Archaeological Analogues for Assessing the Long-Term Performance of a Mined Geologic Repository for High-Level Radioactive Waste

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
gram	0.03527	ounce, avoirdupois
kilometer (km)	0.6214	mile
liter (L)	0.2642	gallon
meter (m)	2.281	foot
millimeter (mm)	0.0394	inch

Temperature in degree Celsius (°C) can be converted to degree Fahrenheit (°F) as follows:

$$°F = 1.8\ (°C) + 32$$

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Abstract

A mined geologic repository must isolate radioactive waste from the environment for a minimum of 10,000 years; however, the interaction of water with the waste may pose the greatest hazard to that objective. Mathematical models for Yucca Mountain in southern Nevada predict that, under conditions of low to moderate infiltration flux, most of the water passing through the unsaturated zone at the level of a potential repository would be diverted around the storage tunnels that would contain radioactive waste. Evidence collected from natural analogues, including Paleolithic to Neolithic paintings in caves and rock shelters, biological remains preserved in caves and rock shelters, and artifacts and paintings preserved in manmade underground openings, strongly supports these models and shows that flow around openings in the unsaturated zone is both a long-term feature and one that can be observed in a variety of climates and for a variety of geologic media. Analogue information also shows that fragile and easily destroyed items are better preserved when open to circulating air than when buried within the unsaturated zone, which suggests that backfilling a mined geologic repository in the unsaturated zone may not enhance its performance.

INTRODUCTION

The safe disposal of high-level radioactive waste is one of the more serious problems facing developed nations today. There has been a general consensus that a mined geologic repository will provide the best solution (National Academy of Sciences National Research Council, 1957, 1978; Witherspoon, 1996). However, demonstrating that the waste will not adversely affect later generations is 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, U.S. Department of Energy, 1998), but direct testing is not possible. The 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, U.S. Department of Energy, 1993, and in their proposed rule, U.S. Department of Energy, 1999), a time span that is greater than all of recorded history. Natural analogues taken from the geologic record can be used to address the time aspect for predicting future performance. An additional advantage of using analogues from the archaeologic record is that these analogues are generally more comprehensible to the public than are mathematical models (Winograd, 1986). In other words, the long-term performance of a natural analogue can be qualitatively compared to the performance of a mined geologic repository predicted by a model such as Total System Performance Assessment (U.S. Department of Energy, 1998).

There are no analogues that are exactly like a mined geologic repository. No one buried high-level radioactive wastes thousands of years ago and in the exact same geologic setting for which predictions are being made, but there is an abundance of examples for various aspects of a repository. Perhaps the most important aspects are within the field of hydrology because water would 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 tunnels include caves and ancient underground workings that have been open for centuries to tens of millennia. This paper describes several of these examples and examines the factors that appear to account for the long-term preservation of natural and archaeological materials present in these environments.

BACKGROUND

Yucca Mountain in southern Nevada is currently being studied as a potential site for a mined geologic repository for high-level radioactive waste. Several geotechnical aspects of this site can be addressed with the use of natural analogues. Before doing so, a few technical terms and concepts should be described.

Age terms used in this report are approximately: Paleolithic, before 10 thousand years ago; Mesolithic, 10 to 7 thousand years ago; Neolithic, 7 to 4.6 thousand years ago; and Chalcolithic, 4.6 to 2.7 thousand years ago.

Yucca Mountain is composed of a variety of volcanic products, the most common being ash-flow tuffs. These rocks originate as extremely hot ash that is blown out of a large volcano with subsequent outward flow sustained by expanding gases. The gases create a very low internal friction for the ash such that flow can occur down shallow slopes until enough gas has escaped for the flow to come to rest. At that time, most of the ash is in the form of minute fragments of glass, and, where that glass is hot enough, the pressure of overlying ash causes the fragments to deform and to weld together until nearly all voids and air bubbles are gone. The resulting rock is called a welded tuff. Where there is insufficient heat or pressure to weld the ash, the resulting rock is called a nonwelded tuff. Such a rock may contain as much as 40 percent voids or pore spaces. Welded tuffs are extremely hard and brittle, and they fracture readily in response to geologic stresses. The differences between the two types of tuff cause them to affect the flow of ground water in different ways: water moves through welded tuff mainly along fractures (fracture flow) and through nonwelded tuff mainly through connected pore spaces (matrix flow).

Yucca Mountain differs from sites being considered by other countries for the disposal of high-level radioactive waste (for example, Witherspoon, 1996) in that the potential repository would be above the water table in what is called the unsaturated zone. In this zone, not all voids are filled with water. Wells in the unsaturated zone cannot produce water, and therefore, the movement of water in this zone has historically received much less study than water in the saturated zone. Direct observation of water movement in the unsaturated zone is hampered by apparent slow rates of movement and the need for long-term observation. Thus, natural analogues for ground-water flow at Yucca Mountain provide a means to examine long-term flow in the unsaturated zone for both fracture and matrix flow.

Recent work at Yucca Mountain (Wang and others, 1999) and theoretical studies (Birkholzer and others, 1999) have suggested that most water moving through the unsaturated zone should move around tunnels driven into the ash-flow tuffs. Mangin and Andrieux (1984) also concluded from field observations that much water preferentially flowed around caves. Of the water that seeped into caves, most flowed down the walls or dripped from specific points in the ceiling such as asperities along fractures. The caves examined by Mangin and Andrieux (1984) are in limestone, which is hydrologically similar to welded tuff in that water moves through both rock types principally by flow along fractures. If most water moving through the unsaturated zone does not drip into underground openings, there should be abundant evidence in the geologic and archaeologic records that could provide excellent long-term analogues to a potential mined geologic repository for radioactive waste.

HYDROLOGIC ANALOGUES IN THE NATURAL SYSTEM

Abundant qualitative information is available about the preservation of materials both in natural and manmade openings in the unsaturated zone. The following examples are rarely defined in the literature cited as being from the unsaturated zone, but the fact that they are not flooded or being actively dewatered demonstrates that they are within that hydrologic zone. The examples chosen do not constitute an exhaustive listing but rather are representative and are largely from sources that are readily available to nonspecialists in the scientific disciplines.

Caves provide an excellent analogue to a mined geologic repository for the flow of water in the unsaturated zone. Water flow around caves and tunnels depends in part on the size of the opening (Philip and others, 1989; Philip, 1998). Water is more likely to be diverted around small openings than around large ones, and most caves cited in this study have as large or larger cross-sectional area than that proposed for a mined geologic repository. In addition, both environments are humid. For example, the humidity at Chauvet (southern France) is measured at 99 percent (Balter, 1999).

Perhaps the best known of the older examples of preservation within the unsaturated zone are the Paleolithic cave paintings of southern Europe (fig. 1). The oldest authenticated of these is the recently discovered Chauvet. The cave is located in a subhumid region where reported annual precipitation totals within the region range from 58 to 78 cm (centimeters). The cave contains paintings of animals that are extinct, such as mammoths, and other species that no longer live in Europe, such as rhinoceroses (Chauvet and others, 1996). The paintings in the French caves were largely made with oxides of iron and minor amounts of manganese and small amounts of clay and silica (Leroi-Gourhan, 1984; Ruspoli, 1986). Charcoal was

Figure 1. Locations of prehistoric art work in France and Spain.

commonly used for black. None of these materials would be expected to survive long in the presence of abundant water.

