Heterogeneous seepage at the Nopal I natural analogue site, Chihuahua, Mexico

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Abstract

An integrated field, laboratory, and modeling study of the Peña Blanca (Chihuahua, Mexico) natural analogue site is being conducted to evaluate processes that control the mobilization and transport of radionuclides from a uranium ore deposit. One component of this study is an evaluation of the potential for radionuclide transport through the unsaturated zone (UZ) via a seepage study in an adit at the Nopal I uranium mine, excavated 10 m below a mined level surface. Seasonal rainfall on the exposed level surface infiltrates into the fractured rhyolitic ash-flow tuff and seeps into the adit. An instrumented seepage collection system and local automated weather station permit direct correlation between local precipitation events and seepage within the Nopal I +00 adit. Monitoring of seepage within the adit between April 2005 and December 2006 indicates that seepage is highly heterogeneous with respect to time, location, and quantity. Within the back adit area, a few zones where large volumes of water have been collected are linked to fast flow path fractures (0-4 h transit times) presumably associated with focused flow. In most locations, however, there is a 1-6 month time lag between major precipitation events and seepage within the adit, with longer residence times observed for the front adit area. Seepage data obtained from this study will be used to provide input to flow and transport models being developed for the Nopal I hydrogeologic system.

1. Introduction

The primary objectives of the Peña Blanca natural analogue study are to evaluate processes governing the transport of radionuclides from the Nopal I uranium deposit into the surrounding environment and to compare behavior predicted from flow and transport models with field observations. The Peña Blanca system has numerous similarities to the proposed geologic repository of nuclear waste at Yucca Mountain, making it a good analogue for evaluating flow and transport processes (e.g., Murphy, 2002; Murphy et al., 2002). Similarities include:

- Thick (>200 m) unsaturated zone
- Host rock consisting of welded rhyolitic ash-flow tuffs
- Semiarid climate with low infiltration rates
- Basin and Range structural setting
- Orebody mineralogy similar to the spent nuclear fuel scheduled for disposal at Yucca Mountain

The goal of the seepage study at the Nopal I mine is to characterize the nature of fluid flow within the unsaturated zone, which can then be used to provide input to flow and transport models (e.g., Saulnier and Statham, 2006) and to evaluate radionuclide mobility and transport within the UZ. This study consists of evaluating seepage rates and volumes using a high spatial resolution collection system, and correlating seepage events with seasonal precipitation at the Nopal I site. These data will subsequently be used in to develop numerical models that capture the observed variations in seepage. A companion paper (Dobson et al., in prep.) evaluates the variations in isotopic composition for the seepage waters and associated ground waters for this area.

1.1. Study Site

The Nopal I uranium deposit, located ~50 km NE of Chihuahua, Chihuahua, Mexico in the Sierra Peña Blanca (Figure 1), is hosted by two rhyolitic ash-flow tuff units, the Nopal Formation (44 Ma) and the Coloradas Formation (Reyes-Cortés, 2002). The ore deposit is exposed at the ground surface with visible U mineralization over an area of 18 by 30 m; the orebody extends to a depth of ~100 m (Pearcy et al., 1995). The deposit was actively mined in the 1970s and 1980s, but is currently abandoned. As part of the mining activities, a number of benches and adits were constructed. The benches represent horizontal surfaces with exposed bedrock where infiltration occurs. The +10 level bench was the subject of a detailed fracture study conducted by Pearcy et al. (1995) and Reyes-Cortés (1997). An adit on the +00 m level of the mine intersects the orebody and goes beneath the exposed +10 m bench; this adit is where the seepage collectors for this study are deployed (Figures 2 and 3).

Three wells were drilled in 2003 around the Nopal I deposit down to the water table to provide stratigraphic information, determine the water table depth, and permit sampling of the saturated zone water (Dobson et al., 2008). The water table is located at a depth of ~220 m below the +10 m bench, thus indicating that the Nopal I uranium orebody is located entirely within the vadose zone. The well PB-1, located immediately adjacent to the +00 level adit, was cored, providing good stratigraphic control. The portion of the +00 level adit where seepage collectors were deployed is located in the lower portion of the Nopal Formation ash-flow tuff, just above the contact with the basal vitrophyre.

1.2. Previous Studies

Prior mapping and characterization of the Nopal I site (Pearcy et al., 1995; Prikryl et al., 1997) demonstrated that the distribution of U outside of the main orebody is concentrated along mineralized fractures, suggesting that fluid flow through fractures is the primary mechanism for transport of radionuclides away from the orebody. Stable isotope and ion probe analyses of U minerals at the Nopal I deposit indicate that U mobilization has occurred repeatedly over the past 30 Ma, and at relatively low (<80°C) temperatures (Fayek et al., 2006; Calas et al., 2008). Thus, an understanding of fluid flow within the thick unsaturated zone at Nopal I is needed to develop models describing the flow and transport of radionuclides from the uranium orebody into the surrounding environment.

Previous workers proposed a similar seepage study at the Nopal I site (Green and Rice, 1995), but only limited seepage information was collected at the site prior to our study. Pickett and Murphy (1999) report major anion and cation concentration and Th and U isotope data for two seepage samples collected from the back adit of the Nopal I mine. The samples were collected using ~2 m square plastic sheets that were connected with funnels and tubing to collection bottles. Rapid infiltration into the +00 adit was reported to occur after a succession of rainstorms in September of 1995, but the total seepage volumes and sampling duration for these samples were not given. Simmons et al. (2002) reported U isotopic data from a series of seepage samples collected from the Nopal adit using the plastic sheet collection method. Goldstein et al. (2006) interpreted the observed uranium isotope mixing relations from collected seepage waters to indicate that samples from the back adit have lower U dissolution rates and shorter water-rock interaction times relative to those from the front adit area of the Nopal I mine. All of these earlier studies were limited by a lack of constraints on seepage sampling and the timing of discrete rainfall events.

2. Methods

A rudimentary water collection system consisting of plastic sheeting and wooden frames had been installed by previous investigators within the +00 m adit of the Nopal I mine to collect water that infiltrated from the +10 m level and seeped into the adit (Pickett and Murphy, 1999; Simmons et al., 2002). This collection system was upgraded in April of 2005, when the plastic collection tarps were replaced with a 240-bottle collection system to collect spatially discretized samples and reduce potential water losses resulting from evaporation. The new seepage capture system, similar to that utilized by Trautz and Wang (2002) at Yucca Mountain, consists of four aluminum racks deployed within different portions of the +00 adit (Figure 2). Each rack has a 12 by 5 array of Lexan compartments (30.5 cm x 30 cm by 15 cm deep) that are mounted on top of the rack near the adit ceiling. The rows of collection compartments are numbered 1 through 48 starting from the innermost compartment in the back adit, and the columns are labeled A through E from left to right (see Figure 2). The compartments are individually connected by Tygon tubing to 125 ml Nalgene bottles (Figure 4). This system was further enhanced in November of 2005, when instrumentation was added to six selected collector sites within the back adit (locations 3C, 8C, 18A, 24C, 30D, and 34E) to measure seepage rates continuously within 1.905 cm ID by 70 cm high Plexiglas collection columns fitted with absolute pressure transducers (Setra) (Figure 5). These locations were chosen to provide spatial variability (two sites per frame in the back adit) as well as to provide more detailed characterization of low seepage and high seepage areas as identified from seepage measurements made between April and November of 2005.

In November 2005, sensors were installed within the back adit to monitor changes in temperature, atmospheric pressure, and relative humidity. The pressure transducers (Setra) and temperature-relative humidity sensors (Vaisala) were connected to a battery-powered datalogger (Campbell Scientific Inc., Logan, UT), with measurements recorded every two hours. An automated weather station (Vantage Pro 2, Davis Instruments Inc., Hayward, CA) was installed at the site in March of 2006 (at a location ~65 WSW of the adit collectors) to permit direct correlation of local precipitation events with seepage. The absolute pressure transducers (Setra) were replaced with gauge pressure transducers (Druck) in June of 2006.

Prior to the installation of the seepage collection trays, the ceiling of the adit was photographed and major fractures were identified relative to the location of the tray frames (Figure 6). Most of these fractures were observed to be steeply dipping. One of these features (shown in Figure 6 as a slightly thicker line cutting across the middle frame of the frontmost set of collection trays in the back adit) was identified as a fault, having a strike and dip of N37E, 81SE. The surface of the adit roof was quite irregular. Measured distances between the top of the collection trays (located ~1.8 m above the floor of the adit) to the adit ceiling ranged from 0 to 89 cm. The front adit collectors are located only 2–5 meters away from the margin of the uranium orebody, whereas the back adit collectors are a bit more distant (7–21 m) from the deposit (Figure 2).

