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NATURAL ANALOGUES AS A CHECK OF PREDICTED DRIFT STABILITY AT YUCCA MOUNTAIN, NEVADA

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ABSTRACT

Calculations made by the U.S. Department of Energy's Yucca Mountain Project as part of the licensing of a proposed geologic repository (in southwestern Nevada) for the disposal of high-level radioactive waste, predict that emplacement tunnels will remain open with little collapse long after ground support has disintegrated. This conclusion includes the effects of anticipated seismic events. Natural analogues cannot provide a quantitative test of this conclusion, but they can provide a reasonableness test by examining the natural and anthropogenic examples of stability of subterranean openings. Available data from a variety of sources, combined with limited observations by the author, show that natural underground openings tend to resist collapse for millions of years and that anthropogenic subterranean openings have remained open from before recorded history through today. This stability is true even in seismically active areas. In fact, the archaeological record is heavily skewed toward preservation of underground structures relative to those found at the surface.

I. INTRODUCTION

The collapse of underground excavations, or their ability to remain open under ambient conditions, depends on a number of variables, including (1) rock strength; (2) size, shape, and orientation of the opening; (3) orientation, length, and frequency of fracturing; and (4) effectiveness of ground support. Values for these variables (excluding ground support) used in calculations for tunnels at Yucca Mountain, Nevada (the site chosen for the licensing of a proposed geologic repository for the disposal of high-level radioactive waste) have led to the prediction that only limited failure of drifts and tunnels in the Miocene volcanic rocks should occur over a period of thousands of years¹. Such long-term stability, even after ground support degrades, affects the integrity of the waste packages as well as the flow of groundwater flow, because the tunnels should divert a substantial amount of water moving through the unsaturated zone away from the canisters and create a "drift shadow" or dryout zone beneath the tunnels.

The proposed repository at Yucca Mountain would be excavated in two subunits of the Miocene Topopah Spring Tuff. The welded nonlithophysal^a unit is brittle and jointed. The lithophysal tuff is less jointed but somewhat more friable. Emplacement tunnels (for the storage of radioactive waste) would be bored with a diameter of 5.5 m, and would be oriented for optimum stability relative to the joint orientations. Access drifts would be bored at a larger diameter (~ 8 m), but these are proposed to be backfilled, and as such, collapse is a moot point.

There are no exact analogues to the openings that would be created for the proposed repository at Yucca Mountain, but there are numerous examples demonstrating that both natural and man-made underground openings can exist for thousands of years in a wide variety of geologic settings, even with minimal or no engineered supports.

At Yucca Mountain, collapse induced by seismic activity must be considered. Once again, exact analogues do not exist, but considerable anecdotal information about underground openings subjected to seismic activity is available. By comparison to the examples of underground openings documented in this paper, it is possible that seismic events would cause little damage in the tunnels at Yucca Mountain.

II. NATURAL UNDERGROUND OPENINGS

Caves are natural subterranean openings, which can be used as analogues for the stability of drifts in the proposed repository. They are abundant worldwide, form in a variety of rock types (although carbonates are the most common host rock), and, in many cases, can be shown to have stayed open for very long spans of time. The oldest documented examples noted in the current study are from the limestone formations of the Guadalupe Mountains in New Mexico. Alunite, which was deposited on the floors of caves during their formation, has been dated by K-Ar at 4.0 to 3.9 Ma for the Big Room at Carlsbad Caverns and 6.0 to 5.7 Ma for the upper level of the nearby Lechuguilla Cave². K-Ar ages for alunite from other nearby caves show a trend of increasing age with increasing elevation, with one cave as old as 11.3 Ma³. Although there are sections of the caves with blocks that appear to have fallen from the ceiling (referred to as breakdown), the timing of these collapses is not known, and these blocks may have fallen during cave formation. Regardless of the age of the breakdown, the sections of cave sampled for the dating study have not been buried by rock from the ceiling, and the preservation of original floors is

^a Lithophysae originate as gas-filled cavities during the welding of an ash flow. Welding is a process whereby hot particles of ash and crystals compact and decrease pore space between particles to almost zero.

complete enough to allow the demonstration of increasing age of formation with elevation. Many of these openings, which have been stable for millions of years, are as large as or larger than those proposed for Yucca Mountain.

Most areas of Carlsbad Caverns open to the public have no obvious breakdown on the floor of the cavern or holes in the ceiling from which blocks might have fallen. Any breakdown that may have occurred at the time of cave formation has since been covered by stalagmites or flow stone. Polyak and Asmerom⁴ and Polyak and others⁵ have dated younger speleothems from three separate caves including Carlsbad Caverns as part of their studies of past climates. Their results show continuous growth during the last pluvial (30,000 to 10,500 B.P.) and therefore, these areas must have had no collapse for at least the last 30,000 years.

