NATURAL ANALOGUES – ONE WAY TO HELP BUILD PUBLIC CONFIDENCE IN THE PREDICTED PERFORMANCE OF A MINED GEOLOGIC REPOSITORY FOR NUCLEAR WASTE

John S. Stuckless, U.S. Geological Survey, MS 421, Denver Federal Ctr., Denver, CO 80225

ABSTRACT

The general public needs to have a way to judge the predicted long-term performance of the potential high-level nuclear waste repository at Yucca Mountain. The applicability and reliability of mathematical models used to make this prediction are neither easily understood nor accepted by the public. Natural analogues can provide the average person with a tool to assess the predicted performance and other scientific conclusions. For example, hydrologists with the Yucca Mountain Project have predicted that most of the water moving through the unsaturated zone at Yucca Mountain, Nevada will move through the host rock and around tunnels. Thus, seepage into tunnels is predicted to be a small percentage of available infiltration. This hypothesis can be tested experimentally and with some quantitative analogues. It can also be tested qualitatively using a variety of analogues such as (1) well-preserved Paleolithic to Neolithic paintings in caves and rock shelters, (2) biological remains preserved in caves and rock shelters, and (3) artifacts and paintings preserved in man-made underground openings. These examples can be found in materials that are generally available to the non-scientific public and can demonstrate the surprising degree of preservation of fragile and easily destroyed materials for very long periods of time within the unsaturated zone.

INTRODUCTION

The safe disposal of high-level radioactive waste is one of the more serious problems facing developed nations today. Many of the world's scientific and political communities have concluded that a mined geologic repository will provide the best solution for safe and effective waste disposal (1, 2, 3, and 4). Unfortunately, demonstrating to a skeptical public that the waste will not adversely affect them or later generations has become one of the most difficult aspects of the disposal problem. Mathematical models have been developed that simulate the performance of a repository under a spectrum of anticipated future conditions (for example, 5), but direct testing is not possible. This dilemma is compounded by the great length of time during which a repository must safely isolate waste from the environment (10,000 years is specified by the Nuclear Regulatory Commission in their rule 10CFR63 and by the Environmental Protection Agency in their rule 40CFR197; both rules are applicable to Yucca Mountain). This time span is greater than that of all human recorded history. Natural analogues taken from the geologic or archaeologic record can be used to address the time aspect and for qualitatively predicting future performance of a repository. Archaeologic analogues have an additional advantage in that they are generally more comprehensible to the public (6) than some of then more purely geologic ones. Conversely, geologic examples may provide more quantitative data.

There are no analogues that are exactly like a mined geologic repository, which means that there are no analogues to the total system performance of a repository. However, there is an abundance of examples for various aspects of a repository. Perhaps the most important aspects are within the field of hydrology, which is fortunate because water will be the principal transport medium for nuclear waste from a potential repository to the accessible environment. Analogues available for studying the long-term behavior of water in underground openings include caves, ancient tombs, and tunnels that have been open for centuries to tens of millennia.

Analogues must be chosen with care and properly explained to the audience. For example, in an arid climate like that of Egypt, a tomb carved into limestone may not seem to the public like an appropriate analogue to a repository excavated into volcanic rock in a semi-arid environment. However, in both cases, most of the water flow is through fractures in the rock, and in both climates, the influx of water is mainly during large precipitation events, although they are less frequent in the arid climate.

This paper will provide an example of the use of analogues by examining the theoretical prediction (7) that most water moving through the unsaturated zone (UZ) at Yucca Mountain, Nevada should move around tunnels. The analogues chosen to test this theory will utilize reference materials and examples that are generally available to the non-scientific public. For purposes of this paper, the term infiltration will be used for precipitation that is not lost by runoff, evaporation or transpiration, and seepage is used for that portion of the infiltration within the UZ that enters tunnels or other underground openings.

GEOLOGIC EXAMPLES

The physical properties of water lead to the prediction that much of the infiltrating water in the UZ will be preferentially diverted around openings such as tunnels at the potential repository at Yucca Mountain. The percentage of infiltration that can become seepage decreases as infiltration decreases, and at low infiltration rates (<5 mm/yr) and most permeabilities, no seepage occurs (8, p. 4-92). Two natural analogue studies confirm the prediction that most infiltration does not becomes seepage.