Seepage amounts were monitored at each collection location during visits to the site in September and November of 2005 and January, March, June, August, and December of 2006 to determine the timing and amounts of seepage within the adit. For sites with bottles, the water levels in the collection bottles were noted during each visit by marking the water level on the bottle and comparing water levels with a calibrated bottle, thus permitting a volumetric estimate of seepage volumes between each site visit. Bottles were routinely collected (usually when they had accumulated more than 40 ml of water) and replaced with new bottles beginning with the

November 2005 visit. Collected bottles were used to determine seepage volumes at the corresponding marks more accurately (±2 ml) in the laboratory, and selected seepage water samples were chosen for isotopic and chemical analyses.

3. Results

Rainfall in central Chihuahua is seasonal, with most precipitation occurring during the summer monsoon period (June through September). Historical average monthly rainfall data (1961-1972) from the Los Pozos weather station of the Servicio Meterológico Nacional located about 5 km ESE of Nopal I indicates an annual total rainfall of 300 mm. Rainfall data obtained during March – December of 2006 from the automated weather station installed at the Nopal I site is consistent with this trend, with little rainfall occurring in the spring and significant rain events during the summer months (Figure 7). There were three major (> 25 mm) precipitation events and 14 minor (5-10 mm) events observed during the 2006 rainy season.

The +10 level above the +00 adit was excavated when the uranium mine was active, and consists of flat exposed bedrock (Figure 8). The area was cleared of debris during the fracture mapping conducted by Southwest Research Institute in the 1990s (Pearcy et al., 1995), and since that time, only small amounts of grasses and sagebrush have taken root in the back (NW) portion of this area. Precipitation falling on this surface tends to pool in small depressions on the excavated bedrock surface and infiltrates along fractures and into the pore spaces of the exposed bedrock. Runoff is presumed to be minimized by the lack of slope on the mined surface, and the lack of vegetation likely minimizes transpiration losses. However, the absence of soil on the +10 level could lead to rapid evaporation of any standing pools of water in this arid climate.

Using the data recorded from the individual seepage collection bottles and the instrumented seepage columns, two types of seepage data are available. For the majority of the seepage collection sites, seepage amounts are averaged over the time between site visits, thus providing a time resolution of several months between measurements (Figures 9-12). These results do not permit correlation of seepage with individual rainfall events, but do provide important insights into the overall temporal and detailed spatial distribution of seepage within the adit. These results can be combined to look at the spatial variability of cumulative seepage (Figure 13) over the duration of the monitoring period (April 2005-December 2006). Detailed temporal seepage information is available from the six instrumented seepage columns, where continuous seepage data were recorded, thus permitting direct correlation between rainfall events and changes in seepage behavior (Figure 14).

Both collector types (bottles and instrumented columns) were limited by the total storage volume. When the volume of the containers (~135 ml) or columns (~340 ml) was exceeded, in most cases, water leaked out of the connection between the containers and the Nalgene tubing. In several instances, this connection did not leak, and large volumes of water were preserved in the Lexan trays, which have an additional capacity of ~6750 ml. Thus, for instances where the containers or columns were full, the measured values represent a minimum seepage volume for that collection interval.

Comparison of the timing of seepage from the instrumented collectors in the Nopal I adit with precipitation events (Figure 14) indicates that while some locations (collectors 3C, 8C, and 18A) had large increases in seepage immediately following the 3 major rain events (July 6, August 12, and Sept 2, 2006), other locations (collectors 24B, 30D, 34E) had little or no seepage during the onset of the summer rainy season, and experienced slight increases in seepage rates several months after the initiation of rainfall. As seen in the bulk seepage pattern (Figures 9-13), there is a large variability in seepage within each collection frame, as some 30.5 cm × 30 cm collectors have captured more than 6 L of water over the deployment period, while nearby collectors within the same frame captured very little (<150 ml) seepage water. In general, seepage within the back adit area occurred earlier than in the front adit region, where water infiltrating from the summer rainfall did not reach the adit until November to January, about 6 months after the start of the rainy season.

4. Discussion

Initial modeling of infiltration and seepage as occurring through a series of planar, vertical fractures was conducted to evaluate flow transit times and seepage rates (Ghezzehei et al., 2006). Using a range of fracture apertures and frequencies, and assuming no fracture-matrix interaction (which would retard the flow of fluid movement), infiltration through the 8 m high vertical fracture system and seepage into the adit were predicted to occur within 24 hours after a 6 hour rainfall event. This result contrasts with the long (1-6 month) time lags in seepage observed at many of the collection locations at the Nopal I study site.

There are abundant steeply dipping fractures within the adit (Figure 6). The presence of these features appears to influence where the flow of water from the ground surface to the adit collectors occurs in less than 4 h following large (>25 mm) rain events, indicating the existence of what will hereafter be termed a "fast flow path". The presence of roots along some of the fractures in the +00 adit indicates that there are continuous fracture pathways that connect the adit with the surface (Figure 15). Results from the instrumented seepage collection columns within the back adit area indicate that seepage for individual collection sites vary temporally and spatially. Of the six instrumented collection sites (Figure 14), three (18A, 8C, and to a lesser degree, 3C) experienced high volumes of seepage (>300 ml within 12 hours) after large (>25 mm) precipitation events. These fast-flow sites appear to be linked to fractures, as there are two mapped fractures that intersect above the 18A collector, a major fracture that cuts across the ceiling above the 8C collector, and a fracture that goes through the edge of the 3C collector area. A fault does cut above a portion of the 30D collector, but this feature does not appear to contribute to the fast flow of water, as the neighboring collectors where this feature is also present also lack evidence for high-volume fluid flow. There were no mapped fractures above the 24B and 34E collectors, consistent with the absence of fast-flow seepage in these areas.

In addition to the fracture-related flow events that occur immediately following large rainfall events, there is a pattern of general seepage that appears to be spatially variable and seasonally controlled. Because of the presence of a summer monsoon period and a dry winter season (Figure 7), infiltration of water at the surface is mostly restricted to the months of June to September. There is a time lag of weeks to months between the onset of the rainy season and the first appearance of seepage in many of the adit collectors. After seasonal seepage is initiated in the adit, seepage rates appear to be quite uniform over sustained periods, and then seepage diminishes to either very low levels or ceases altogether until the next year's seepage event begins. There is a general trend towards earlier water arrival times in the back adit (e.g., Figure 9) and later arrival times in the front adit (Figure 12). This may be influenced by an increase in rock alteration and the presence of shorter average fracture lengths within the U orebody (Pearcy, 1993), which could result in lower fracture network permeability for the front adit region. Although there was no collection instrumentation in the front adit location, the absence of seepage water in all but one of the collectors during the June-August 2006 collection period (when two of the three large precipitation events occurred) at this site (Figure 12) suggests that this area does not have any fast flow paths.

There are a number of additional factors that could affect the measured seepage values. First, some of the collected volumes may have been affected by evaporation from the collection bottles or columns. However, this effect appears to have been minor, as only rarely did water levels in partially filled bottles show any decrease in volume. In the back adit area, where temperature, relative humidity, and barometric pressure values were monitored, temperatures were stable and moderate (15-19°C) and relative humidity levels were quite high (> 85%) throughout the seepage collection period (Figure 16), which would prevent much evaporative loss from occurring; this is in contrast with the large variations in outside temperature and the much lower relative humidity values in this arid environment. The restricted hose connection between the collection vessel and the seepage trays also limited evaporative loss. This would not have been the case for the plastic sheets that were originally used in collecting seepage samples for previous studies. Although there was no continuous monitoring of the relative humidity and temperature levels for the front adit area, the proximity of the front adit collectors to the adit entrance (Row 48 is 11.3 m from the door) likely resulted in increased evaporation of water from the adit walls, which could explain the lower seepage volumes collected throughout this area (Figure 13), especially during the hotter summer months when no seepage is observed in the front adit.

Field studies and modeling work conducted by Ghezzehei et al (2004) indicate that the effects of evaporation are minimal for seepage into cavities when elevated (>85%) relative humidity conditions are present. Ghezzehei et al (2004) also found that evaporation from cavity walls significantly reduces seepage in tests conducted under ventilated conditions at Yucca Mountain, where relative humidity fluctuated between 20% and 95%. In some portions of their study site, seepage was completely halted when relative humidity values dropped below 40%.