Lava tubes are another common type of cave. The US National Park Service has parks and monuments in Hawaii, Idaho, California, Arizona, and New Mexico with lava tubes. Most dated lava tubes are a few thousand to a few hundred thousand years old. They are commonly ellipsoidal to circular in cross section and several meters in diameter. Some of the most extensive lava tubes are in the Undara region of Australia. In this locality, 190,000-year-old tubes reach an aggregate length of 30 km and are as much as 20⁶ m wide⁷. Lava tubes also are common in Hawaii and in the Cascade Range where ages are modern to a few thousand years. Most lava tubes exhibit areas of collapse where their rooves are thin, but large sections persist as open tunnels for long periods of time.

The San Antonio Mountain Cave in northern New Mexico is an example of a lava tube that has remained open over a long period of time. This cave, a lava tube in 3.4- to 3.9- Ma basalt⁸, is 170 m long and generally several meters wide. In places, the ceiling is as much as 12 m high. The large size of the openings combined with abundant cooling fractures and great antiquity has resulted in fallen blocks, generally less than 0.75 m in diameter, that cover about 30 percent of the cave's floor. Several low areas on the floor of the cave preserve a long record (as much as 1 m.y. as evidenced by the fossil record⁸) of sediment accumulation (as much as 1 m thick) with no collapse.

Some of the largest and best studied lava tubes are in the Canary Islands. Cueva del Viento on Tenerife is one of the longest lava tubes in the world (more than 17 km), is as much as 25 m wide, and has been dated at 17,570 +/- 150 B.P. by ¹⁴C analyses of roots carbonized by the erupted volcanic rocks⁹. Tubo Volcánico Corona on Lanzarote (fig. 1) is 8 km long, and as much as 35 m wide¹⁰ and large enough to house a theater, restaurant,

swimming pool, museum, and conference room. The host lava has been dated by ^{39}Ar - ^{40}Ar at $21 \pm 6.5 \text{ ka}^{11}$. The last 1.8 km section of this lava tube is below sea level, by as much as 80 m, owing to the much lower sea level during the last glacial advance. There is no report of collapse of the underwater portion.

Kebara Cave in Mount Carmel, Israel, is a large opening (20 by 26 m), and sediments on the floor of the cave yield ages as old as 50,000 years¹². Although this main portion of the cave shows no sign of collapse, a terrace in front of the cave entrance was formed by collapse sometime after 30,000 years ago¹². However, even this collapsed section must have stood open for more than 20,000 years because the section was the entrance from before 50,000 until 30,000 years ago.

FIG. 1. On the left is a photograph of Tubo Volcánico Corona, Lanzarote with a man shown for scale. On the right are schematic cross sections of the lava tube: 1) at the time of formation with sea level at least 80 m lower than at present and 2) as the lava tube exists today with a few collapse windows and modern sea level (Photograph provided by José Mangas Viñuela; sketch after Carracedo and Day¹⁰).

The maximum length of time that caves have stood open is generally not known. The very old caves in the Guadalupe Mountains discussed above may be exceptional in terms of age, but many caves contain biologic or archaeologic materials providing evidence that no collapse occurred for extended periods of time. Studied packrat middens typically are thousands to tens of thousands of years old, and Davis¹³ reported that more than 1,000 have been studied in caves of the western United States. Davis¹³ also cites studies of cave sediments in Europe that are as old as 1.5 m.y., which suggests that long-term stability of caves is a common feature. Stuckless¹⁴ reported on several limestone caves that contain Neolithic paintings that have been dated at 14,000 to 32,000 years old. Photographs from several of these caves show no evidence of roof collapse since the paintings were made^{15,16,17,18}.

however, Breisch¹⁹ reported that a small block fell out of one of the paintings on the ceiling at Lascaux and that a rock found on the floor of the cave fit geometrically in the hole in the painting.

Surprisingly, caves in sandstone are fairly common, although no ages seem to be reported, and therefore the length of time this rock type can support an opening cannot be judged. Sandstone is the host rock for 30 percent of the 250 recorded caves in Wisconsin²⁰. The Nangwarry cave system in southeast Australia is reported to be 407 m in length with one section having a floor of 3 by 7 m and a height of 8 to 9 m²¹. One sandstone cave in southern Egypt gained notoriety because its paintings depicting people swimming made it unique among Neolithic cave paintings, and the cave became the back drop of a book and movie of the same name "The English Patient". It is not likely that the paintings are very old. The paintings in the northern Sahara Desert date from 12,000 to 4,000 years old; the rate of weathering (presumably by wind ablation) is high²².

III. ANTHROPOGENIC UNDERGROUND OPENINGS

Anthropogenic underground openings do not provide as long a history as natural openings, but they may provide a closer analogy to a mined geologic repository. Here too, there are abundant examples from around the world, in different rock types, and for different purposes that exhibit considerable stability for hundreds to thousands of years even with minimal engineering. The oldest examples are the Paleolithic flint mines of England and northern Europe. The English deposits were mined into chalk beds. These mines have shafts 6 to 14 m deep, which access galleries 4 to 24 m long and 60 to 150 m high²³. The mines are dated at 3,010 to 3,250 B.C.²³ and are still open today largely because prehistoric man seems to have utilized the 30- to 60-cm joint spacing so as to leave none of the roof totally unsupported. (Note that ages for the anthropogenic examples are given with respect to B.C. or A.D. as these are the designations given in the data sources.)