The charcoal in Chauvet (fig. 1) has been dated by the ^{14}C method as 32,410 to 32,340 B.P. (before present)[1] with errors of approximately ±600 years. Because this method determines the age of the charcoal, including carbon removed from the atmosphere while the plant was alive, there has been some controversy about the possibility that the paintings were created recently using old charcoal. To address this possibility, Chauvet and others (1996) also collected soot deposited on the ceiling of the cave by the oil lamps used for illumination by prehistoric humans. The samples of soot yielded ages of 26,980 (two samples) and 26,120 B.P. with errors of approximately ±400 years. (The fact that even soot can be preserved on the roof of a cave for nearly 30,000 years is testament to the protection afforded by openings within the unsaturated zone.) The dated soot, together with the pictures of animals no longer indigenous to the area, demonstrates the antiquity of the artwork.

Chauvet cave also provides evidence of water flow down the walls of the caves. Some of the paintings show deterioration where water has flowed across them (fig. 2). Water also has been observed directly in contact with paintings. Breisch (1987) reported that during wet years in some caves, water oozes out of the wall and coats the paints with a film of water. In these instances, there does not appear to have been sufficient flow to remove the paintings, but evaporation of this water could have deposited thin (4-mm-thick) layers of calcite ($CaCO_3$) over some paintings, as has been observed at Chauvet (Balter, 1999) and elsewhere.

The cave of Chauvet is more than 100 m long, and the painted areas are generally more than 5 m wide and several meters high. Thus, the opening is generally larger than that proposed for a potential mined geologic repository at Yucca Mountain, which is proposed to be about 5 m in diameter.

There are more than 100 caves in France with prehistoric art work. At least two others merit some description. The cave of Cosquer (Clottes and Courtin, 1996) appears to be unique in that the entrance is currently 37 m below sea level and thus must have been occupied prior to the current interglacial period (that began approximately 10,000 years ago). The cave is also the first discovered to have two greatly different sets of ages (27,000 and 18,500 B.P.) for its paintings. These dates correspond to approximate sea-level decreases of 131 m and 121 m relative to present-day levels (Fairbanks, 1989). The size of the painted area (approximately 15 m by 30 m) of the cave is again larger than the opening proposed for a mined geologic repository at Yucca Mountain. As at Chauvet, several of the Cosquer paintings have a thin layer of calcite precipitated over them. Unlike Chauvet, paintings in the Cosquer cave have been destroyed up to the high-tide mark, and none exist along the sloping entrance, which is currently under water. A map and cross section, as well as a few paintings, can be examined on the web site for the French Ministry of Culture (http://www.culture.fr/, accessed 02/29/00).

Lascaux (fig. 1), with some 600 paintings, is perhaps the best known of the prehistoric caves in France. It was discovered September 12, 1940, and became a tourist attraction in 1949. The art work can be seen in a book by Ruspoli (1986), which has the most complete photographic record of the cave, or in the October 1988 issue of National Geographic (Rigaud, 1988). In addition, there are several web sites with pictures and other information that can be accessed by searching the name "Lascaux." Like Chauvet and Cosquer, the openings in the Lascaux cave are larger than that proposed for the potential repository at Yucca Mountain. The Great Hall of the Bulls is approximately 8 m by 20 m (Leroi-Gourhan, 1984). No quantitative dates for the paintings of Lascaux were found in the current literature search, but the style of the paintings suggests an age of 13,000 to 17,000 B.P.

Lascaux cave provides an alternate line of evidence that enough water would destroy the paintings. A block has fallen out of one of the paintings on the ceiling and landed on the moist floor of the cave. The block was found on the floor of the cave, and it fits geometrically in the hole in the painting, but all the paint dissolved while the block was on the floor of the cave (Breisch, 1987).

In 1960, a deterioration of the art work was noted, and the Lascaux cave was closed for 3 years. The deterioration was due to patches of green algae, which was introduced by the hundreds of tourists visiting the site and exacerbated by changes in atmo-

[1]By convention, years before present is measured as before 1950 and implies that a correction has been made for the non-uniform rate of production of ^{14}C in the atmosphere as a function of time.

Figure 2. Painted rhinoceroses and horses from Chauvet cave showing evidence of water flow (from Chauvet and others, 1996, used with permission of the French Ministry of Antiquity).

spheric conditions in the cave and by artificial lighting. It is estimated that each visitor expires 40 liters of carbon dioxide per hour and introduces 40 grams of water per hour (Breisch, 1987). The carbon dioxide changes the stability of calcite (the principal mineral in the wall rock of the caves and a potential coating of the paintings). Such chemical changes should not occur in a mined geologic repository, and so the observed deterioration would not be part of the analogy between caves and a potential underground repository.

In addition to paintings on the walls and ceilings of caves, the prehistoric art of France includes a set of three clay sculptures that were found on the floor of Le Tuc d'Audoubert (Ariege region). A photograph of these can be seen in National Geographic (Putman, 1988). Figure 3 shows one of the bison with the only visible damage being cracks. The clay floor of the nearby Niaux cave still preserves the footprints of a prehistoric artist (White, 1986).

All of the cited examples from France are in a subhumid climatic zone with rainfall in excess of 50 cm per year. In contrast, rainfall at Yucca Mountain is approximately 15 cm per year. These climatic conditions have not been constant at either location during the period 15,000 to 30,000 years ago. In both regions the climate was significantly cooler (by 5° to $10^{\circ}C$) during the glacial period, and rainfall at Yucca Mountain may have been twice that of today (Forester and others, 1999).

There are dozens of painted caves in Spain (fig. 1). One of the first to be discovered and one of the best studied is Altamira (Saura, 1998). The cave was discovered in 1875 by Marcelino Sanz de Sautuola. It is located in the province of Santander about 156 m above sea level and 120 m above the Saja River, which is 2 km away. The cave is 270 m long and varies in width from 2 m to 20 m. The ceiling is 2 to 12 m high, and averages approximately 9 m below land surface (Saura, 1998). There are abundant fractures visible in the bedrock, but few drip water, and the paintings that cross the fractures do not appear to be damaged (fig. 4). Also found were shoulder blades of deer engraved with heads of doe. Carbon-14 dating of charcoal from one of the painted bulls yielded an age of 14,000 ±400 B.P. (Valladas and others, 1992).