In a two-year study at Kartchner Caverns, Arizona, yearly precipitation ranged from 288 mm to 607 mm. The average (448 mm/yr) is similar to the long-term average precipitation at two near-by stations (9, p. 108-109) and is thus probably representative of long-term conditions. Estimates of seepage into the cave by three methods ranged from 4.3 mm/yr to 12.4 mm/yr, with an average of 7.9 mm/yr (9, p. 110). Thus, less than 2% of the available moisture became seepage. This low seepage rate occurs even though the cave is cut by more than 60 mapped faults in a block of ground that is only about 5500 by 350 m (10, p. 49 and fig. 3).

The cave at Altamira, Spain was monitored for 22 months by (11). The volume of water flowing from 9 of 14 "significant drips" was measured and an average total seepage of 7 liters/mo. was reported. This volume was estimated to represent about 80 percent of the total seepage (12), which would bring the seepage rate up to almost 9 liters/mo. (11) also measured the average rainfall and reported an average of approximately 0.095 liters/mo (1140 mm/yr). The average evapotranspiration was calculated as approximately 0.055 liters/mo., which results in an average net infiltration of about 0.040 liters/mo. The area of the painted cave studied was reported as 150 m^2 , which would result in a monthly volume of infiltration water of about 6,000 liters/mo. As was the case at Kartchner Cavern, the rock is obviously fractured (fig. 1). Nonetheless, less than 1 percent of the infiltrating water seeped into the cave. The fact that the paintings have not been bleached or dissolved near the fractures suggests that little water has seeped in along fractures during the last 14,000 yrs, which is the age of the paintings (13).

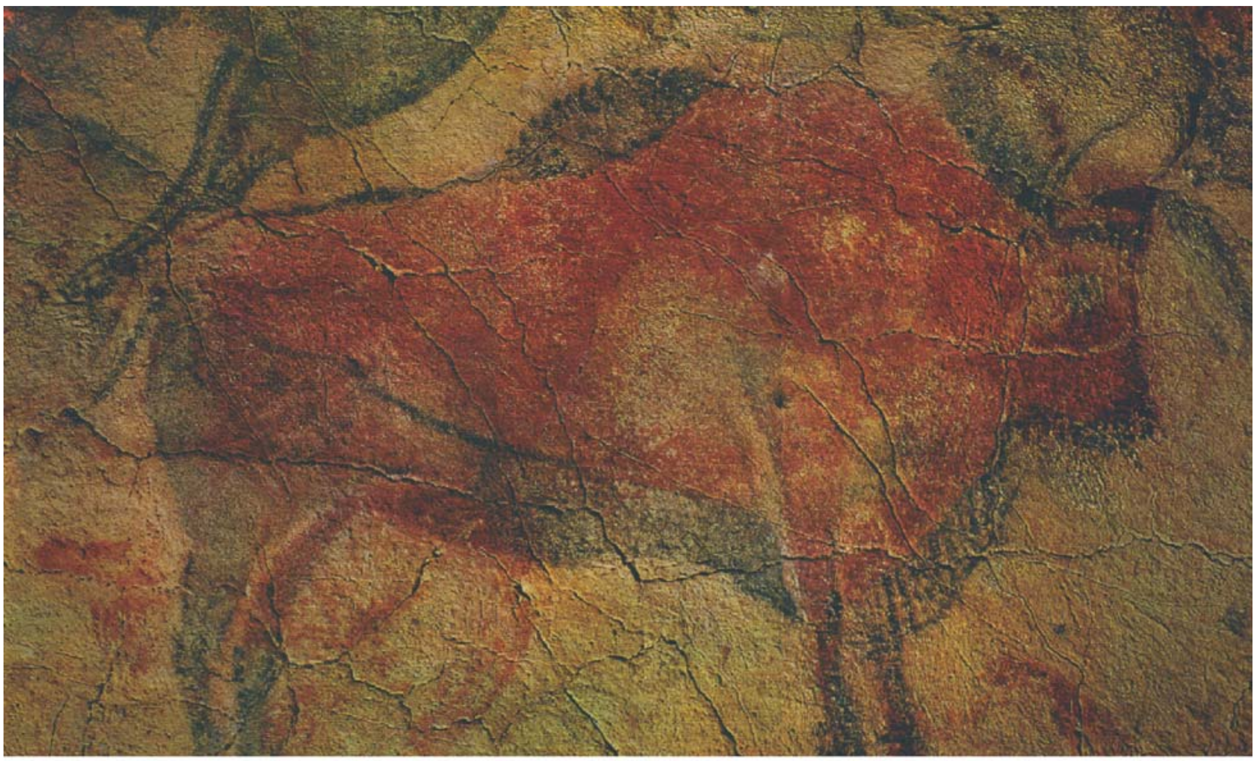

Figure 1. Painted bison from the ceiling of the cave at Altamira, Spain. Note that there is no apparent water damage near fractures through both the iron oxide and charcoal portions of the 14,000-year-old painting.