Another process that could affect seepage is condensation occurring within the adit. During times of elevated seepage (and thus, elevated humidity within the adit), condensation droplets were often observed on the outside of the seepage trays and collection bottles. To evaluate the potential for condensed water contributing to the water collected in the seepage trays, a separate condensate tray was installed in the back adit, with a Lexan roof mounted above it so that water could not drip directly into the collection tray. This collector was placed in a portion of the back adit where abundant condensate had been observed previously, and where a set of pressure-temperature sensors deployed adjacent to site 25A was rendered inoperative as a result of condensation affecting the electronics of the sensors. No condensate was found in the tray during the time when seepage was not occurring in this portion of the adit, but a significant amount (≥135 ml) of water was observed in the condensate collector for one time interval where seepage was extensive in this portion of the adit (Aug.-Dec., 2006). Thus, a fraction of the collected "seepage" water may result from local condensation dripping down from the roof or occurring directly within the collection trays in certain regions of the adit. However, the original source of both seepage and condensate water is likely to be from precipitation that has infiltrated through the rock mass above the adit.

An unexpected aspect of the collection system was the attraction of stored water to small animals of the Chihuahuan desert. The adit entrance is protected by a corrugated metal door, but it does not completely seal off the adit from the outside environment. During the spring of 2006, a number of the bottles located on the edges of the collection trays were attacked by an animal (perhaps a bat (which was observed during one of our visits) or a climbing rodent) looking for water. Some of the bottles were physically pulled off of the tubing, and in other instances, there were teeth marks on the bottle. These affected samples were easy to identify, and thus the volumes collected in these sites represent minimum seepage values.

Two other aspects to consider in evaluating the seepage volumes within the adit relate to surface flow on the adit ceiling and the development of a capillary barrier that could divert flow away from the adit. Although active seepage was not observed in the adit during our visits to the site, we did see features on the ceiling of the adit that appear to serve as drip points. These features often exhibited white mineralization with drops of water, and were located either near fractures (Figure 17) or on low-lying points along the roof. The mined surface of the adit was quite uneven, so film flow along the ceiling could help focus seepage collection to these lower hanging features. In contrast, the one area in the back adit where the ceiling was elevated, forming a nave about 90 cm high (Figure 18), had some of the lowest observed seepage rates in the back adit (see row 24 in Figure 10 and collector 24B in Figure 14b).

The concept of a flow diversion around mined excavations in the unsaturated zone resulting from capillary barrier effects has been postulated as a potential process that would reduce seepage (Philip et al., 1989; Houseworth et al., 2003). Seepage within the adit is distributed in a very heterogeneous fashion, with mapped fractures and faults appearing to be related to zones of elevated seepage. There were two distinct collection regions within the adit where seepage was limited in volume. The first is the front adit area (Figures 12 and 13), which is close to the adit entrance, where lower humidity and higher temperatures would result in greater evaporative loss from the rock mass, and thus lower seepage volumes. The second area where total seepage volumes were greatly reduced was in the back end of the back adit (Figures 9 and 13). This site would be expected to have the least impact from evaporation, as it is furthest from the adit entrance. However, this is the one area where there are three walls (two sides of the adit, and the rear of the adit) where capillary flow diversion could occur, making it the one location where this effect would be expected to be strongest.

5. Conclusions and Relevance to Yucca Mountain

The following observations and interpretations can be made from the results of our seepage study.

1. Observed seepage volumes and arrival times in the Nopal +00 mine adit were highly heterogeneous.
2. Seepage rates and arrival times were much lower/longer than those predicted by a simple planar fracture model for most collection locations, suggesting that flow paths are complex. A few flow paths in the back adit carried large volumes of water, with large volumes of seepage occurring between July and November 2005 and again during the summer monsoon period in July – September of 2006. These seepage episodes are directly correlated with large rainfall events, and are likely associated with major fractures.
3. Most of the remaining portions of the front and back adit exhibited slow, steady seepage that begins after the start of the rainy season and persists for 4-6 months.
4. The arrival of the gradual seasonal seepage pulse occurred earlier in the back adit than in the front adit. This distribution of seepage vs. time could be due to the greater residual saturation in the back adit relative to the front adit, in accordance to evaporation and humidity factors previously discussed, as well as differences in the fracture-matrix flow pathways.

5. Condensation occurred within portions of the adit and contributed to the overall volume of "seepage" water collected within the adit.

These observations indicate that even a relatively thin (8 m) rock mass can exert a noticeable damping effect on infiltration, and that flow and transport models must incorporate fracture flow heterogeneity. Our general model is that for the Nopal I site, there is a seasonal pulse of infiltration associated with the rainy season. For areas with fast flow paths, there are punctuated large-flow events associated with episodes of heavy precipitation. It appears that there is a threshold amount of rain (> 25 mm) that is necessary to trigger such a flow event. These punctuated flow events are accompanied by a slower, more gradual pulse of infiltrating water that moves through the 8 m thick rock mass over a period of 1-6 months, with a much longer (3-6 month) flow duration. Seepage is also affected by evaporation (particularly in the front adit area) and condensation of water vapor within portions of the adit.

The localization of these two types of flow within the fractured ash-flow tuff is dependant on the permeability distribution. Matrix permeability of the Nopal tuff is extremely low, with measured values ranging from 0.001 to 0.098 md (Meyer, 1995; Dobson et al., 2008). Thus, most of the flow is likely to be focused through the fracture network. There is a similar density of fractures within and outside of the Nopal ore deposit (Leslie et al., 2005), but fractures within the U orebody are generally shorter in length (Pearcy, 1994) and appear to have more extensive mineralization, resulting in lower fracture permeability, which may explain why no fast flow paths were observed in the front adit area.

Fluid flow through unsaturated fractured rock has been the subject of numerous previous field and modeling studies (e.g., Shimojima et al., 1993; Davidson et al., 1998; Liu et al., 1998;

Finsterle, 2000; Bagtzoglou and Cesano, 2007a). Infiltration of precipitation, heterogeneous fluid flow through fractures and matrix in unsaturated tuffs, and the existence of fast flow paths are key components of flow and transport process models for Yucca Mountain (e.g., Wang et al., 1999; Flint et al., 2001a, b; Bodvarsson et al., 2003; Liu et al., 2003; Bagtzoglou and Cesano, 2007b). Enhanced fluid flow in regions containing high permeability faults and fractures could increase the opportunity for transport of dissolved constituents in these areas.

However, there are a number of differences between Yucca Mountain and the Nopal I analogue that should be considered when applying the observations and conclusions reached in our study to Yucca Mountain. Current rainfall at Nopal I (~300 mm/y) is significantly higher than at Yucca Mountain (177 mm/y; Sharpe, 2007). Rain at Nopal I is intercepted by a flat surface that is unlikely to produce significant runoff, which would not be the case on the rugged slopes of Yucca Mountain. Rainwater at Nopal is transported through a relatively thin layer (8 m) of fractured tuff that has no overlying soil horizon, whereas at Yucca Mountain water would pass through a thick (~300 m) unsaturated zone prior to reaching the proposed repository horizon. In addition, the unsaturated zone at Yucca Mountain contains a layer of nonwelded and relatively unfractured porous tuff (nonwelded Paintbrush tuff) in between several layers of fractured tuff, which would serve to redistribute water flow and perhaps reduce flow heterogeneity (Flint et al., 2001b). At Nopal I, some of the observed fractures extend from the ground surface down to the +00 adit, providing direct and rapid pathways for percolation waters. While similar fast flow features have been documented at Yucca Mountain (Flint et al., 2001b), it is likely that they are less abundant, and primarily restricted to areas near major faults. The presence of the open fractures at Nopal I is likely responsible for the highly heterogeneous (in space and time) seepage patterns observed at Nopal I.

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7. Figure Captions

Figure 1. Location map of Nopal I uranium mine, Chihuahua, Mexico.

Figure 2. Plan view map of the Nopal I uranium deposit, indicating the location of the +00 adit, the seepage collector arrays (with a depiction of the array numbering system), and the PB-1 well. The locations of mapped fractures and U orebody are from Pearcy et al. (1995). Grid divisions are in meters. The Nopal I weather station is located ~63 m WSW of the PB-1 well.

Figure 3. Schematic cross section of collection system in +00 level adit at Nopal I.

Figure 4. Array of collection bins and associated bottles within front rack of seepage collection system.

Figure 5. Instrumented collection columns (sites 24C, 18A, 8C, and 3C, from foreground to background) within seepage collection system.