Villar and others (1985) studied the hydrology of Altamira. They measured the volume of water flowing from 9 of 14 "significant drips" for 22 months and found an average total seepage of 7,000 mm/mo (millimeters per month), which Solana (University of Santander, Spain, written commun., 2000) estimates represented about 80 percent of the total seepage. They also measured the average rainfall and reported an average of approximately 95 mm/mo. The average evapotranspiration was calculated as approximately 55 mm/mo, which results in an average net infiltration of about 40 mm/mo. The area of the painted cave studied was reported as 150 m^2 (square meters), which would result in a monthly volume of infiltration water of more than 6,000 liters. The material overlying the study area was reported as approximately 7 m of interbedded limestone and mudstone; figure 4 shows that the rock is obviously fractured. Nonetheless, less than 1 percent of the infiltrating water seeped into the cave.

The study of Palomera cave in Burgos, Spain (fig. 1), is used as a final example of preservation in a Paleolithic cave in southern Europe. The painted section of the cave is 60 m by 25 m and is 30 m in height. Four ^{14}C dates for charcoal range from 10,950 ±100 to 11,540 ±100 B.P. (Corchon and others, 1996). The cave has had a stream flowing in it at times, which has left organic debris plastered to heights of several meters on the walls. Flooding postdates the paintings and has apparently destroyed the paintings to the height of the flooding.

Reports of Paleolithic art preserved in caves are common only in southern Europe, but examples of late Paleolithic, and more commonly, Neolithic art are known throughout the world. Podesta (1996) reports ^{14}C dates for charcoal from two sites in Argentina that range from 9,200 to 10,600 B.P. Similar and perhaps older ages are suspected in Brazil, but most of the early art seems to date from 4,000 to 7,000 years ago (Prous, 1996). Prins and Woodhouse (1996) report one cave painting from South Africa dated at 26,000 B.P., which is probably the Apollo cave (fig. 3) mentioned by Coulson (1999). Very little cave art is known in China, but a few examples exist that may date back to 5,000 B.P. (Fu, 1996). A few other sites throughout the world are summarized by Saura (1998) and Bahn (1996).

Although many examples of Paleolithic art are preserved in western Europe, there persists a question of whether of not an equal or perhaps even larger number have been completely destroyed. Null evidence cannot be evaluated easily, but two lines of evidence suggest that Paleolithic paintings have not

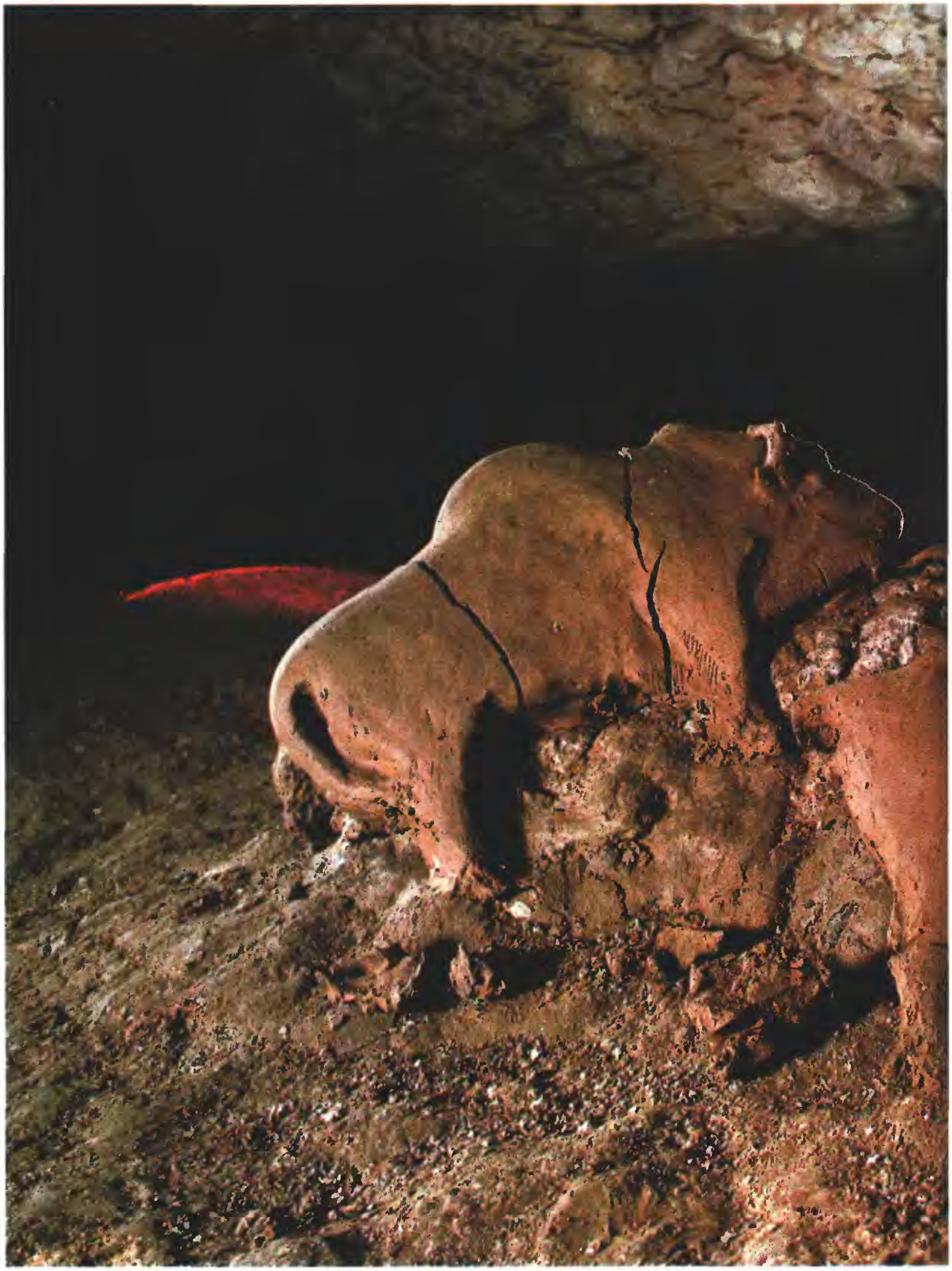

Figure 3. Sculpted bison 14,000 years old from Tuc d'Audoubert (from Putman, 1988).