Both of these examples are from limestone caves, and thus, UZ flow would be dominated by fracture flow, just as it is at Yucca Mountain. Both caves are much closer to the surface than a potential repository at Yucca Mountain, and therefore, there is a much greater probability for fractures to communicate directly between the underground opening and the surface, thereby facilitating seepage. In both cases, precipitation exceeds current and predicted future precipitation at Yucca Mountain (125 mm/yr and 266 to 321 mm/yr respectively (14, p. 6.4-10)). Thus, the data measured and observed from natural analogues support the conclusion that seepage into a potential repository at Yucca Mountain will be very small.

ARCHAEOLOGICAL EXAMPLES

Long-term hydrologic studies such as those cited above are not common, but the preservation of abundant fragile and easily destroyed items is qualitative evidence that openings in the UZ divert much infiltration, thereby providing protection. The examples that follow are from both natural and man-made underground openings and include preservation of both anthropogenic and biological materials. The examples chosen are representative and are not meant to constitute an exhaustive listing.

The oldest, and perhaps the best known of the examples of preservation of anthropogenic items within the UZ, are the Paleolithic cave paintings of southwestern Europe. There are dozens of caves with paintings (c.f. 15, fig. 1); the oldest authenticated of these is the recently discovered cave of Chauvet, France (fig. 2). The cave is located in a subhumid region with reported precipitation totals within the region ranging from 580 to 780 mm/yr. The cave paintings depict animals that are now extinct, such as mammoths, and other species that no longer live in Europe, such as rhinoceroses (16), which attest to a much different paleoclimate. The paintings in the French caves were made mostly with oxides of iron and other minor constituents (17, 18). Charcoal was commonly used for black. Neither the iron oxides nor charcoal would be expected to survive long in the presence of abundant oxidizing water. This is evidenced by a block that fell from a painting of a bull at Lascaux, France, and lay painted side down on the damp floor. Although the block fit back into the painting, it had lost all evidence of paint (19, p. 286).

Well preserved Paleolithic art is common only in the caves of southern Europe, but examples of late Paleolithic, and more commonly, Neolithic art are known throughout the world. Stuckless (15) provides a summary and references for paintings in Africa, South America, North America, and Asia. In most of the world, painted rock shelters are more common than painted caves, which demonstrates that even a few meters of overhang can protect fragile items from infiltrating water. Stuckless (15) discusses these occurrences and includes references.

Figure 2. 32,000-year-old painted auroches and horses from Chauvet Cave, France. Note that although there is evidence of water flow down the wall, most of the painting is well preserved. (From 15, used with permission of the French Ministry of Antiquity).

In addition to paintings, caves have preserved fragile artifacts such as the 14,000-year-old clay bison in a cave near Tuc d'Audoubert, France (15). Some caves are located in zones of such low percolation flux that they have little, if any, measurable seepage flux. One cave in Israel provides such an example. Here cloth, ivory, reed mats, and many bronze items have been preserved in a nearly perfect state (20, 21). These artifacts date from about 3,800 B.C., and although the climate is currently drier than that at Yucca Mountain, the preservation demonstrates that the lack of water allows even easily destroyed items to endure for long periods of time. The preservation further suggests that the predicted zero seepage at low infiltration rates is likely correct.

Relatively dry caves are common throughout the southwestern United States. Because of the dryness, pollen and other delicate plant and animal material have been preserved for tens of thousands to hundreds of thousands of years (22, 23). In fact, Davis (22, p. 338) notes that dryness in caves is critical to preservation of biotic remains. That such preservation is common is supported by the fact that over 1,000 packrat middens have been studied throughout the semi-arid to arid North America (22, p. 341), and some are older than 40,000 yrs. The middens are cemented with dried urine, which would dissolve readily in water. Nonetheless, the middens older than about 20,000 yrs (and some of these were found near Yucca Mountain) have survived much wetter past climates such as those predicted for the future climate at Yucca Mountain.