Figure 6. Photomosaic of adit roof (plan view projection) depicting the four seepage collection frames in the back and front portions of the +00 m adit. Major mapped fractures observed in the Nopal tuff are highlighted as black lines. Each collection frame covers an area measuring 1.5 m by 3.6 m. Individual bins within collection trays mounted within the frames collect seepage water over an area of 915 cm^2.

Figure 7. Average rainfall, Los Pozos, Chihuahua (29° 05' 03" N, 105° 58' 02" W, 1200 masl; 1961-1972 data from Servicio Meteorológico Nacional — station 08179) and Nopal I weather station, Chihuahua (29° 06' 41" N, 106° 02' 09", 1476 masl), 2006 data (data recorded from Mar. 20 until Dec. 14, 2006).

Figure 8. View of +10 level of Nopal I mine, where infiltration of rainwater occurs. Entrance to +00 adit is located just below and left of PB-1 wellhead (yellow cement feature in left

center portion of photo). Nopal weather station is located on +20 level just above PB-2 well.

Figure 9. Seepage amounts between visits for collectors (Rows 1-12) in Frame 1 (back adit); the highlighted boxes (☐) indicate the location of automated seepage collectors.

Figure 10. Seepage amounts between visits for collectors (Rows 13-24) in Frame 2 (back adit). Losses in bottles around edge of frame for June 2006 visit caused by animal in adit; the highlighted boxes (☐) indicate the location of automated seepage collectors.

Figure 11. Seepage amounts between visits for collectors (Rows 25-36) in Frame 3 (back adit). Losses in bottles around edge of frame for June 2006 visit caused by animal in adit; the highlighted boxes (☐) indicate the location of automated seepage collectors.

Figure 12. Seepage amounts between visits for collectors (Rows 37-48) in Frame 4 (front adit).

Figure 13. Cumulative seepage amounts collected for each station between installation of seepage collection system in April 2005 and final visit to site in December 2006.

Figure 14. Cumulative rainfall (a) and measured seepage volumes (b) for the Nopal I site. Note that steps in seepage amounts represent filling of 340 ml collector column volume, and thus these plots (in the case of collectors 3C, 8C, and 18A) represent minimum seepage volumes. Seepage collection in 34E did not begin until January 2006.

Figure 15. Steeply dipping fracture face with roots near Row 13 in back adit.

Figure 16. Measured temperature (a) and relative humidity (b) values from the back portion (Row 1) of the +00 adit (inside) and the Nopal I weather station (outside).

Figure 17. Seepage drip point marked by white mineralization and droplets adjacent to fracture between collection frames 1 and 2.

Figure 18. Frame 2 in back adit illustrating elevated height of ceiling above Row 24.

Figures

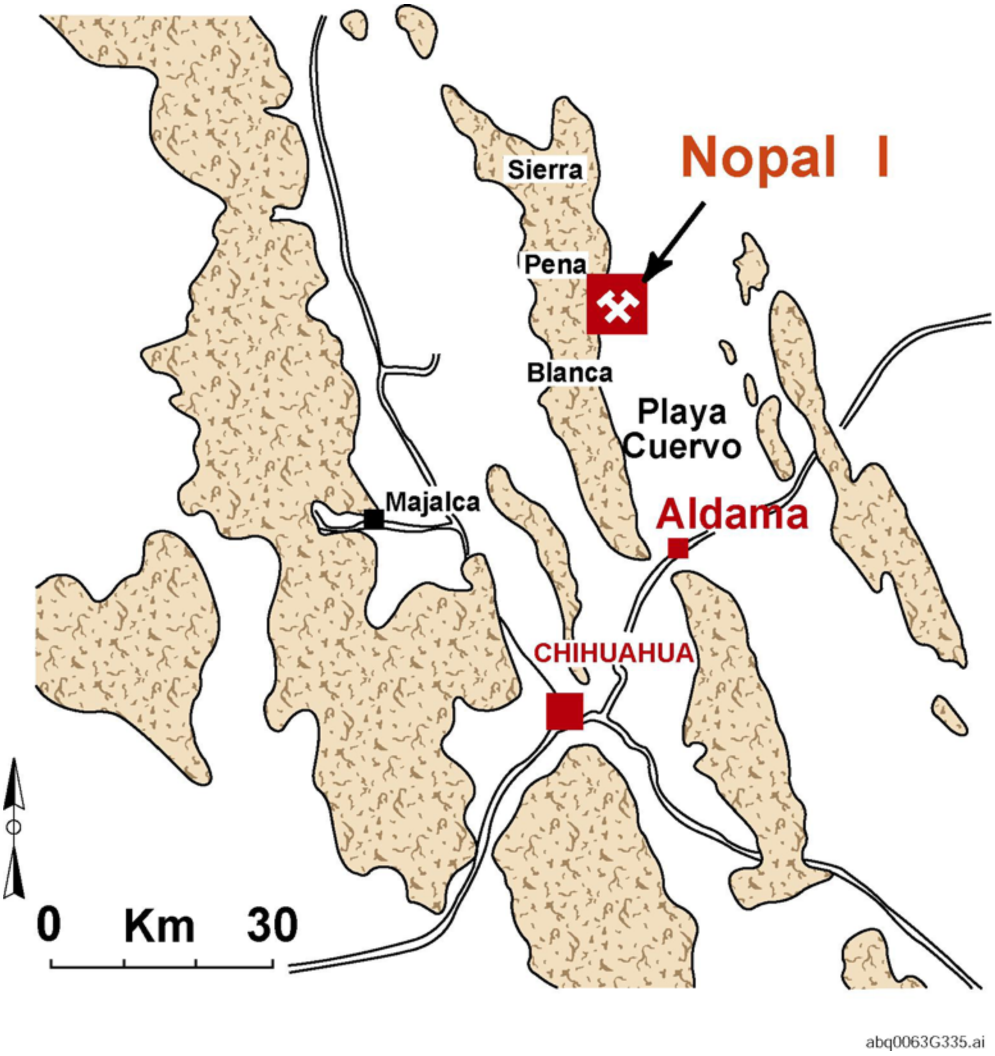

Figure 1.

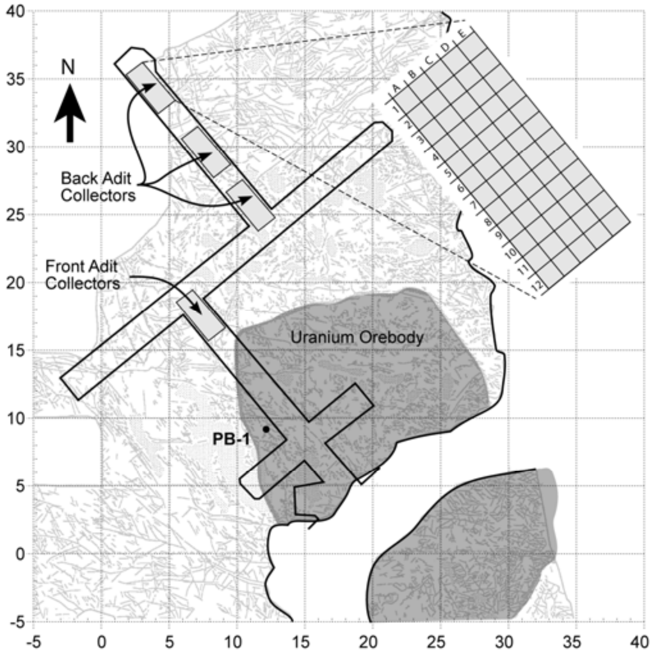
N
Back Adit Collectors
Front Adit Collectors
Uranium Orebody
PB-1
A
B
C
D
E
1
2
3
4
5
6
7
8
9
10
11
12
40
35
30
25
20
15
10
5
0
-5
-5
0
5
10
15
20
25
30
35
40

Figure 2.