Flint mines in Poland are about the same age. They are assigned to the Funnel Beaker culture which existed from about 4,100 to 2,800 B.C. The mines were excavated in limestone, with cross sections as large as 4 by 4 m and lengths up to 15 m in areas where jointing was sparse and by smaller corridors-and-pillar methods where jointing was more closely spaced (<http://archterra.cilea.it/exhibits/>, last accessed 2/2/2006).

Around 1,500 B.C., the Egyptians began excavating tombs on the west bank of the Nile River across from Luxor for pharaohs, queens, nobles, and even workers. The tombs were excavated in limestone, which is massively bedded and jointed. The tombs are generally several meters in length and width and about 2 m in height; many have entrance corridors tens of meters in length and as much as 3 by 4 m in cross section. The total length for the pharaohs' tombs ranges from 25 to 200 m²⁴. Many tombs have pillars left for support in the larger rooms. Today, 62 tombs are known in the Valley of the Kings, 84 in the Valley of the Queens, and more than 500 tombs for workers and nobles²⁴ (p. 13, 72, 73, 140), which were excavated between the two famous valleys. Many of the tombs are open to the public, and of these most have incurred some water damage to plaster and paintings on the walls and ceilings, but none seems to have suffered collapse. Siliotti²⁴ suggested that some tomb sites were abandoned when the workers encountered "unsuitable rock formation", and thus the apparent lack of collapse may be due to careful selection of host rock.

Mining of metallic ores has produced subterranean openings in a variety of rock types, and in many cases, in badly altered or fractured rock. Unfortunately, many of the oldest examples have been mined continuously or reopened in more modern times to obtain the lower grade ore left by the ancient miners. For example, the Great Orme Mine in Wales was thought to be a Roman copper mine, but recent work by archaeologists from Liverpool has failed to confirm that the Romans ever worked the deposit (J.J. Taylor, University of Liverpool, written comm., 1/14/2001). Charcoal recovered from the early workings yields ¹⁴C dates from 900 to 1,800 B.C., which indicates the workings are of Bronze age. Part of the reason for the confusion as to the true age is that in 1832 and again in 1849, miners broke into caverns so well preserved that no one thought they could be older than Roman. The cavern discovered in 1832 was nearly 40 m long and contained stone hammers and bones²⁵; it was mined into limestone and had stood open for nearly 4,000 years. As of 2001, more than 7 km of old workings had been mapped with more than 3 times that amount remaining to be mapped (J.J. Taylor, University of Liverpool, written comm., 1/14/2001). The old mine has been open for public tours since 1991 (<http://www.walesdirectory.co.uk./mines>, last accessed 8/16/05).

The Laurion mines, about 40 km south of Athens, Greece, were first mined about 2,000 to 1,500 B.C., but were mined most actively from 600 to 300 B.C.²⁵ The mines are in a gently dipping sequence of mica schists and marble, and sulfides occur along the contacts. Shafts of 1.25 to 1.4 m by 1.5 to 1.9 m were sunk to depths as much as 111 m²⁵. Underground workings are 140 km in length; tunnels average 1 m in width and 1.75 m in height²⁵. Ore

zones were mined by underhand stoping that left large cavities a couple of meters high and a few meters in diameter that are still open today. Pillars of inferior ore-grade rock supported these cavities. Under Athenian mining laws, removal of rock from any pillars was punishable by death²⁵.

Phlogopite schist, in contact with a granite stock, formed the host rock for a low-grade emerald mine at Wadi Sikait, Egypt. The mine was first opened during the 1st century B.C. and was mined by the Romans until about the 6th century A.D. Tunnels reached as deep as 100 m²⁶. Also excavated at Wadi Sikait is a 1st-century B.C. temple, which was carved into a talc schist. In spite of the poor rock quality, the temple has not collapsed, though roof lintels and support pillars are badly cracked (J.M. Bunbury, Cambridge University, written comm., 1/23/2002).

The Israelis, Greeks, Persians, and Romans constructed a large number of tunnels, largely for the purpose of transporting water. One of the oldest of these is the Hezekiah tunnel, which was excavated in the 8th century B.C. The tunnel is under Jerusalem and was excavated in limestone. The tunnel is 553 m long, about 2 m high, and less than a meter wide. The tunnel is mentioned in two different books of the Bible.

The tunnel of Eupalinus (fig. 2), on the Greek island of Samos (fig. 3), was constructed around 530 B.C. to transport water beneath Mount Castro. The tunnel is 1.8 by 1.8 m in cross section, 1,045 m in length, and as much as 180 m below land surface. Comparison of the maps of Ring and others²⁷ and Apostol²⁸ shows that the tunnel was constructed in Neogene sedimentary rocks, and from several pictures, it is likely that the tunnel is within the carbonate portion of that section, which is 400 m thick. Water was actually transported in ceramic pipes below the level of the tunnel shown in figure 2.

FIG. 2. A. Tunnel of Eupalinus, copyrighted photograph courtesy of "Engineering & Science"²⁸ (also viewable at <http://www.mlahanas.de/Greeks/Eupalinos.htm>, last accessed 2/2/06).