Underground openings in the UZ have been excavated by early civilizations, but these examples are generally much younger than those from the natural system. Nevertheless, they also provide evidence of the robust protection provided against the effects of water. In addition, these anthropogenic examples broaden the range of geologic settings that can be examined as analogues for a potential repository at Yucca Mountain.

Man-made underground openings include the Egyptian tombs across the Nile River from Luxor. These were excavated in limestone approximately 3,500 to 3,000 years ago. As noted earlier, this host rock is hydrologically similar to the welded tuffs of Yucca Mountain. Although the climate is somewhat dryer than that at Yucca Mountain, precipitation events have been strong enough at times to cause mud flows within the Valley of the Kings (24). Seepage into the tombs is indicated by small areas of spallation of plaster, which can be seen in many tombs for both areas of wall and ceilings (fig. 3), but evidence of dripping, such as efflorescence or stalactitic formations seems to be lacking.

Buddhist monks carved several temples into basalt flows at Ajanta, India between the second century B.C. and the sixth century A.D. Water flow within the basalts would again be dominated by fracture flow. The interiors of the temples are painted. The paintings were done on a plaster that consisted of mud, rock dust, and vegetable fiber (25). The climate at Ajanta is monsoonal such that the precipitation, which is more than five times that at Yucca Mountain, falls in four months (15). Nonetheless, most of the paintings are well preserved, except for small areas of spalling (fig. 4).

The Christians of Cappadocia, Turkey, excavated underground cities and churches during the second through eleventh centuries A.D. The geology here is similar to that of southern Nevada in that the bedrock is a thick sequence of silicic volcanic rocks. Visits to the underground cities and churches detected no evidence of dripping from the ceiling, but a kitchen in the underground monastery at Goreme, evidence for flow down a wall was found where a fracture intersected the wall (15). As with the Egyptian tombs and Buddhist temples, some of the church painting showed evidence of spalling and vandalism (fig. 5).

Figure 3. The painted interior of the tomb of Sennefer shows no evidence of dripping from the ceiling, but plaster on the wall has been damaged by moisture, and some of the paint shows evidence of water flow down the wall. The tomb was excavated in limestone about 1,400 B.C.

Figure 4. This painting from the underground Ajanta temple in India is fairly well preserved in spite of its age and the wet climate. The hexagonal column is from the second century B.C. (25).

Figure 5. Frescos on the ceiling and walls of the Karanlik church at Goreme, Turkey show varying degrees of preservation, but no evidence of dripping from the ceiling. The perfectly preserved painting on the left was painted in the eleventh century A.D. The painting on the right shows damage from vandals and from spalling of the plaster (from 15).

The caves at Carlsbad Caverns, New Mexico, have stood open for as much as 11 million years (26). During that time, seepage occurred as evidenced by stalactites, stalagmites, and flowstone. Today, only a small percentage of the seeps are active in spite of an average precipitation of approximately 40 cm/yr. This is nearly three times the amount currently observed at Yucca Mountain and larger that that predicted for likely future climates.

In addition to showing that most infiltration does not become seepage, natural analogues demonstrate that much of the seepage that does occur stays on the walls rather than dripping into the opening. Figures 2 and 3 both show evidence of water flow down walls. Figure 6 shows the soot-covered wall and ceiling of a monastery kitchen excavated in the ash-flow tuffs of Goreme, Turkey. The soot deposited along the fracture in the ceiling has been removed, presumably because of infiltrating oxygenated water. Stalactitic deposits that might indicate dripping water do not exist, but the removal of soot below the fracture on the wall must be due to some flow of water down the wall.