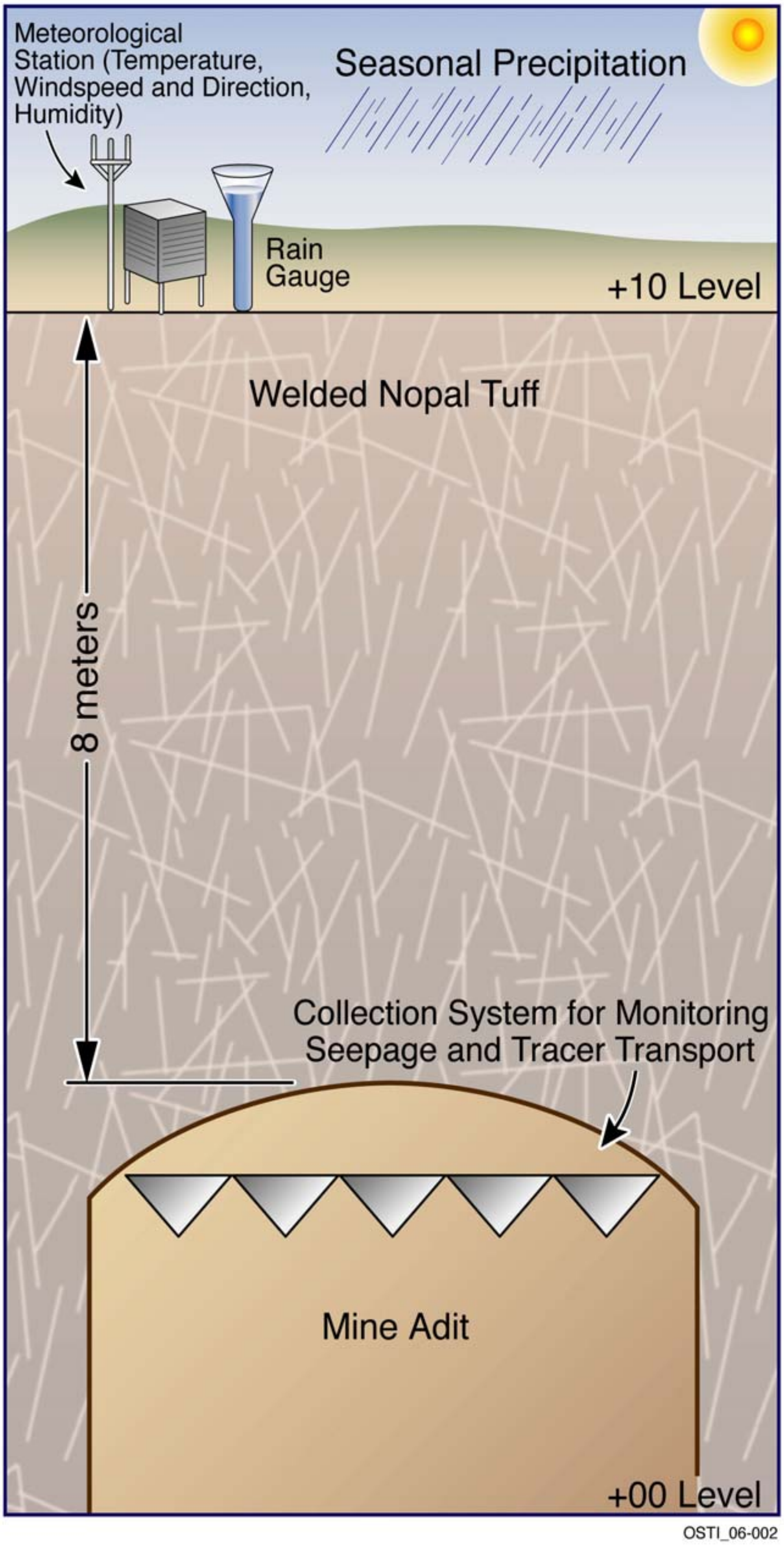
Meteorological Station (Temperature, Windspeed and Direction, Humidity)
Seasonal Precipitation
Rain Gauge
+10 Level
Welded Nopal Tuff
8 meters
Collection System for Monitoring Seepage and Tracer Transport
Mine Adit
+00 Level
OSTI_06-002

Figure 3.

Figure 4.

Figure 5.

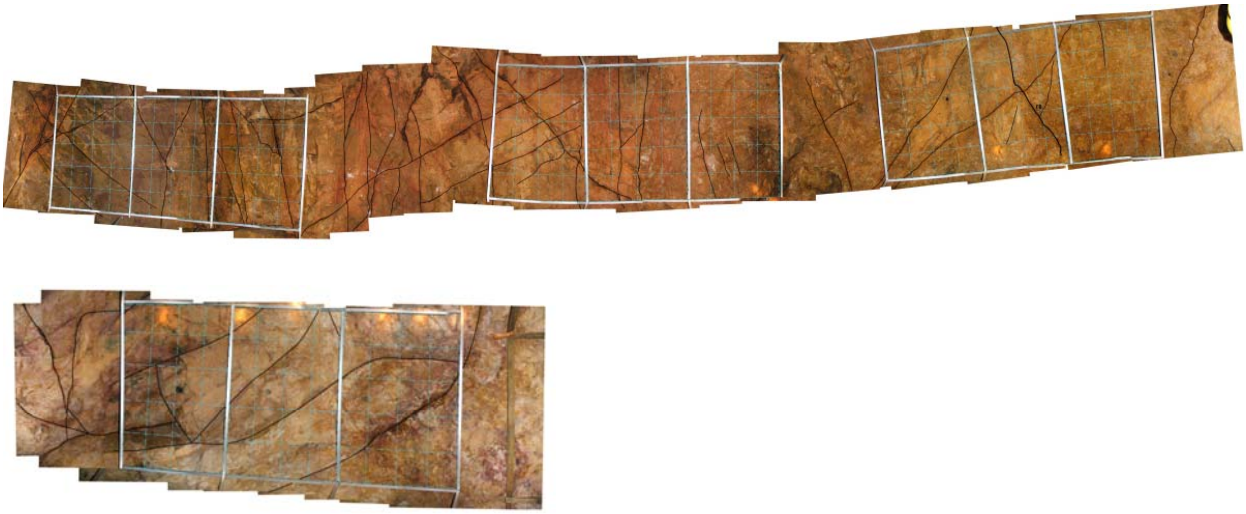

Figure 6.

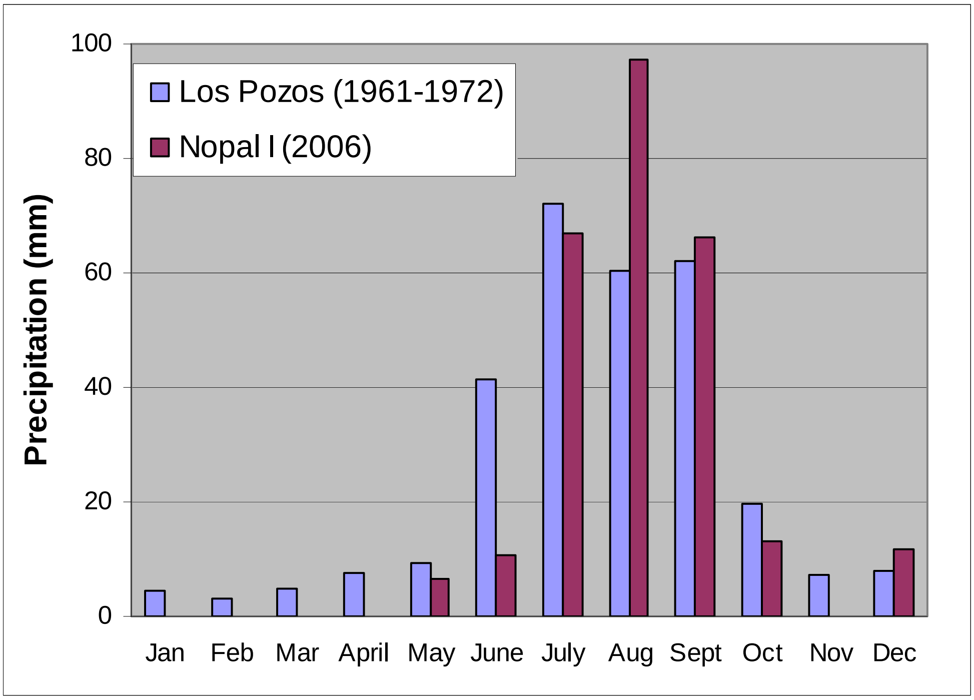
100
80
60
40
20
0
Precipitation (mm)
Los Pozos (1961-1972)
Nopal I (2006)
Jan
Feb
Mar
April
May
June
July
Aug
Sept
Oct
Nov
Dec

Figure 7.