The Greeks excavated several tunnels in what is now Italy. The Albano tunnel (approximately 20 km southeast of Rome, Italy (fig. 3)) is 1,450 m long, and was excavated in the 5th century B.C.²⁹ The tunnel supplies the Albano Cistern. The cistern is a large underground opening with an area of about 1436 m² and a total volume of 10,123 m³. The roof is supported by masonry pillars and brick arches. Two pictures are shown at <http://goeurope.about.com/gi/dynamic/offsite.htm?site=http://www.underome.com/> (last accessed 1/29/2006, click underground sites list). The Nemi tunnel (also southeast of Rome, Italy, fig. 3) is 1,653 m long, and was probably excavated around the end of the 6th or early 5th century B.C.²⁹ The age is assigned on the basis of a lack of written record (making it pre-Roman) and on the age of a temple on the shore of Lake Nemi.

The aqueduct beneath Naples, Italy (fig. 3) differs from the previous examples in that it was modified several times in its history. The Greeks excavated the original aqueduct in tuff during the 5th century B.C.³⁰ It was about 6.4 km long, and as much as 40 m below the city. In 326 B.C., the Romans expanded the system³⁰ to 400 km in length, and lined the bottom with concrete because the porous tuff absorbed much of the water during transport and storage. There are sections of the aqueduct that are like the tunnel pictured in figure 2, and these are probably original openings. However, some sections are very large, being several meters in length, width, and height (fig. 4).

FIG. 3. Location map for the Greek and Roman tunnels discussed in the text and for the Italian caves studied for paleoseismicity: A, Albano Tunnel; B, Nemi Tunnel; C, the aqueduct of Naples; D, Eupalinus Tunnel; E, Grotta del Cervo and Grotta a Male; F, Spipola and Buco Dei Buoi caves just south of Bologna; G, Frassimo cave of Lombardi.

FIG. 4. Large cisterns excavated in tuff 40 m below Naples, Italy, and part of the 400-km-long aqueduct system.

The Persians excavated aqueducts most commonly transliterated as qanats, kanats, ganats, or quanats, but other spellings and regional variations, such as kahriz or khattara, also occur. As recently as 1935, Teheran, Iran, with a population at that time of 275,000, was supplied by 36 kanats 13 to 26 km in length and as deep as 150 m, and these had been in use for at least 200 years³¹ (p. 6-9). One kanat supplying a suburb of Teheran with water was reportedly 60 m deep. As recently as 1968, kanats supplied 75 percent of the water used in Iran³². Kanat building has been going on since at least 800 B.C. Many have been excavated in the alluvial fans, which are dominantly

derived from tuff and limestone³¹. The latter supplies enough calcium carbonate to at least partly indurate the fans. About 22,000 kanats are known in Iran, consisting of more than 270,000 km of tunnels³². Throughout most of their length, kanats have no ground support but in unstable ground, oval hoops of baked clay are used as ground support. Kanat openings are about 1 by 1.5 m, and the first 3 to 5 m are commonly reinforced with stone, mainly as a protection from storm-water surges³².

Based on the current literature search, it is uncertain whether any of the kanats dating from several centuries B.C. have been in continuous use from antiquity to the present. It is likely that some kanats are old because there are reports of continuous maintenance, which is required to remove silt and to repair occasional areas of collapse. The Bam earthquake of December 26, 2003 (M= 6.6) caused serious damage to the kanats used for irrigation in the affected region (UN press release SAG/211). Web site <http://www.iraniantrade.org/NewsUpdates/00000877.htm> provides more information on kanats and notes that they are found in at least 34 countries.

Kanats were introduced to Egypt around 500 B.C. where they irrigated more than 4,600 km² of land³¹. Although their individual lengths are not known, they likely extend hundreds of kilometers under the desert eastward to intersect seepage from the Nile River³¹. Until the early 20th century, some of the Egyptian kanats were still flowing and were thought to be natural springs until ancient documentation and investigation showed that they were indeed kanats.

The Etruscans buried their dead in excavated tombs starting in the mid-7th century B.C.³³ More than 6,000 tombs have been discovered and there may be 2 to 3 times that number. The town of Tarquinia, which is about 100 km north of Rome, is home to some of the more famous tombs. East of town, there are about 20 tombs mostly constructed around 500 B.C., but one is as young as 125 B.C.; twelve of the tombs could be visited by tourists in May of 2003. The tombs, excavated in tuff, have openings roughly 4 by 5 by 2 m, and the ceilings are only about 2 m below ground surface. One of the tombs visited in 2003 had a large spall from the roof caused by apparent movement on a subvertical joint, but there was no other evidence of collapse.

The following information was taken from <http://www.catacombe.roma.it/> and http://en.wikipedia.org/wiki/Catacombs_of_Rome (last accessed Aug. 2, 2005). In the 2nd century A.D., Christians

started burying their dead in excavated catacombs. There are 5 known in and around Naples and 60 in the vicinity of Rome; 5 of the catacombs in the vicinity of Rome are open for public tours. The catacombs of Rome occupy about 600 acres (nearly 250 hectares), are about 1,000 km in length, and are 7 to 19 m deep. Apparently all of the catacombs of Naples and Rome are excavated in tuff. Passageways in the catacombs are generally narrow (2.5 by 1 m), but some of the galleries are several meters in length, width, and height.