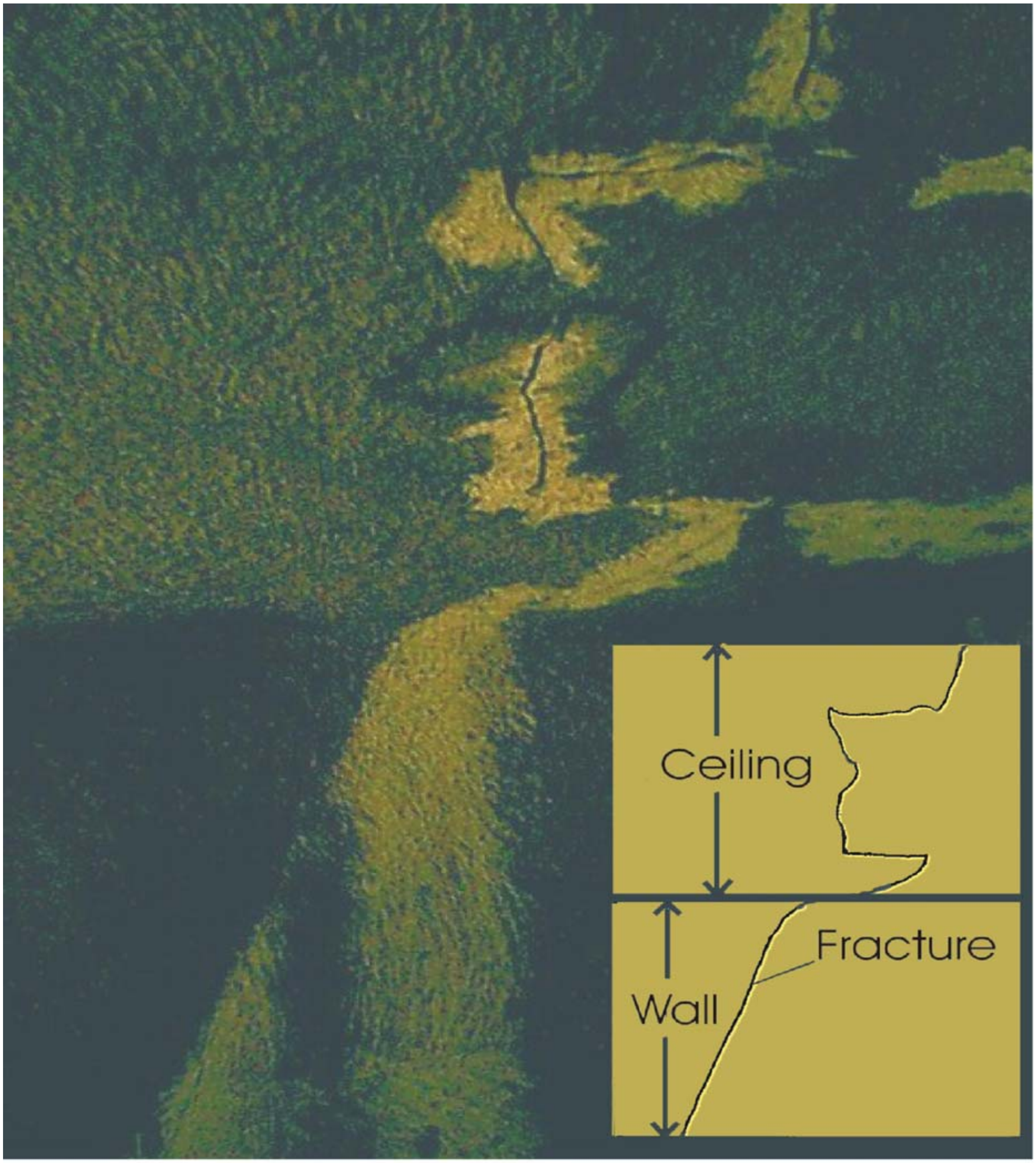

Figure 6. Photograph and drawing of a fracture in the soot-covered wall and ceiling of a kitchen in a subterranean monastery at Goreme, Turkey. The kitchen was excavated into ash-flow tuff and was probably in use until the twelfth century A.D. The soot has been removed adjacent to the fracture in the ceiling, possibly by oxidation. Flow has occurred down the wall as evidenced by removal of some of the soot below the fracture (from 15).

Perhaps the best analogue for water that might seep into the tunnels at Yucca Mountain can be seen at Building 810 on the Denver Federal Center, Colorado (Figure 7). The roof of this building is constructed of a series of arches called barrels. Each represents a segment of a cylinder with a diameter of 7.6 m, which is the same diameter as the Exploratory Studies Facility at Yucca Mountain. As shown by the white efflorescent salt deposits, water has seeped through the roof over the loading dock along fractures in the concrete and then flowed on the underside of the roof until it either evaporates or reaches the vertical sections along the sides of the barrels, where it can drip. The under surface shown in figure 7 is smoother than much of the tunnels would be at Yucca Mountain, and thus it may be more effective in diverting seepage to the walls. Nonetheless, it demonstrates a process affecting flow into the tunnels.


Figure 7. Photograph of building 810 on the Denver Federal Center, Colorado and a close-up of the underside of the roof over the loading dock. Note that water has seeped through along fractures in the concrete, but that rather than dripping, it has flowed along the curvature of the roof.