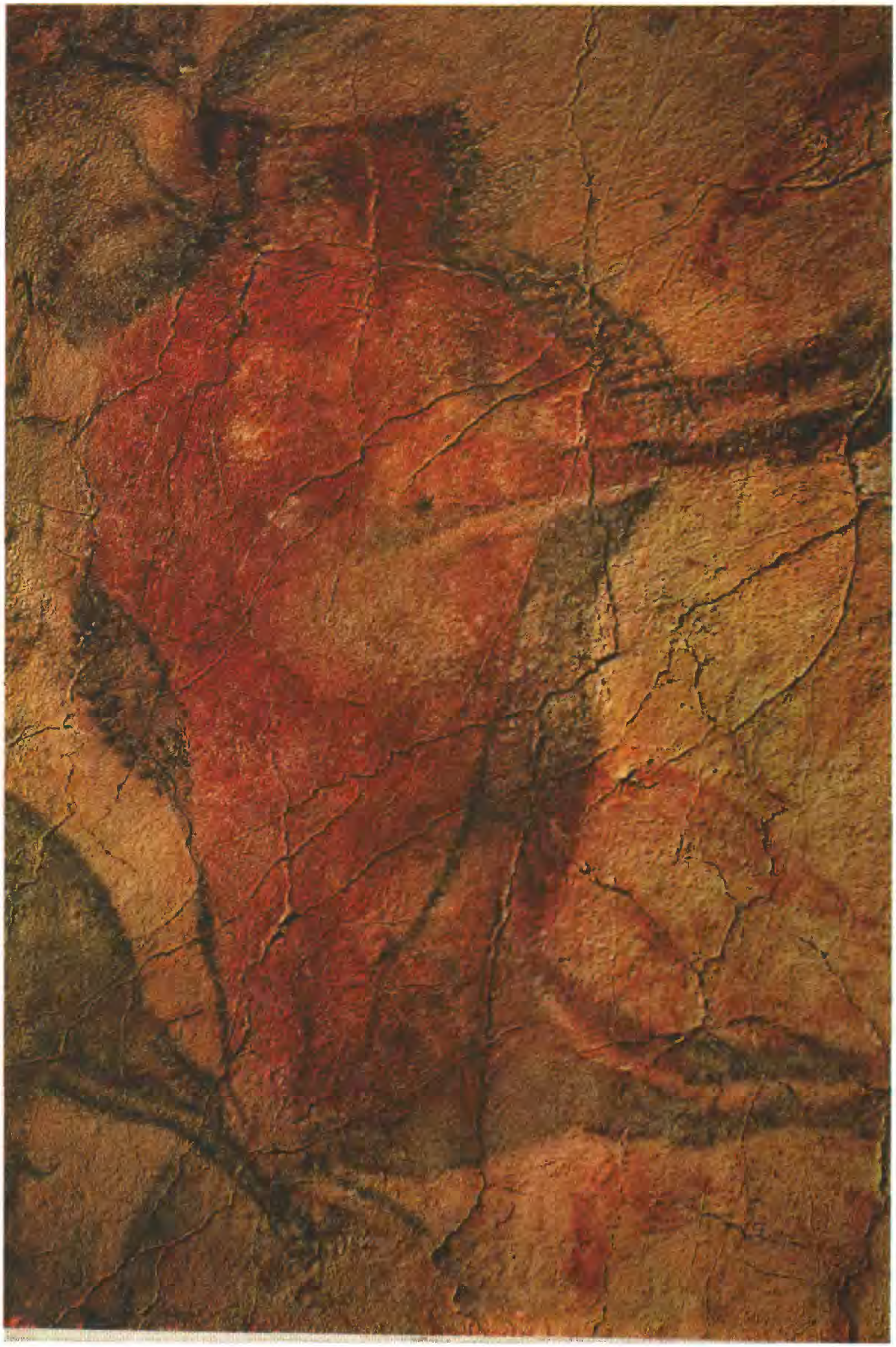

Figure 4. Painted bison from the ceiling of Altamira showing fractures through both the iron oxide and charcoal portions of the 14,000-year-old painting, but no apparent water damage.

been totally destroyed in caves where they may have once existed. First is the common association of painted carvings into the rock. At Cosquer, some etchings exist below high-water mark, but paint and charcoal are gone (Clottes and Courtin, 1996). Reports of similar etchings without paint in caves seem to be lacking. Second, if some caves, or even parts of caves, had their paintings completely destroyed, one would expect most, if not all localities, to exhibit a spectrum of preservation from largely destroyed to fully preserved paintings. Such 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. Finally, 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 locus of flow for thousands of years and would likely have been avoided by early man because they were too wet to paint.

On a worldwide basis, painted rock shelters are more common than painted caves. Many of the sites in figure 1 are actually painted shelters, and, in Portugal, decorated shelters (which seems to include both pictographs and petroglyphs) are much more common than decorated caves (Simoes de Abreu and Jaffe, 1996). The greater abundance of painted shelters is not surprising considering that the geologic processes that create shallow overhangs—that is, rock shelters—are more common than those that create true caves. In addition, painting in rock shelters does not require artificial light. It is surprising, however, that even an overhang of a few meters can protect paintings from infiltrating water for long periods of time.

Painted rock shelters had been noted in India 12 years before the discovery of Altamira in Spain (Neumayer, 1983). These painted shelters are apparently very common in India and are found in a variety of climatic zones. Mathpal (1996) in a recent compilation, lists over 400 sites. The broad distribution of prehistoric painted sites in India can be seen on web site http://lavanya-indology.com/rockart.htm (accessed 03/01/00). The paintings have not been found within limestone caves like those of southern Europe, but rather are common in shelters formed in a metamorphosed sandstone (Neumayer, 1983). In some shelters, the roots of banyan trees have provided 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" (Neumayer, 1983, p. 6). Note that many of these paintings are in areas that receive 100 to 150 cm of rain per year.

Quantitative age information on the painted rock shelters of India appears to be lacking, but the oldest paintings are thought to be Mesolithic (Neumayer, 1983) and thus to have survived for thousands of years. The paintings were done using hematite [iron oxide (Fe_2O_3)] for red and glauconite (a clay formed during the weathering of basalts of the famous Deccan Traps) for green. Some of the best preserved art work is at Bhimbetka; an example can be seen on web site www.mptourism.com/dest/bhimbetka.html (accessed 03/01/00).

Painted rock shelters are widespread throughout Africa (fig. 5), As of 1981, The Archaeological Data Recording Center in Cape Town, South Africa, had recorded 3,931 sites, and several others were known but not yet recorded (Lewis-Williams, 1981). The paintings are generally a few thousand years old, but in the Sahara, there are reports of paintings as old as 7,000 years (Coulson, 1999). Gutierrez (1996) describes one 20-m-long painting in a rock shelter in Angola in which red, yellow, black, and white colors were used, the white created with ivory. Coulson (1999) shows one well-preserved, 18-cm-high pictograph that is at least 4,000 years old, which is reproduced in figure 6. In the southern part of Africa, some of the painted surfaces are friable sandstone that can be flaked or pulverized by the touch (Vinnicombe, 1976). Such shelters probably formed largely by wind ablation and as such, that process, rather than the actions of water, is likely responsible for the loss of paintings. Surprisingly, wind "abrasion" is identified as the destroying agent for more than 90 percent of the paintings in one gallery in the cave of Lascaux (Breisch, 1987).

There is extensive literature on prehistoric art in North America. Hyder (1996) notes in his summary on the subject that as early as 1979, more than 1,000 published articles existed. Both paintings and mud figurines exist on the walls of caves. Less quantitative dating seems to exist in North America than in Europe, and the oldest ages so far are around 3,500 B.P. (Hyder, 1996).

In addition to prehistoric art, caves and rock shelters of the desert Southwestern United States preserve large amounts of biologic remains that would have been destroyed if exposed to much water. There

Figure 5. Location of known painted rock shelters in Africa (Coulson, 1999, used with permission of the National Geographic Society).