Underground mining for metals throughout Europe was common during the reign of the Roman Empire. This era of mining erased evidence of the size and state of preservation of earlier mines, and much of the preservation of Roman mines, in turn, has been destroyed by subsequent mining, especially open pit mining. For example, the sulfide deposits at Rio Tinto, Spain, have been mined by the Tartessans about 5,000 years ago, followed by the Phoenicians, Carthaginians, Romans, Visigoths, Moors, and British^{35,34}. The last mining was by open pit, which by 1935 had left only a few galleys exposed in the walls of the pit³⁴. Shepherd²⁵ and Davies³⁵ presented location information and descriptions for most of the ancient mines, two of the gold mines (Dacia in Romania and Dolaucothi in Wales) are currently open for tours. In addition to mining for metals, the Romans created large tunnels to transport water. The tunnel at Tresminas, Portugal, is 60 m wide, 80 m high, and 480 m long, and the tunnel at Corta das Coras is 100 m by 100 m and 350 m long²⁵.

Another example of man-made openings are the Buddhist temples excavated in the Deccan basalts of west-central India. These date from approximately the 2nd century B.C. until the 10th century A.D.³⁶ Although man-made, these excavations are commonly referred to as Buddhist caves. There are 31 caves at Ajanta, some of which date back to the 2nd century B.C., but most were excavated in the late 5th or early 6th century A.D. They 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. The monsoonal climate has destroyed the exterior stone structures exposed to the elements, but subterranean openings are well preserved.

The sizes of the Buddhist caves at Ajanta are reported and each excavation has a larger cross section than that proposed for the mined geologic repository at Yucca Mountain. 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 m³⁶ (p.31). 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, there is no reported collapse. As in the case of the Egyptian tombs, most of the Ajanta paintings appear to have suffered some water damage and vandalism.

Similarly preserved are Buddhist caves from the 5th through the 10th centuries A.D. at Ellora and from the 9th century A.D. at the Jain caves at Sittanavasal³⁶. The Jain monks also excavated caves into the sandstone in northeastern India in the 2nd century B.C. The 25 excavated Buddhist caves are currently standing open and are advertised as a tourist attraction (<http://www.indyahills.com/orissa/udaygiri.html>, last accessed July 21, 2005). Buddhist monks also excavated caves in the sandstone of Dunhuang, China. These range in age from 4th to 14th centuries A.D. A total of 812 caves are known with rooms large enough to contain paintings that cover more than 45,000 m²³⁷.

During the 2nd through 11th centuries A.D., the Christians of Cappadocia, Turkey, excavated underground cities and churches. One of these cities, Derinkuyu, covered approximately 4 km² and had an estimated 15,000 to 20,000 inhabitants³⁸ during much of the first millennium A.D. As of 1994, eight levels of ancient habitation had been investigated. Access to the underground cities was by way of narrow passageways that could be closed by rolling a 1.5-m-diameter millstone across the opening (fig. 5). The excavated rooms were generally several meters across and more than 10 m long.

FIG. 5. Photograph of a room in the underground city of Kaymakli, Turkey. The millstone is about 1.5 m diameter [14, p. 21]

The geology of Cappadocia³⁸ is similar to that of southern Nevada³⁹. In both regions, the upper Tertiary section is composed of a thick sequence of silicic volcanic rocks. At Yucca Mountain, the host rock for the proposed repository is a densely welded, quartz latite ash-flow tuff formed about 11.8 Ma, whereas the underground cities of Cappadocia are hosted by a partially welded, rhyolite ash-flow tuff formed about 4.5 Ma. The difference in welding for the proposed repository horizon at Yucca Mountain and the hostrock for the underground cities of Cappadocia results in a markedly different fracture density and engineering properties. Fracture density, which is a major variable contributing to underground collapse, is much less in the underground cities, and no ground support was used (fig. 5). Thus, the fact that there has been no collapse in the underground cities during the past 1,500 to 1,800 years suggests that excavations in tuff should be stable for long periods of time. In the case of Yucca Mountain, where fracture density is greater, ground support will be carefully engineered, but even after that support degrades, there is little predicted collapse for the emplacement tunnels¹. The Cappadocia example seems to support this prediction.

Churches were excavated into the tuff at Goreme, north of the underground cities, during the 9th to 13th centuries A.D.³⁸ All but one of these shows no evidence of collapse, the exception being collapse of a cliff face, exposing part of the inside of one church. The interior portions of the church are still in excellent condition, and the painted walls and ceilings are well preserved except for minor water damage and vandalism¹⁴ (p. 19).