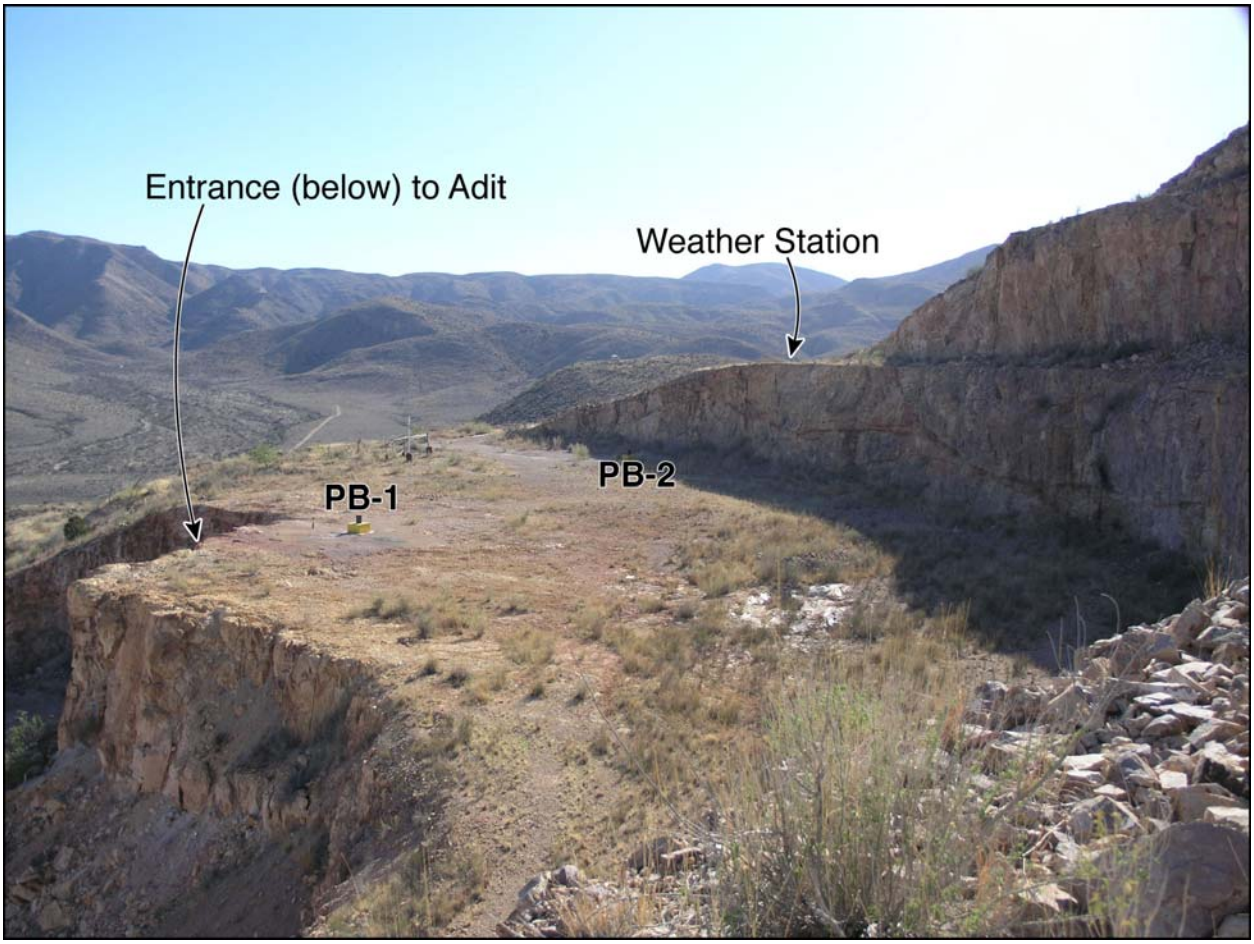

Figure 8.

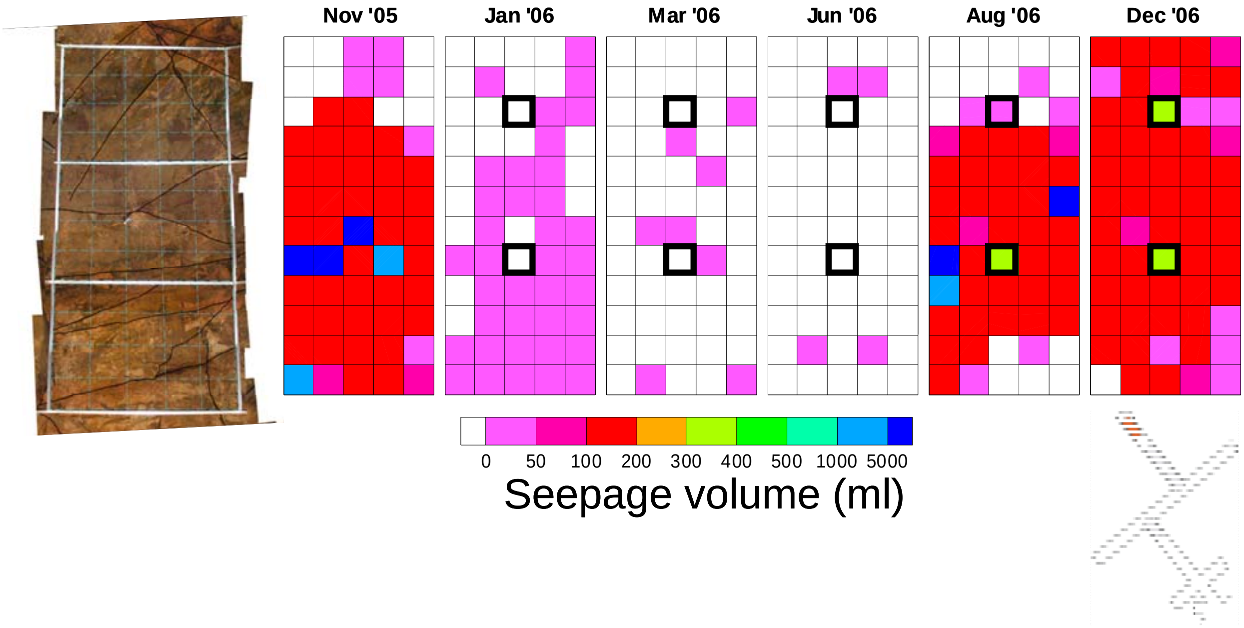

Figure 9.

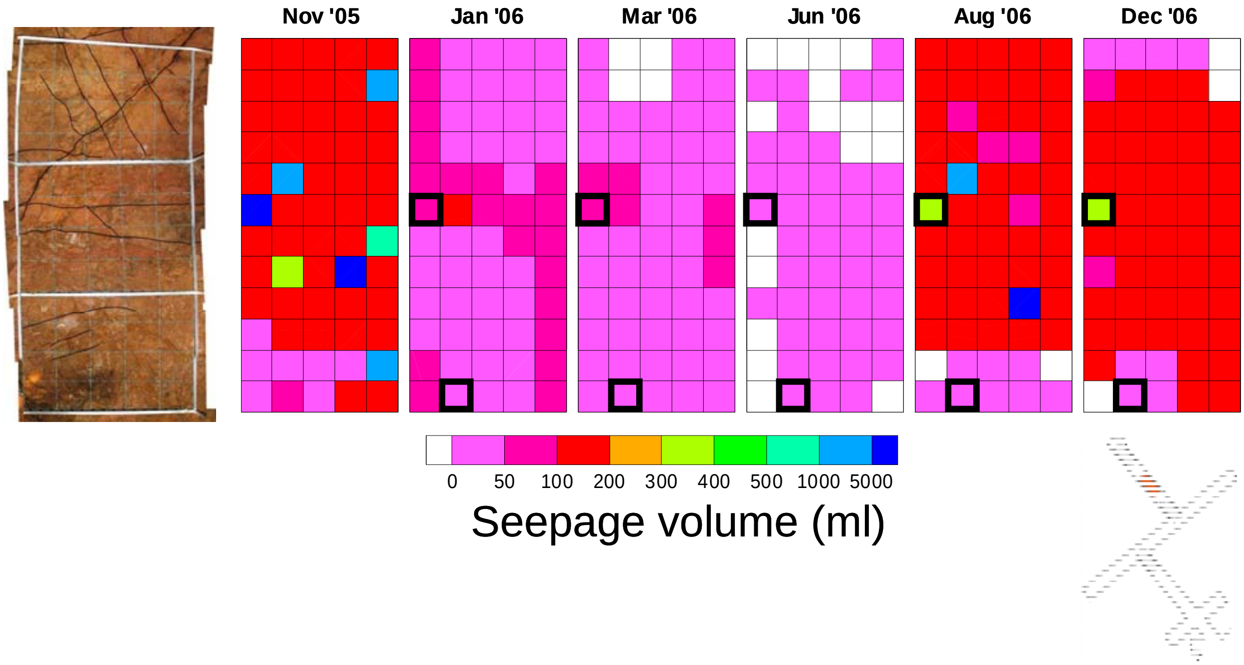

Figure 10.