Figure 6. Painting of the "hair dresser" from a rock shelter in the Sahara thought to be at least 4,000 years old (Coulson, 1999, used with permission of the author).

are many studies of packrat middens (fig. 7) that have ages as great as 50,000 B.P. (for example, Spaulding, 1985). The middens are composed of twigs, fecal pellets, and other debris cemented by dried packrat urine, and yet caves and even shallow overhangs in the semiarid climate have diverted enough water such that the middens remain well preserved. Additional examples of paleontological remains from dozens of caves are described by Davis (1990). These include bones, dung from extinct animals, and pollen. In Europe, similar sorts of remains found in caves were the focus of the first modern studies of early man.

An archaeologic site of Neolithic to Chalcolithic age in Israel provides a different example of materials preserved in caves of the unsaturated zone and is described in the National Geographic (Ozment, 1999). Cloth, ivory, and many bronze items (fig. 8) have been preserved in a nearly perfect state (Schick, 1998; Ozment, 1999). Carbon-14 dates on wood and fabric from the site yield a calibrated age of 3,912 to 3,770 B.C. (Jull and others, 1998). This site is currently much drier than Yucca Mountain and probably has been drier for at least the last 5,000 years (Dalfes and others, 1997).

HYDROLOGIC ANALOGUES IN THE ANTHROPOGENIC SYSTEMS

Manmade openings in the unsaturated zone are generally much younger than those from the natural system, but nonetheless, they provide further evidence of the robust nature of protection provided against the effects of water. In addition, the anthropogenic examples broaden the range of geologic settings that can be examined as analogues to a mined geologic repository. Dates given in source materials for this section are generally reported relative to the start of the Christian era, and therefore, this section reports ages as B.C. or A.D.

The oldest anthropogenic underground structure found during the current survey was a passage grave (stone tomb) in Newgrange, Ireland, built around 3100 to 3200 B.C. The tomb is described in a couple of web sites (www.stonepages.com/Ireland/Ireland.html, accessed 03/16/00 and www.meathtourism.ie/historic-Meath/newgrange.htm, accessed 03/01/00) and a cross section is shown by Constable and others, 1987). The tomb is under an earthen mound that is 85 m in diameter and 13.5 m in height. The stone tomb is 5.2 by 6.5 m with a corbeled ceiling that reaches a height of 6 m. The ceiling is constructed of horizontally laid layers of large slabs, each layer resting on the one below it and partially overhanging it (corbels) such that with each layer of rock, the diameter of the vaulted ceiling diminishes until finally a single large capstone closes the opening (fig. 9). The outer ends of the first layers of the corbels are buried and tilted slightly downward and outward; this serves to divert percolating water around the tomb. There are no reported artifacts from the open part of the tomb, but human bones and other artifacts were found in an excavated central chamber. The tomb has apparently stayed dry throughout its history in spite of a modern rainfall in the area of more than 65 cm/yr.

The oldest, well-documented anthropogenic examples of preservation are the tombs of the pharaohs and other nobles. Some of the early tombs, although not truly tunnels, provide long-term evidence of preservation in the unsaturated zone. For example, along the southern base of the great pyramid of Giza, two subterranean burial chambers were found that were capped with 81 limestone blocks, each block nearly 2 m thick. The burial chambers were about 3 m deep, thereby creating the equivalent of a shallow cave in the unsaturated zone. Each chamber contained a disassembled cedar boat, one of which has been removed and reassembled. Even after 4,500 years, the wood appears to have been perfectly preserved (Papanek and others, 1992).

Another example comes from the tomb of Meketre, a functionary of the court during the Eleventh Dynasty (Papanek and others, 1992). Although tomb robbers had greatly damaged the main burial chamber, an adjacent room was untouched. The room contained several miniature boats with painted wooden figurines. In addition, there were 24 small boxes, each with multiple painted wooden figurines depicting scenes from Egyptian life from 2040 to 1991 B.C. One depicted scene includes a single carved wooden block of men butchering an ox, with their wooden arms and plaster feet added after the main carving was completed. All of the wood, paint, and plaster are perfectly preserved (D'Auria and others, 1988). Another scene shows Meketre taking inventory of his livestock (fig. 10).

Figure 7. Packrat midden from the Sheep Range, Nevada, dated at 10,000 B.P. Quarter is shown for scale (Photograph provided by I.J. Winograd, U.S. Geological Survey).

Figure 8. Artifacts including nearly 6,000-year-old cloth, ivory, and brass from the Cave of the Warrior (Schick, 1998, and Ozment, 1999, used with permission of the National Geographic Society).

