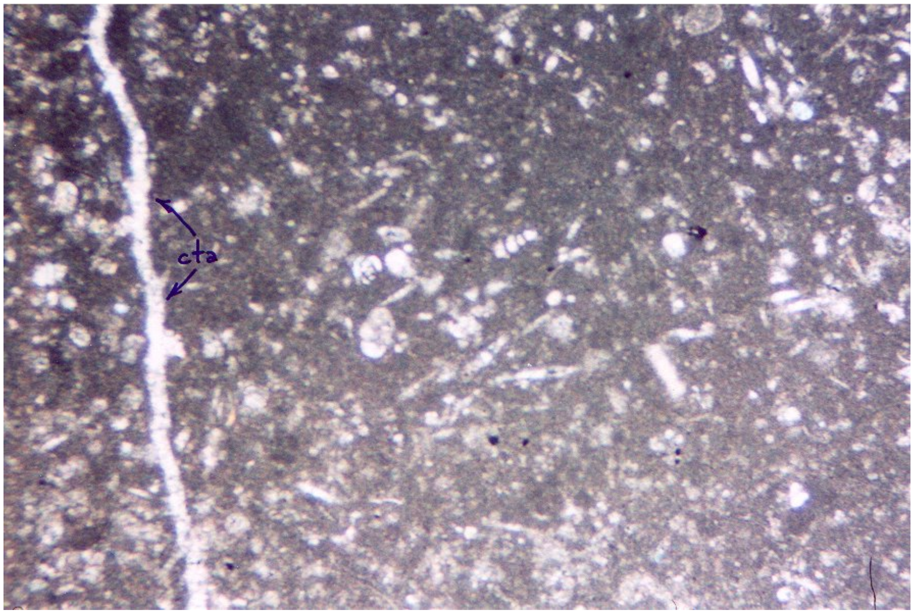


Figure 8

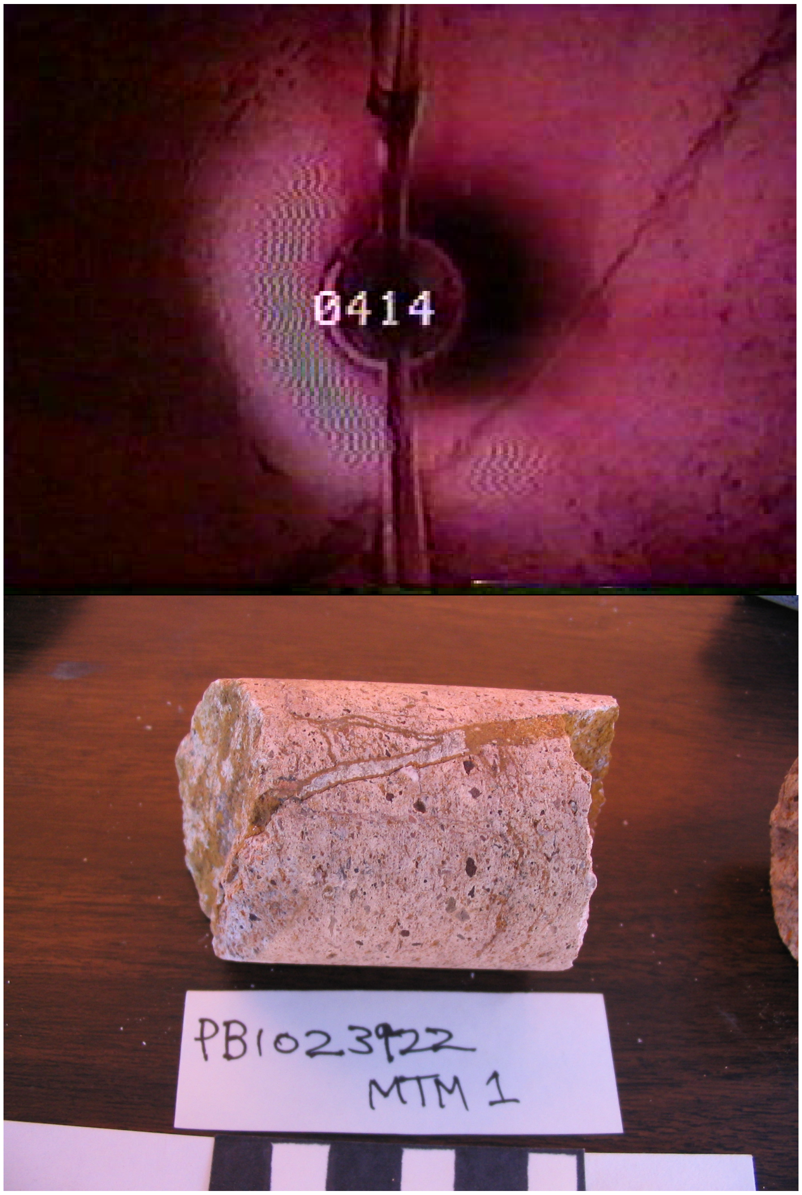


Figure 9

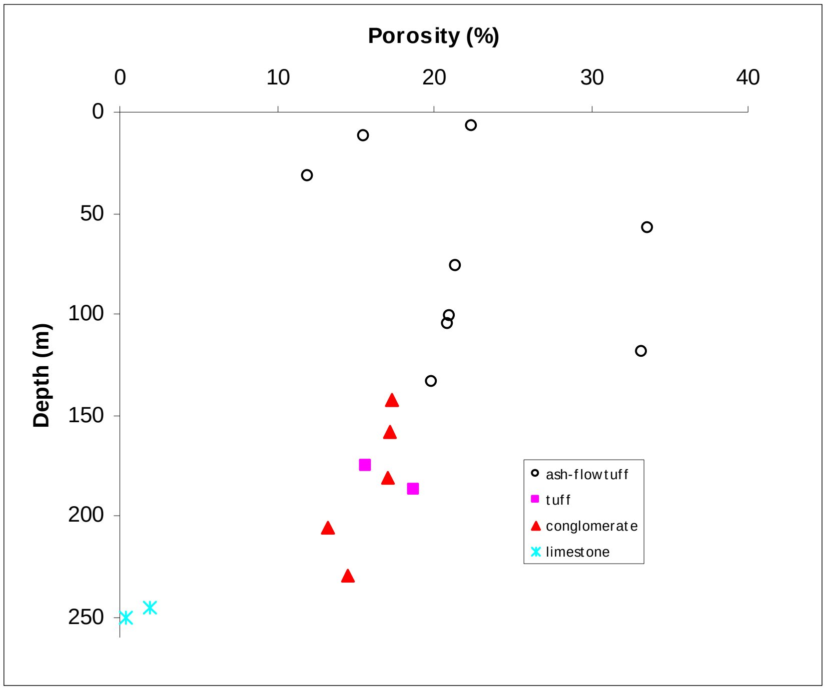


Figure 10

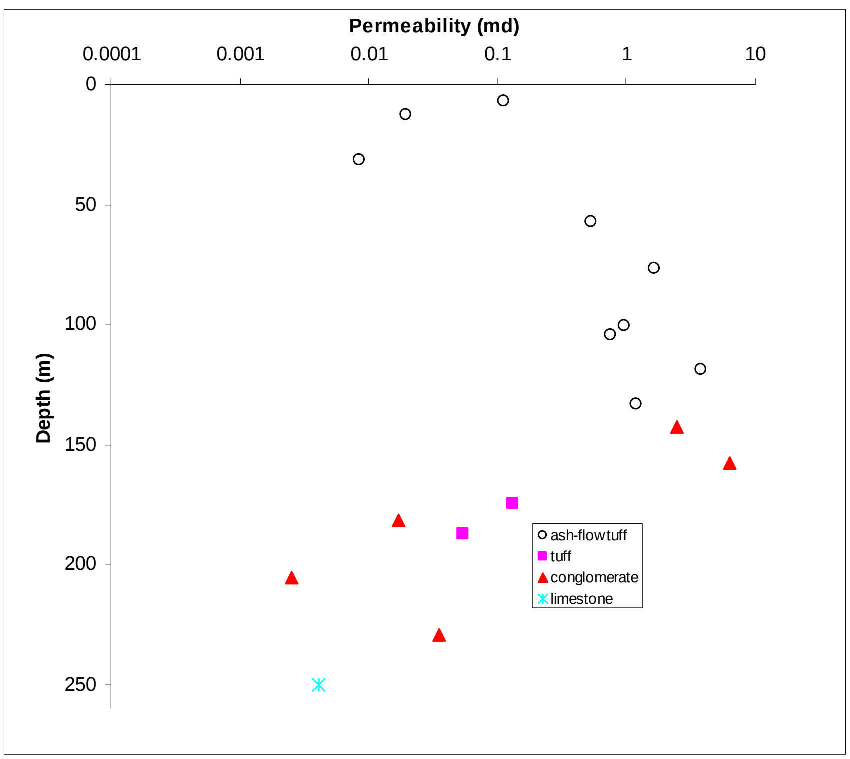


Figure 11

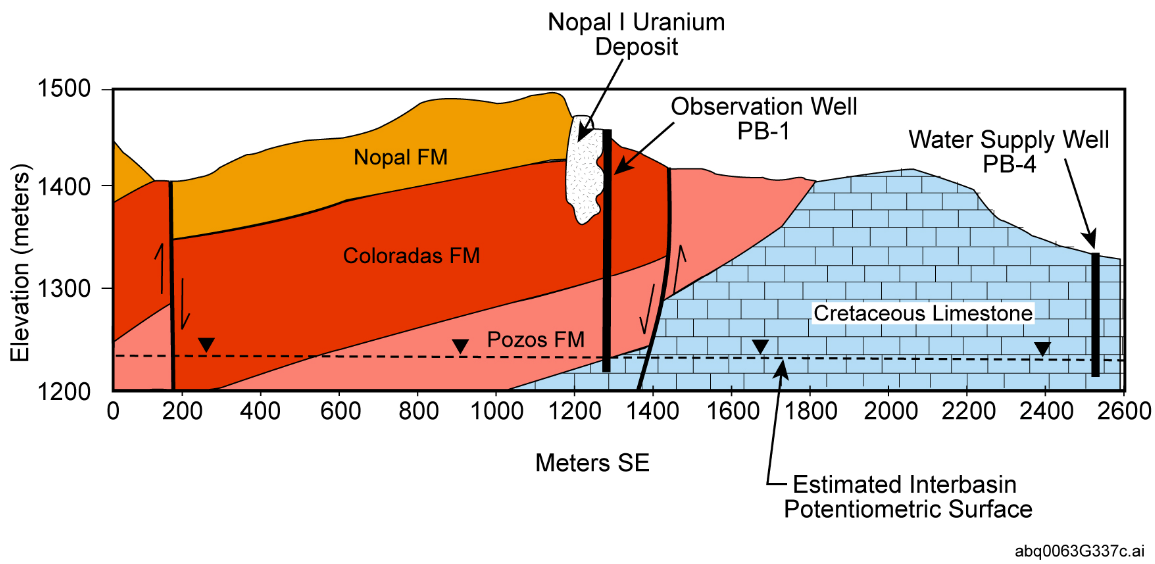

Nopal I Uranium
Deposit
Observation Well
PB-1
Water Supply Well
PB-4
1500
1400
1300
1200
Elevation (meters)
Nopal FM
Coloradas FM
Pozos FM
Cretaceous Limestone
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
Meters SE
Estimated Interbasin
Potentiometric Surface
abq0063G337c.ai

Figure 12

Table 1: Laboratory rock property values for PB-1 core samples

Depth (m)	Formation	Lithology	Porosity (%)	Bulk density (g/cm^3)	Grain density (g/cm^3)	Permeability (md)	Klinkenberg permeability (md)
6.81	Nopal	ash-flow tuff	22.4	2.00	2.58	0.113	0.043
12.35	Nopal	ash-flow tuff	15.5	2.22	2.62	0.020	0.008