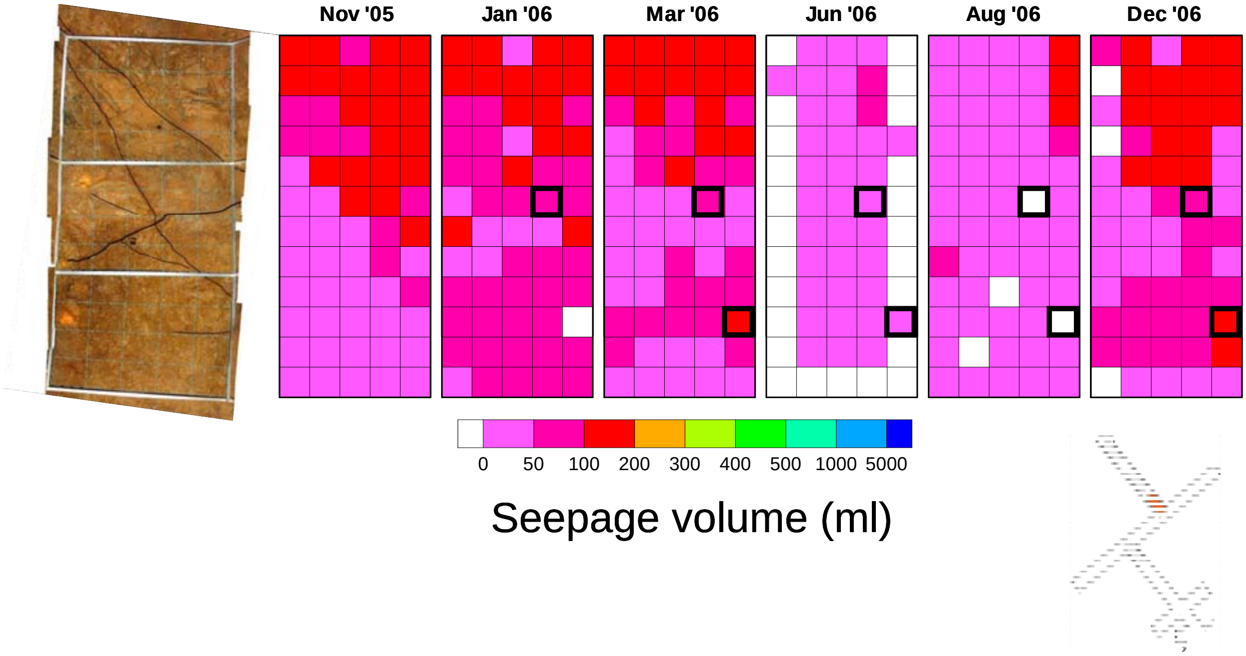

Figure 11.

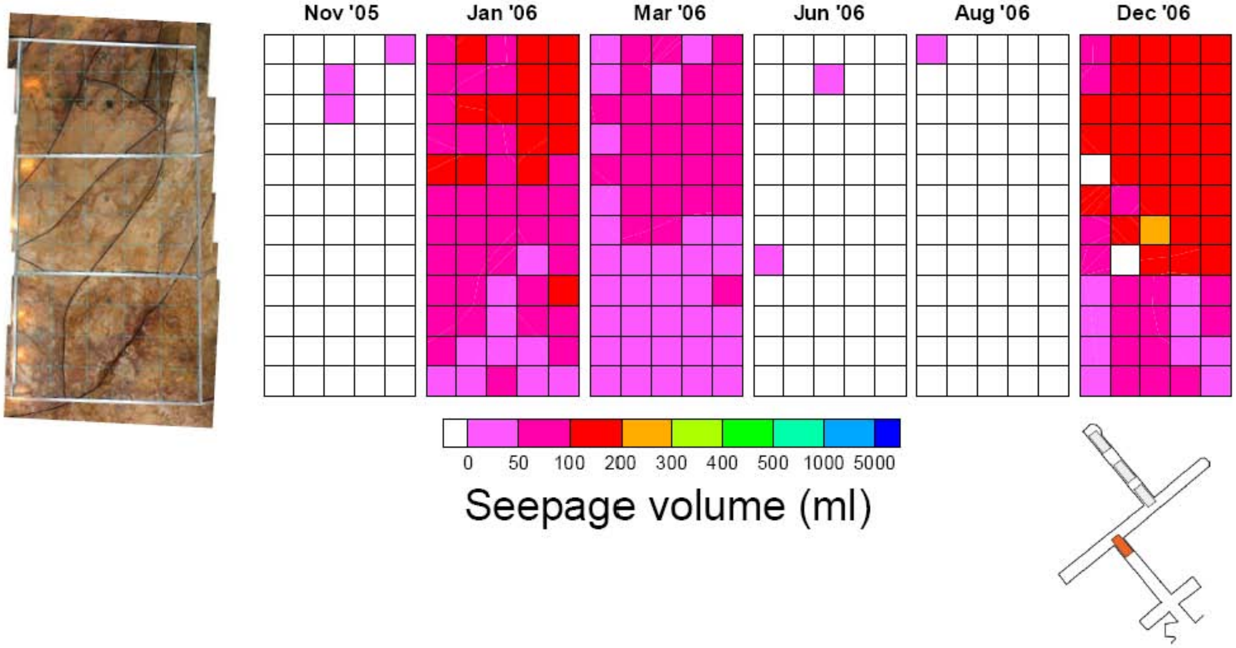

Figure 12.

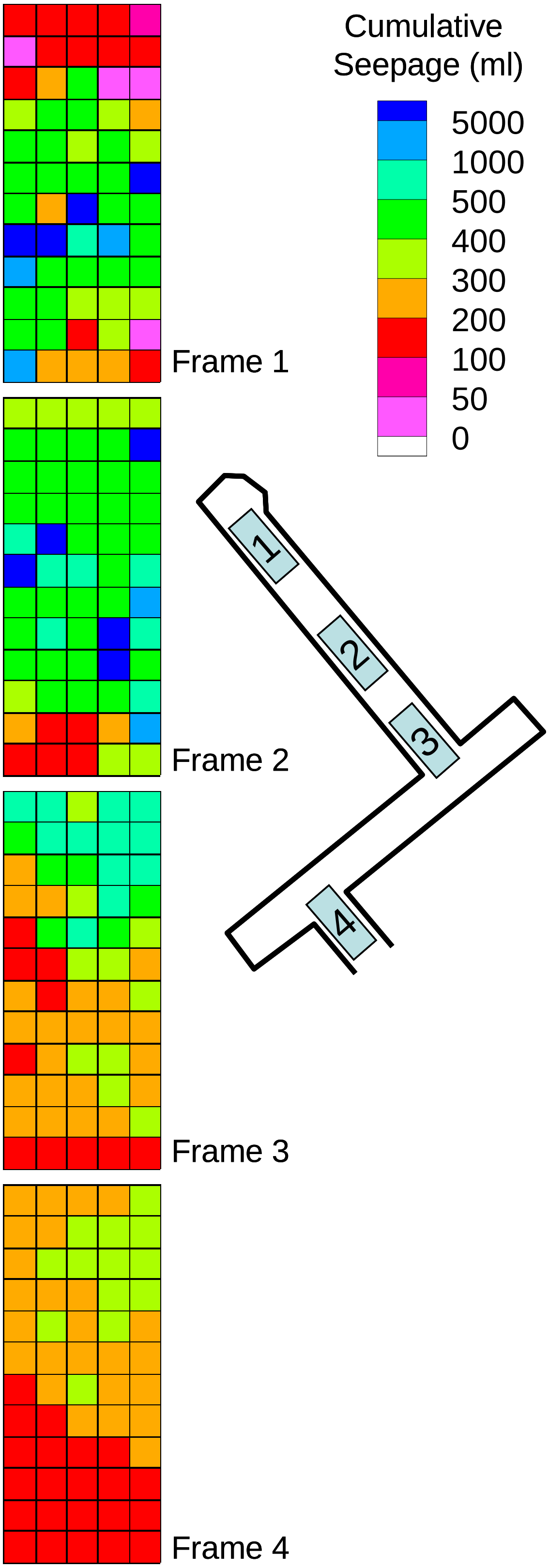
Cumulative Seepage (ml)
5000
1000
500
400
300
200
100
50
0
Frame 1
Frame 2
Frame 3
Frame 4
1
2
3
4

Figure 13.