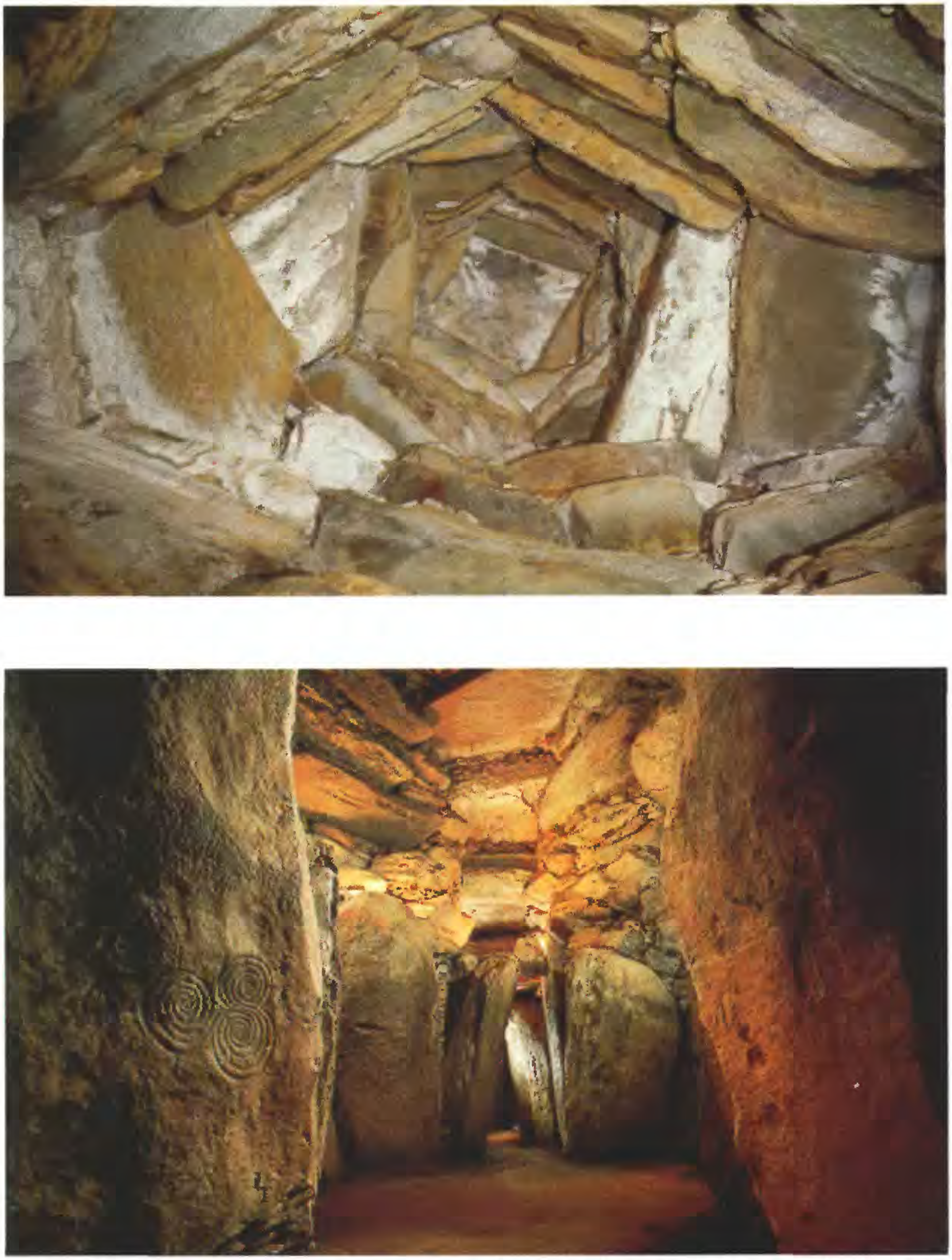

Figure 9. Pictures from the inside of the passage grave at Newgate, Ireland, showing the central chamber and the corbeled ceiling.

Figure 10. Painted wooden figurines from the tomb of Meketre, 1991 B.C.

During the Eighteenth Dynasty (about 1500 B.C.) the Egyptians started excavating true subterranean burial chambers in limestone in order to stop grave robbers, who had pillaged the above-ground tombs. The degree of preservation in the excavated tombs is not always good, in part because grave robbers eventually penetrated these structures as well. The only known exception for a pharaoh's tomb is the tomb of Tutankhamen (King Tut). This tomb, discovered in 1922, contained reed baskets of fruit and bread and 30 jugs of wine. Also found were linen gloves, a shiny iron knife that may have been made from a meteorite, and dried cornflowers, all from about 1331 B.C. Even an ebony and ivory chair and a small throne for the boy king are perfectly preserved (fig. 11).

The Greeks, Carthaginians, and other ancient people all mined metals, but underground workings did not become common until Roman times. There is considerable published information about the geology and geometry of the Roman mines as well as artifacts associated with them (Davies, 1935; Pinedo, 1962; Blanco and Luzon, 1969; Adaro, 1988; Merideth, 1998), but little information seems to exist on the degree of preservation or the circumstances of preservation. Davies (1935) reported that a skeleton was found in a mine in what is now Romania, but the age of the skeleton is not given. Another skeleton was found chained in a mine in Kamareza (Greece), and in this case, the inference is that it dates to the first century B.C. In A.D. 1772, a 2-mm-thick copper plaque was found at Riotinto in Spain with an inscription to Nerva (Pinedo, 1962), who lived between A.D. 32 and 98. This presumably was preserved within the unsaturated zone of the mine for nearly 2,000 years.

Davies (1935), Pinedo (1962) and Blanco and Luzon (1969) all describe water wheels and/or archimedian screws for removal of water from the parts of the mines that were below the water table. Each author cites museums where these machines can be viewed, but neither gives either the ages nor degrees of preservation. The descriptions include types of wood used as well as descriptions of wooden and copper buckets, which implies a good degree of preservation. A bronze pump from the second century A.D. is on display at the Museo Arqueologico Nacional in Madrid, and it appears to be in excellent condition. Also on display are leather ore buckets and hemp items recovered from Roman mines, all of which are well preserved. Roman lamps have been found in several mines, including Minas de Mouros in Portugal, where they were found at a depth of about 20 m in tunnels about 6.5 km long.

Reports of iron tools found in mines are common (for example, Davies, 1935), but the degree of preservation is not usually given. Pinedo (1962) reported numerous bronze tools from Riotinto but noted the lack of iron tools, which he ascribed to the action of the acid mine waters generated in the high-pyrite (iron sulfide) environment.

Davies (1935) reported preservation of wooden supports but noted that supports were not in common use owing to the narrow dimensions of the Roman mines. Pinedo (1962) also noted that most Roman mines were small (relative to the diameter of opening proposed for a mined geologic repository), but several mines had large enough openings to be considered acceptable analogues.

Buddhist monks have carved temples into the Deccan basalts of west-central India for nearly a millennium (Behl, 1998; Malandra, 1993). These are true manmade excavations but are generally referred to as Buddhist caves. Some of the 31 caves of Ajanta date back to the second century B.C., but most were excavated in the late fifth or early sixth century A.D. The caves are carved along a 550-m-long, horseshoe-shaped gorge of the Waghora River. Each temple originally had steps carved into the rock leading up to it, but only cave #16 still has a vestige of steps. (Caves are numbered sequentially upstream on the Waghora River). As shown later in this report, even though the monsoonal climate has destroyed the exterior stone structures exposed to the elements, delicate subterranean artifacts have been well preserved.

The earliest paintings were made using five basic colors: white from calcite, kaolin, and gypsum; red and yellow both derived from iron oxide; black from charcoal; and green from glauconite. In addition to the five basic colors, later painters used lapis lazuli for blue. The paintings are not frescoes. The basalt walls were first covered with a layer of thick mud with rock grit, vegetable fibers, grass, and so forth. A second layer made of finer mud with rock dust and finer vegetable material was then applied. A third layer of dried lime wash was used as the final surface to be painted. Paint was then bound with a "glue," for which a composition was not specified (Behl, 1998, p. 35).

Figure 11. Ivory and ebony chairs from the tomb of Tutankhamen from about 1131 B.C.

All of the described materials, as well as the paintings, should be susceptible to destruction by water, and in fact, most of the paintings photographed by Behl (1998) show some evidence of spallation (fig. 12), but none appear to have had sufficient water flow across them to cause the paints to dissolve or run. Similar Buddhist paintings are preserved from the fifth through the tenth centuries A.D. at Ellora and from the ninth century A.D. at the Jain caves at Sittanavasal (Behl, 1998).

The cross-sectional dimensions of most of the temples at Ajanta (Behl, 1998) are larger than that proposed for a mined geologic repository. For example, Cave #10 is 30.5 by 12.2 m. Cave #1 is 2.82 m by 6.73 m with a ceiling height of 4.11 m. Cave numbers 4, 16, 17, 21, 23, and 24 are of similar size. Cave #2 has a verandah of 14.10 m by 2.36 m, a main hall of 14.73 m by 14.5 m, and a shrine of 4.27 m by 3.35 m. Cave #16 has a verandah of 19.8 m by 3.25 m and a main hall of 22.25 m on a side with a height of 4.6 m. Cave 17 has a verandah of 19.5 m by 3 m and a main hall that is 19.5 m square. In spite of these large sizes, water flow within the unsaturated zone apparently has largely been diverted around the temples rather into or through them.