Some of the underground openings excavated into the tuffs of Cappadocia are still used as dwellings. There are at least two other places where underground excavations also are still used as dwellings. 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 limestone⁴⁰. The limestone is composed of 2-m-thick layers of poorly indurated limestone, which are easily mined out, as well as better indurated layers of similar thickness, which form ceilings. Room sizes are typically 2 to 2.5 m on a side with flat ceilings that may have a supporting column in the center. In northern China, there are thick deposits of loess, which is only slightly indurated and easily excavated. However, its internal structure is such that it can form vertical cliffs as much as 30 m high. The underground dwellings accommodate more than 10 million people who farm the land above their houses⁴⁰.

Although all the examples given so far either lack ground support or utilize only unmined pillars, there are examples of wooden ground support. Around the beginning of the second century A.D., the Roman Emperor Hadrian mandated the use of wooden supports in all mines²⁵. Shepherd²⁵ provided a discussion of some examples, but did not comment on the stability of openings that were shored up. Tombs in China provide a different kind of example. Sixteen emperors from the Ming Dynasty (1368 to 1644 A.D.) were buried in tombs excavated in rock near Beijing. The earliest of the tombs has 32 sandalwood pillars 1.17 m in diameter, and all are still intact and sturdy⁴¹.

IV. RESPONSE OF CAVES TO SEISMICITY

The foregoing discussion shows that both natural and man-made underground openings hold up well in an undisturbed setting. In actual fact, many of the examples given, as well as several others not discussed, have probably survived significant ground shaking. For example, the caves of Ajunta are within a seismically active area of India, and the Laurion mines, as well as the Israeli, Greek, and Roman tunnels are within seismically active areas around the Mediterranean Sea. Yucca Mountain also is within a moderately seismic region and some degree of ground shaking will likely occur during the 10,000-year post-closure time, and almost certainly during the next million years.

Natural analogues provide one possible way of assessing ground motion because they can add a dimension of time that is not available with instrumental or even historical records. Archaeological examples such as tombs and tunnels, as well as natural features such as caves and balanced rocks, can provide insight into long-term seismic records. For example, pillars at the Byzantine church of Sussita in the Golan Heights of Syria were knocked down by an earthquake January 18, 749 A.D., and apparently they were all tipped in the same direction in response to the first motion. Their orientation lying on the ground apparently records the azimuth of that motion.

Seismic damage to caves is well documented in several publications; however, documentation of caves with no damage is probably under-reported. Mitchell Caverns, California is located about 95 km from the Hector Mine Earthquake of 1999 ($M = 7.1$) and 110 km from the Lander Earthquake of 1992 ($M = 7.4$)⁴². The Lander event caused some fracturing of stalagmites near the entrance of the cave, but neither event disturbed delicate formations deeper in the cave (fig. 6). Neither event appears to have caused failure of the roof or walls of the cave.

FIG. 6. Photographs of Mitchell Caverns, California, showing (left) a cracked stalagmite near the entrance and (right) an intact delicate stalactite from deeper in the cave.

The Sutherland Peak Earthquake of 1887 (centered about 20 km SSW of the New Mexico-Arizona border in Sonora, Mexico) had an estimated magnitude of 7.2 and an intensity of XI to XII in the vicinity of the epicenter⁴³. The seismic activity was severe enough at Sutherland Peak Cave to knock over one large stalagmite, although failure may have been largely due to failure of the clay beneath it. Soda straws, which are thin hollow stalactites, were broken off and stuck in the clay floor. The report by Gilli and Serface⁴³, which is specifically about paleoseismic damage to caves, did not mention damage to the roof or walls of the cave. Kartchner Caverns, approximately 50 km to the north but within the same intensity zone of IX⁴⁴, did not incur visible damage.

Damaged soda straws have been used in two separate studies of seismic damage within caves. In the first of these, the orientation of broken soda straws was measured in Paradet Cave, France. These were broken by a 1996 magnitude 5.2 earthquake with an epicenter 10 km away and acquired a strong preferential east-west alignment on the floor of the cave⁴⁵ in response to the direction of ground motion. The damage was common at the 60-m level. This relatively great depth for damage may relate to the fact that the cave is tectonic in origin, being situated on a 50°-dipping reverse fault. Also, the cave is located on a limestone crest, which may have had an amplifying effect. Soda straws are very fragile, and Gilli and others⁴⁵ estimate that peak ground acceleration of 7 m/sec² or greater is needed to cause homogeneous soda straws to break and fall. This acceleration is 5 times greater than that observed on the spectrum with 5 percent damping, but Gilli and others⁴⁵ asserted that accelerations of 3 to 4 m/sec² are

commonly observed for magnitude 5 earthquakes at small distances from the epicenter and 5% damping, and even higher accelerations are possible with smaller percentages of damping. They note that other variables must have been involved, in that all the straws were not broken. Again, there was no mention of damage to the roof or walls of the cave.

The second study involving soda straws was in Observatoire Cave, Monaco, where abundant flowstone on the floor of the cave partly covers some broken soda straws and completely buries others as revealed by drill core taken from the floor of the cave. Gilli⁴⁶ attributed the youngest layer of broken soda straws to an 1887 earthquake, which had an intensity of VIII in the vicinity of the cave. A deeper layer, also with broken soda straws, was likely the result of an earthquake in 1564 for which the cave was just outside the intensity VIII contour. The end of the drill core penetrated a broken stalactite in a layer dated as greater than 35,000 years. This oldest event was likely the only one intense enough to cause roof or wall failure, but any such evidence has been buried by flowstone. No failure of the cave due to earthquakes more recent than 35,000 years was described.