31.4	Coloradas	ash-flow tuff	11.9	2.26	2.56	0.008	0.003
57.02	Coloradas	ash-flow tuff	33.6	1.74	2.63	0.530	0.306
76.57	Coloradas	ash-flow tuff	21.4	2.05	2.61	1.629	1.027
100.75	Coloradas	ash-flow tuff	21.1	2.06	2.61	0.960	0.530
104.35	Coloradas	ash-flow tuff	20.8	2.06	2.60	0.760	0.497
118.91	Coloradas	ash-flow tuff	33.2	1.78	2.66	3.824	2.454
133.33	Coloradas	ash-flow tuff	19.8	2.10	2.62	1.190	0.814
142.31	Pozos	conglomerate	17.4	2.18	2.64	2.449	2.001
157.82	Pozos	conglomerate	17.1	2.20	2.65	6.302	5.182
174.65	Pozos	tuff	15.7	2.22	2.63	0.132	0.080
181.25	Pozos	conglomerate	17.1	2.23	2.69	0.017	0.007
187.05	Pozos	tuff	18.7	2.17	2.67	0.055	0.026
205.60	Pozos	conglomerate	13.2	2.33	2.68	0.003	0.001
229.29	Pozos	conglomerate	14.5	2.29	2.68	0.035	0.017
245.59		limestone	1.9	2.65	2.70	b.d.	b.d.
249.92		limestone	0.3	2.68	2.69	0.004	0.001

b.d. – below detection limit of 0.0005 md.

Table 2: Comparision of Nopal I with Yucca Mountain

Analogue Feature	Nopal I	Proposed Yucca Mountain Repository
Host rock	Rhyolite ash flow tuffs	Rhyolite ash flow tuffs[a, b]
Structural setting	High-angle normal faults and steeply dipping fractures (Basin and Range province	High-angle normal faults and steeply dipping fractures (Basin and Range province[b, c]
Basement lithology	Limestone	Limestone[b, c]
Depth of radionuclides below ground surface	0-110 m	~300 m[c]
Distance between base of radionuclides and water table	~110 m	~300 m[c]
Annual rainfall	~300 mm/y[c]	~177 mm/y[e]

[a]Peterman and Cloke, 2002
[b]Stuckless and O'Leary, 2007
[c]Stuckless and Dudley, 2002
[d]Average annual rainfall recorded at Los Pozos, Chihuahua (1961-72) by the Servicio Meterológico Nacional, Mexico.
[e]Sharpe, 2007