The climate in the vicinity of Ajanta is monsoonal with an average rainfall of nearly 80 cm/yr; as such, the area has much greater effective moisture than would be expected for a potential repository at Yucca Mountain, based on even the wettest past climates (Forester and others, 1999). Note, too, that nearly all of the rainfall occurs in four months (June through September) such that each of these months has about the equivalent of a year's precipitation at Yucca Mountain. The apparent diversion of water around the temples is closely analogous to that predicted for the densely welded tuffs of Yucca Mountain in that both settings are volcanic rocks with little pore space, and thus, flow is dominantly along fractures.

Most of the Ajanta paintings appear to have sustained some damage by spallation, and some of this damage is due to the actions of humans. Varnishes were applied in early restoration efforts. During the period 1920 through 1922, Italian restorers were hired to preserve the paintings. They applied shellac, which later peeled or darkened and yellowed.

During the second through eleventh centuries A.D., the Christians of Cappadocia, Turkey, excavated underground cities and churches. The geology of Cappadocia (Toprak and others, 1994) is similar to that of southern Nevada (Sawyer and others, 1994) in that in both areas, the late Tertiary section [approximately 23.7 to 1.6 Ma (million years ago)] is composed of a thick sequence of silicic volcanic rocks. At Yucca Mountain, the host rock for the potential repository is a densely welded, quartz latite ash-flow tuff formed about 11.6 Ma, whereas the underground dwellings of Cappadocia are hosted by a partially welded, rhyolite ash-flow tuff formed about 4.5 Ma. The latter is virtually identical to a unit stratigraphically above the potential repository horizon (the Yucca Mountain Tuff).

Two of the underground cities, Kaymakli and Derinkuyu, were visited as potential analogues to a mined geologic repository. Both are accessed by narrow passageways that could be closed by rolling a 1.5-m-diameter millstone across the opening (fig. 13). The two cities are reported to be joined by an 8-km-long tunnel, although this was not seen during the site visit. A small perched stream was observed perpendicular to the trace of that tunnel, approximately at its center.

Derinkuyu, which in Turkish means deep well, was a city that covered approximately 4 km^2 and had an estimated 15,000 to 20,000 inhabitants (Toprak and others, 1994) during much of the first millennium A.D. The water table is approximately 90 m deep, and eight levels of ancient habitation above the water table had been investigated as of 1994. As part of the current study, all of the area accessible to the public in Kaymakli and Derinkuyu was examined for active seeps and evidence of minerals deposited by seeps in the past. The only evidence of water in the tunnels and rooms was algae growing on the walls in a few places near electric lights. A retired guide (Necate Olgun), who had worked at Derinkuyu for 40 years, and who had played in the underground city as a child before it was made into a museum, was interviewed. He stated that he had never seen water in any part of the underground city, including those parts not open to the public.

The difference in welding at Yucca Mountain and Derinkuyu results in a markedly different fracture density and hence a difference in the type of flow within the unsaturated zone. The former is dominated by fracture flow, such as that noted in the limestone caves, whereas the latter is dominated by matrix flow. Nonetheless, the fractures at Derinkuyu and Kaymakli were examined particularly closely for evidence of

Figure 12. Paintings from the Ajanta temple in India. The hexagonal column is from the second century B.C. (Behl, 1998, used with permission of the author).

Figure 13. Room in the underground city of Kaymakli, Turkey. The millstone is about 1.5 m diameter and was used to seal the entrance against intruders.

water, but none was found. This is somewhat surprising given that many of the rooms are larger than 3 m by 5 m and some have intersecting fracture sets in the ceiling. Annual precipitation (38 cm/yr) is more than double that at Yucca Mountain.

The churches at Goreme, Turkey (also in the Cappadocia region), were excavated in the same ash-flow tuff as the underground cities of Kaymakli and Derinkuyu. These churches contain frescoes dating from the 9th to 13th centuries A.D. (Toprak and others, 1994). Many of the frescoes have been damaged by vandals, and several show some deterioration by spallation; but, like the paintings at Ajanta, none was observed to have had paint dissolve or run due to the effects of flowing water. Examples of the frescoes are shown in figure 14.

Evidence for fracture flow was noted at Goreme. An underground kitchen that dates from the time when the monastery was occupied (approximately 9th through 13th centuries A.D.) was visited. The walls and ceiling were blackened by years of cooking with open fires (fig. 15). A fracture was observed across the ceiling and at an angle down one wall. The soot was bleached out adjacent to the fracture in the ceiling for a distance of 1 to 10 cm, but no evidence of dripping, such as would be indicated by stalactitic deposits, was observed. Some evidence of flow from the fracture down the walls was noted, but the amount of soot removed was minor as indicated by the degree of streaking on the wall. More pictures and information on Cappadocia are available on web site http://focusmm.com.au/cappa_01.htm (accessed 03/01/00).

The youngest "old" examples of preservation of materials within anthropogenic excavations in the unsaturated zone are from China. Sixteen emperors from the Ming Dynasty (A.D. 1368 to 1644) were buried in tombs excavated in rock near Beijing, which is within a temperate-climate zone. The earliest of the tombs has 32 sandalwood pillars that are 1.17 m in diameter, and all are still intact and sturdy (Golany, 1989).

There are at least three places where manmade underground excavations are still occupied (Golany and Ojima, 1996). In Tunisia, 20 to 40 km south of the city of Gabes, 10 underground villages, some of which date back nine centuries, are excavated in limestone (Golany, 1983). The limestone is composed of alternating layers of hard and poorly indurated limestone approximately 2 m thick. Room sizes are typically 2 to 2.5 m on a side with flat ceilings that may have a supporting column in the center. The walls are generally not painted; however, a main room in which guests might be met is usually whitewashed. Golany (1983) reports that as many as 6,000 people live in the largest underground village, and several hundred live in each of the smaller villages.

In northern China, there are thick deposits of loess (wind-blown dust generally thought to be of glacial origin). Loess is highly porous and only slightly indurated so it is easily excavated, but its internal structure is such that it can form vertical cliffs as much as 30 m in height. The underground dwellings accommodate more than 10 million people who farm the land above their houses (Golany, 1983).

In Cappadocia, Turkey, in the vicinity of the underground churches described for Goreme, a large population still live in homes carved out of the ash-flow tuffs. Unlike previously described dwellings, the ones in Cappadocia are carved into cliff faces and steep slopes of the tuff. A description of living in one of these dwellings is published in National Geographic (Blair, 1970).

None of the descriptions of these modern underground dwellings have mention of water inside the homes, which suggests that they either are dry or only occasionally damp. Golany (1983) noted, however, that the moisture in the loess provides a comfortable humidity in the Chinese dwellings. The Chinese examples are from climates ranging from arid (about 2 cm/yr in the vicinity of Turpan) to subhumid (~60 cm/yr in the vicinity of Xi'an). The Tunisian example represents an arid climate where the water table is more than 60 m deep and perhaps too dry to be a good analogue for Yucca Mountain. The Turkish example is from a semiarid climate with more precipitation than currently occurs at Yucca Mountain. The openings in all three examples are similar in size to that proposed for a potential mined geologic repository, and thus these examples again support the conclusion that seepage flux into a repository at Yucca Mountain should be minimal.