EVALUATING THE ANALOGUES

Although there are many examples of Paleolithic and Neolithic art preserved in caves, questions persist of whether or not an equal or perhaps even larger number of paintings have been completely destroyed by seepage. Null evidence is difficult to evaluate, but a few lines of evidence suggest that paintings have not been totally destroyed in caves where they once may have existed.
First, paintings are commonly on top of carvings into the rock. At Cosquer, France, some etchings exist below high-water mark, but paint and charcoal are gone (27). Reports of similar etchings without paint in caves seem to be lacking. However, some petroglyphs in rock shelters, such as the Coa valley of Portugal, originally may have been painted etchings.

Second, if some caves, or even parts of caves, had their paintings completely destroyed, one would expect most, if not all localities, to exhibit either a spectrum of preservation from largely destroyed to fully preserved paintings. Alternatively, there should be an explanation for the bimodal distribution. A variety in the degrees of preservation of cave art was not found in the current literature search, either within individual caves or in the body of literature as a whole. There is a cave at Palomera in Burgos, Spain, which, like the cave at Cosquer, has had some paintings removed by water while leaving others in good condition. The cave, which has paintings dated at 10,950 +/- 100 to 11,540 +/- 100 B.P. (28) has had a stream flowing in it at times, which has left organic debris plastered to heights of several meters on the walls. The flooding is younger than the paintings and has apparently destroyed the paintings to the height of the flooding. Lascaux provides another example where one gallery has had over 90% of the paintings removed by wind abrasion (19, p. 286).

Third, areas where paintings would be least likely to survive, such as drip sites in the ceiling or flow channels on the walls of caves, have probably been the loci of flow for thousands of years. These areas would likely have been avoided by early man because they were too wet to paint. Exceptions to this hypothesis are known. For example, one painting on the ceiling at Chauvet is partly covered by stalactitic calcite (16, p. 47). Some paintings have thin coatings of calcite caused by evaporation of thin films of water.

Finally, the shear number of painted caves and the number of paintings in some of the caves argues for a high degree of preservation. In France and Spain alone, there are more than 150 painted caves (18, p. 18), several more have been discovered in the last 10 years. Grand (29, p. 28) examined over 2,188 paintings of animals in 110 caves; Lascaux alone has 597 animals (18, P. 164).

In the case of rock shelters, there are some observational data that correlate with preservation or destruction. In some cases, the roots of banyan trees have been noted to provide a preferential path for water across a painting. The part of the painting exposed to water has been destroyed, "while leaving another part of the same figure -- untouched by water -- unscathed" (30, p. 6). Note that many of these paintings are in areas that receive 100 to 150 cm/yr of rain.

Not all underground openings provide appropriate analogues. The Mission Tunnel through the Santa Ynez Mountains near Santa Barbara, California is closer in depth to the potential mined geologic repository at Yucca Mountain (200 to 670 m versus 300 m), and it exhibits rapid response to precipitation events and large amounts of seepage flux (1.23 million m^3/yr). Unfortunately, quantitative measurements have not been made, such that the percentage of infiltration that becomes seepage is unknown. However, the large amount of seepage into the Mission Tunnel apparently is due to flow paths that are within near-vertical, highly transmissive fractured sandstone units (31). Thus, the hydrogeology for this potential analogue is drastically different from that for the potential repository at Yucca Mountain, where the hydrologic units are gently dipping and few through-going fractures have a hydrologic connection with the surface.

OTHER CONSIDERATIONS

One important variable for preservation in underground openings is relative humidity. The Yucca Mountain Project has noted that "if relative humidity in the drift is kept below 100 percent by ventilation, then seepage of liquid water is reduced or completely suppressed" (32, p. 4-6). Most caves are close to, but below 100 percent humidity (e.g. Kartchner RH=99.4 % (9, p. 111), Chauvet RH=99% (33, p. 1835), Lascaux RH= 98 +/- 2% (19, 1987), and Altamira RH 96 to 99% (34, p. 555)). Thus the amount of seepage would be expected to be low.

CONCLUSIONS

The example of using natural analogues provided here is intended to help the public understand a sophisticated concept in UZ flow by providing analogues that can be easily understood and verified. In addition, the example anticipates questions of null evidence, of contradictory, but poor analogues, and of variable analogue arguments for that may be different in the natural analogues and a potential repository. The development of analogue arguments for other subsystems or processes of a potential repository could be very beneficial in augmenting public understanding and acceptance of the safety in a mined geologic repository for high-level nuclear waste.

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