Spipola and Buco Dei Buoi are two caves just south of Bologna, in northeastern Italy (fig. 3) that have experienced considerable tectonic activity. Longitudinal cross sections were cut through 2 stalagmites, one from each of these caves, and for both stalagmites the axis of growth had changed several times. Inasmuch as growth should be vertical, Postpischl and others⁴⁷ concluded that variations in apparent direction of growth were due to tectonic shifts in the surface upon which the stalagmites were growing. They chose to correlate the largest shift in the growth axes to the largest historical earthquake, which had an intensity of X to XI in the vicinity of the caves. They then calculated an average growth rate of 0.12 to 0.15 mm/yr, which was used to approximately date each growth band. Each discontinuity correlated with the timing of a known earthquake for which the epicenter was within 15 km and for which the intensity in the vicinity of the caves was greater than VI (fig. 7). The most intense events knocked over some stalagmites and caused some offset of stalagmite-stalactite pairs, but no general collapse of the caves was reported.

FIG. 7. Cross sections through two stalagmites from caves in northeastern Italy. Dates in ovals were calculated from distance between growth bands. Growth rate was calculated by assuming that the earthquake of January 3, 1117 (marked with an asterisk) created the large change in axis direction. Intensities for the dated events (shown in boxes) from most recent to oldest were VII, VI – VII, VII, VII, VI, VIII, VIII, VII, VII, VIII, VIII, VI, VI, VI-VII, and X-XI⁴⁷.

The acceleration needed to knock over stalagmites was studied by bending tests on previously failed stalagmites from Hotton Cave in Belgium. The results for 35 acceleration tests conducted by Cadorin and others⁴⁸ ranged from 0.3 m/s² to 100 m/s² for height-to-diameter ratios of about 8. The authors noted that other factors must be involved to account for the very large accelerations calculated; for example, the stalagmites were already broken and the breaks may have occurred only on the weak planes

Farther to the north of Bologna in Lombardi, Frassimo cave (fig. 3) has evidence of major tectonism without collapse. One passageway is offset along a gently dipping joint by more than a meter but with no apparent damage to the roof⁴⁹. Offset of passageways without reported roof collapse also has been reported in Costa Rica⁵⁰, where the studied caves are within 50 to 100 km of seven magnitude 7 or greater earthquakes in the last century alone. Bini and

others⁴⁹ reported that speleothems in Frassimo cave that have been knocked down yield U-Th ages (presumably for the outer surfaces) that are greater than 350,000 yrs. Thus, the passageway in which the broken speleothem was found must have remained open for at least 350,000 yrs, in spite of repeated seismic events.

Paleoseismic studies also have been conducted in caves of central Italy, about 70 km east to southeast of Rome. The Grotta del Cervo and Grotta a Male (fig. 3) both have evidence of seismic shaking. The karst area is adjacent to the area affected by the strongest earthquake in Italian history.

The December 1456 earthquake caused a rock slide that closed the entrance to Grotta del Cervo. The cave remained closed until uncovered in 1986. Carbon-14 dating of calcite shows that breakage of speleothems, which now lie on the floor for the first 400 m inside the cave, was due to the 1456 earthquake⁴⁷. The collapsed stalagmites have a preferred orientation on the floor of the cave, which reflects the effects of ground motion. Beyond 400 m, the stalagmites appear to have remained upright, but some fracturing of the wall was noted. In addition to the ¹⁴C dating, speleothems have been dated by the U-Th method. These results reveal four older seismic events intense enough to topple stalagmites (30,000-40,000, 90,000-110,000, 110,000-150,000, and greater than 350,000 years ago). In spite of recurring strong seismicity, there are no reports of roof collapse.

The Soreq and Har-Tuv caves, in Israel, are located approximately 40 km west of the Dead Sea transform, which is a major strike-slip fault and similar in some ways to the San Andreas fault in the western United States. It is 1,000 km long, with a slip rate during the last 1,000 to 1,500 years of 15 to 35 mm/yr⁵¹ as compared to a length of 1200 km and a slip rate of 20 to 35 mm/yr for the San Andreas (http://www.data.scec.org/fault_index/sanandre.html, last accessed 7/26/05). The caves are small (<5,000 m²⁵²), and had no natural opening prior to their discovery during excavation in the 20th century. Damaged speleothems have been dated by the U-Th method and correlated with a lacustrine record. The ages extend back 185,000 years, and there is evidence for 13 to 18 episodes of seismic damage. The authors argue that intensities greater than VI to VII are needed to damage speleothems, noting that a 1927 earthquake with a magnitude of 6.2 did not damage the caves. The authors posit that the observed damage could have been caused by a range in magnitudes from 7.6 to 8.2, with a corresponding range in recurrence intervals of 6,000 to 10,000 years. Some roof collapse in response to seismicity was noted in the study of Soreq and Har-Tuv caves⁵¹, but the collapse did not reach land surface.