Winograd (1986) first pointed out the great degree of preservation of artifacts within the unsaturated zone, but within the unsaturated zone the degree of preservation is greatest within caves and manmade openings. In China, a playable flute carved from an ulna (leg bone) of a red-crowned crane and dating back about 9,000 years was recovered from a tomb (Zhang and others, 1999), but such preservation is rare

Figure 14. Paintings from the Karanlik church at Goreme, Turkey. 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 spallation.

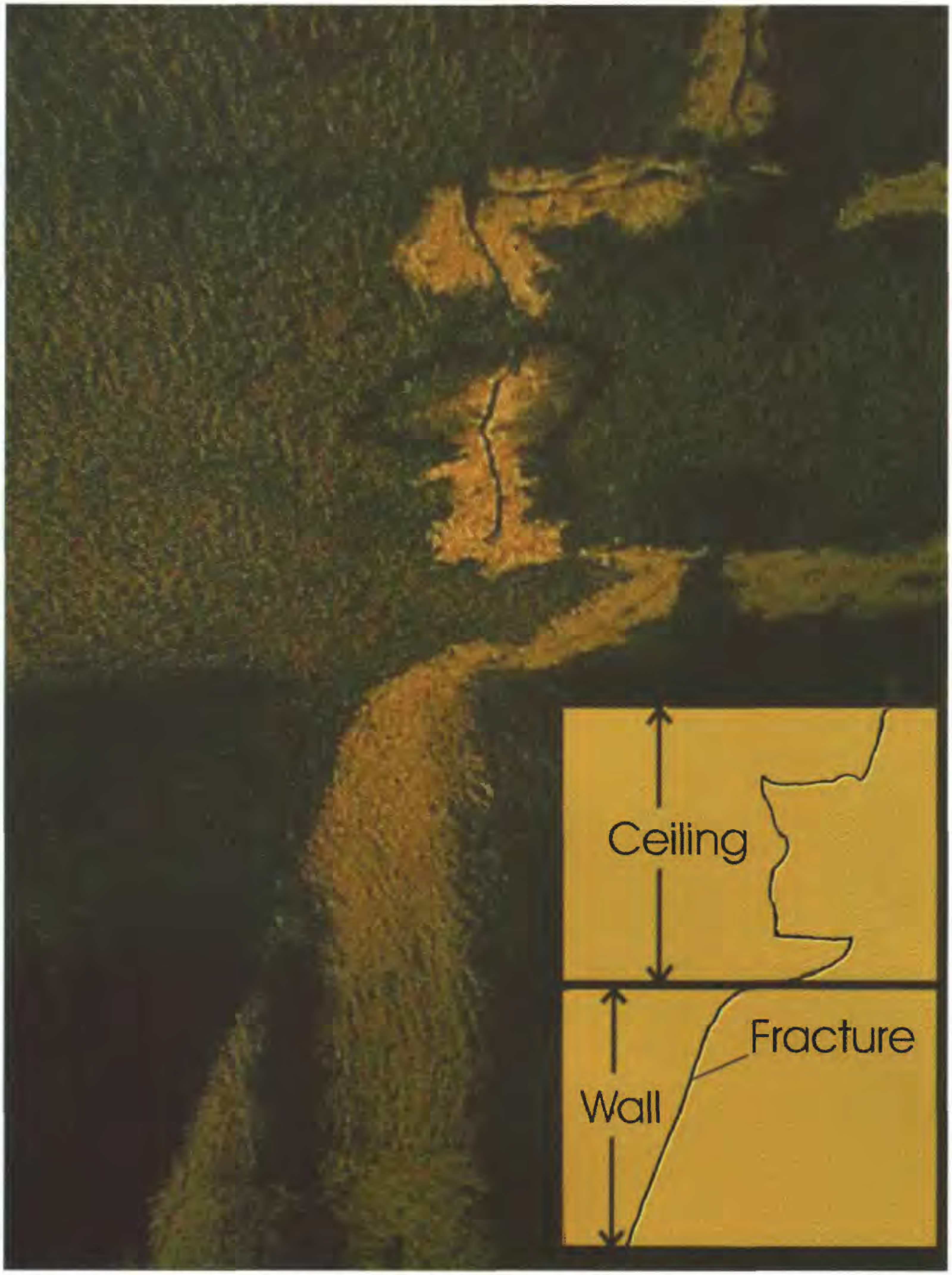

Figure 15. Fracture in the blackened wall and ceiling of a kitchen in a monastery at Goreme, Turkey, which was probably in use until the 12th century B.C. The soot has been removed adjacent to the fracture in the ceiling, possibly by oxidation. On the wall, flow has occurred from the fracture, removing some of the soot below the intersection of the fracture with the wall.

unless the artifact is truly isolated from water. For example, two different Chinese emperors were buried with terra cotta "armies" to guard them. The more than 6,000-man "army" of Qin Shi Huang originally had a wooden ceiling over it in the second century B.C., but this soon collapsed following a fire (Topping, 1978; Mazzatenta, 1996), and although the terra cotta, leather and some metal remain, the paint is gone from the soldiers and almost all are broken (though the latter state may be due to vandals). The 2,100-year-old "army" of Jing Di originally had wooden arms and fabric uniforms, both of which are now gone (Mazzatenta, 1992). These observations contrast with those previously described for delicate artifacts and paintings in caves and manmade excavations.

Hydrologically intermediate between the true openings in the unsaturated zone and burial in soils of the unsaturated zone are underground grain storage bins of China dating from A.D. 581 to 907. In 1971, 287 grain pits of various sizes were discovered near Luoyang. Sixteen have been dug out, and in one, workers found 25,000,000 kilograms of grain, of which 57.2 percent was still "recognizable material" (Golany, 1989). That pit was dug in loess above the water table. The conical pit was 7 m deep and 13.5 to 10.5 m in diameter. The wall had been beaten and fired to decrease permeability, and the floors and ceiling had material added to absorb moisture. Again, the degree of preservation is not as great as that provided by caves and openings where preserved items were surrounded by air.

CONCLUSIONS

The great abundance of examples of materials preserved within the unsaturated zone collected from natural analogues, such as caves and manmade openings and even from partial openings such as rock shelters, demonstrates that the mathematical predictions and short-term experiments, which indicate a preferential flow of water around a mined geologic repository for radioactive wastes in the unsaturated zone, are true for very long time periods. The oldest examples noted in this survey—Paleolithic cave paintings and Quaternary packrat middens and other biologic remains—exceed the 10,000-year-time span for performance of a radioactive waste repository specified in current and proposed regulations of the U.S. Nuclear Regulatory Commission (U.S. Department of Energy, 1983, and U.S. Department of Energy, 1999). In fact, the examples observed in nature suggest that the current total system performance models (U.S. Department of Energy, 1998) may be very conservative in their long-term predictions.

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