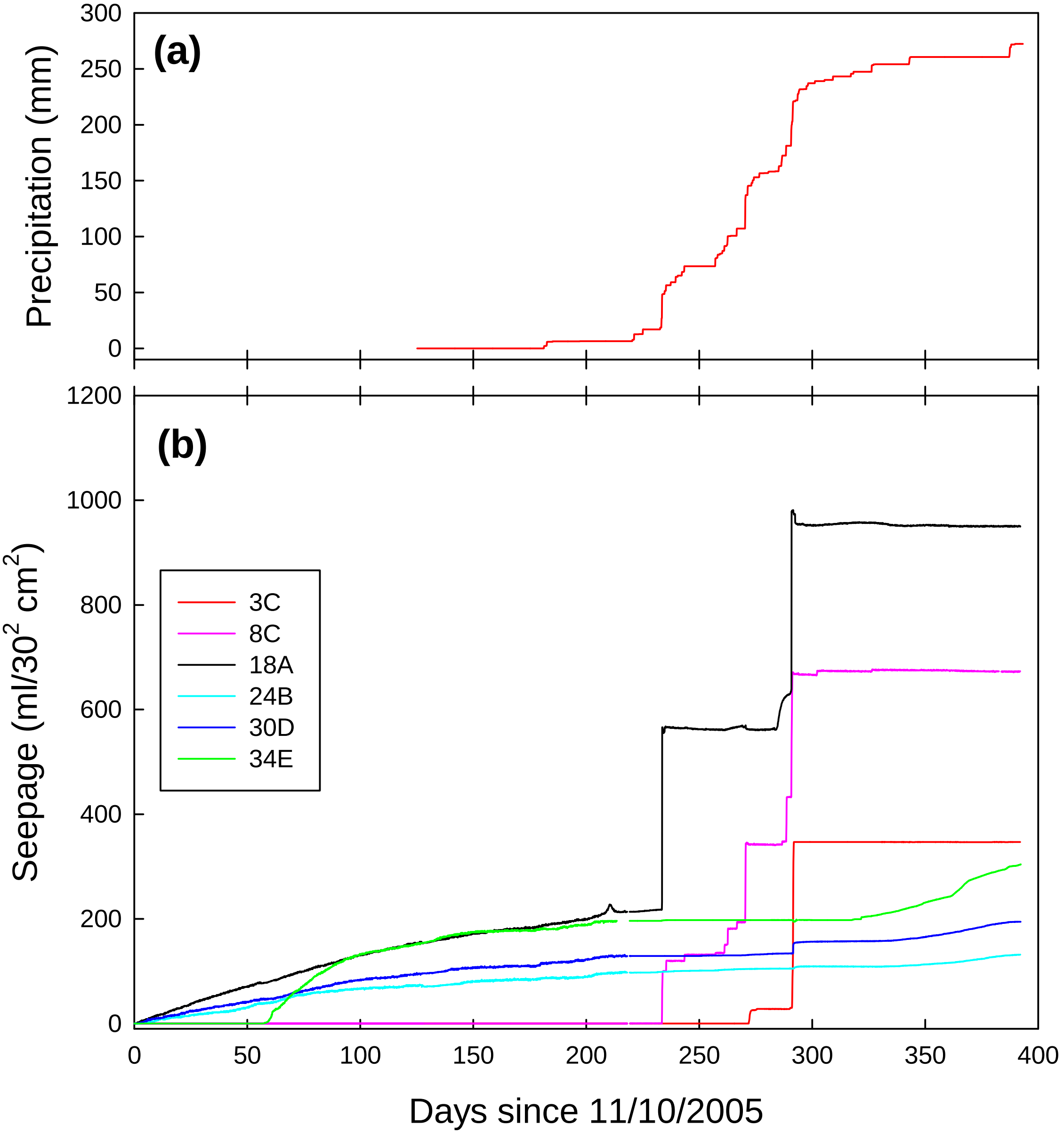
(a)
Precipitation (mm)
300
250
200
150
100
50
0
(b)
Seepage (ml/30^2 cm^2)
1200
1000
800
600
400
200
0
3C
8C
18A
24B
30D
34E
0
50
100
150
200
250
300
350
400
Days since 11/10/2005

Figure 14.

Figure 15.

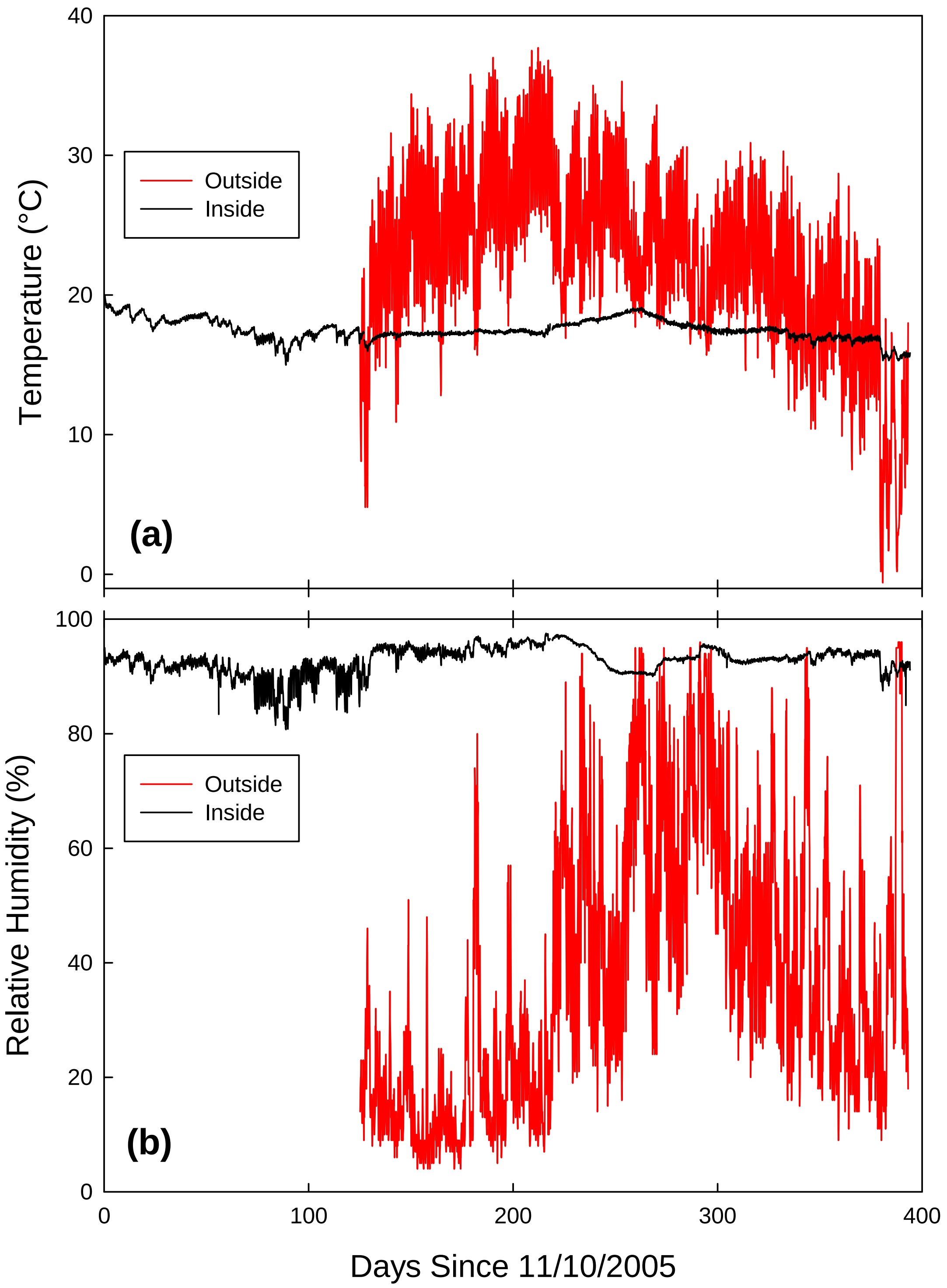
40
30
20
10
0
Temperature (°C)
Outside
Inside
(a)
100
80
60
40
20
0
Relative Humidity (%)
Outside
Inside
(b)
0
100
200
300
400
Days Since 11/10/2005

Figure 16.

Figure 17.

Figure 18.