V. RESPONSE OF ANTHROPOGINIC UNDERGROUND OPENINGS TO SEISMICITY

Several compilations on the response of tunnels to seismic disturbances are available. Considerable information (largely anecdotal) also is available from mines and other subterranean excavations. In all settings, the lack of damage below ground as the result of a seismic event probably is under-reported. This section summarizes information from geologic and archaeologic sources.

Raney⁵³ summarized the effects on western United States mines from 28 historical earthquakes of intensity VIII or greater. Most mines that were close to an earthquake (24) reported no damage at depth; a few (3) reported minor damage such as cracked timbers; a few others (3) reported major or unspecified damage. Damage to surface structures was ubiquitous. For example, the Owens Valley earthquake, California (also referred to as the Lone Pine earthquake) of 1872, had an intensity of X to XI and may have had a magnitude of 8. Effects of this earthquake were reported from many surrounding sites. The earthquake was rumored to have caused breakage of a few sets of timbers in some mines in the vicinity of Austin, Nevada about 320 km to the north-northeast. The earthquake was felt distinctly in the vicinity of Virginia City, Nevada, about 320 km to the north-northwest. The earthquake cracked some timbers in the quartz mines in the vicinity of Jackson, California, about 240 km to the northwest. The mining camp of Cerro Gordo, about 30 km southwest of the epicenter, was severely damaged, but two separate accounts reported that no damage occurred underground. At Hot Springs (presumably Benton, California, which is about 130 km to the northwest), several severe shocks were felt on the surface, but miners at the 60-m level felt nothing. About 50 km south-southwest of the epicenter, there was heavy damage to railroad tracks, roads, and homes at the Eclipse Mine, and damage to the mill of the Kearsarge Mine, but there was no damage reported for the underground workings. At the Eclipse Mine, one miner was injured by a minor rock spall. Finally, miners in the underground in the vicinity of Bakersfield, California (about 130 km southwest of the epicenter), did not feel the earthquake.

Raney's⁵³ only documented example of major mine damage underground was proximal to the epicenter. The Kennedy Mine was reported to be "near the epicenter" of the Pleasant Valley earthquake, Nevada. The earthquake, which occurred in 1915, had an intensity of X and a magnitude of 7.7. It caused "a considerable portion of mine tunnels" to cave in; however, no damage was reported in the underground at the Golconda mine (165 km

from the Kennedy mine) or at Elko (70 km from the Kennedy mine). Brown and others⁵¹ (p. 8) provide a caveat about reports of damage to mines noting that stress changes due to extraction of ore can contribute to the susceptibility of mines to earthquake damage.

Stevens⁵⁵ noted that if the dimensions of mine openings are considerably smaller than the wave length of an incident SH (horizontal shear) wave, ground motion at the surface will be about twice as great as that at depth. Furthermore, solid rock is a good energy transmitter, and as such, waves pass through it without losing velocity. If speed is lost, kinetic energy is maintained by increased amplitude, which in turn causes increased shaking. These factors apparently account for the numerous reports of earthquakes being felt strongly at the surface, but not noticed at depth; Stevens⁵⁵ relates seven such cases. This is not universally true, and Stevens⁵⁵ relates six instances where shaking was felt in mine workings to at least a minor degree. This apparent disparity may be explained by variations in the fundamental period of an earthquake. When the period is less than 1 second, the aboveground amplitude is at least twice the below-ground amplitude, but when the period is increased to 4 seconds or greater, the amplitudes above and below ground are about the same⁵⁴.

As with mines, there is considerable anecdotal information on stability of tunnels during seismic events. Many of the tunnels described earlier are located in seismically active areas, although no specific mention was made of their stability in response to seismic shaking in the literature examined for this paper. The tunnel of Hezekiah is only about 30 km from the Dead Sea transform fault system and as such has probably been subject to several moderate to severe earthquakes; however, there has been no apparent damage. The tunnel of Eupalinus is in close proximity to the ancient Greek town of Ephesus, which has been destroyed by earthquakes several times. Likewise, the Nemi and Albano tunnels of central Italy are within an area of strong seismicity, such as the 1456 earthquake that covered the entrance to Grotto del Cervo with a landslide, but reports of damage are lacking. Eckel⁵⁶ reports that the Good Friday Earthquake (M=9.2) in Alaska (fig. 8) caused no damage to the Alaskan Railroad tunnel near Whittier nor to the coal mines in the Matuska Valley. Minor damage was reported to the intake (which is in soft sediment) for the Eklutna hydroelectric tunnel, and the earthquake may have caused a longitudinal crack in the railroad tunnel between Cooper and Kenai Lakes. These tunnels were in the intensity zones of VII to X.

FIG. 8. Isoseismic map for the 1964 Good Friday Earthquake in Alaska showing location of tunnels near the epicenter. Modified from map on web site http://neic.usgs.gov/neis/eq_depot/usa/1964_03_28_iso.html last accessed 1/30/2006.

The understanding of the response of underground openings to seismic events has advanced greatly in the last 30 years. Sharma and Judd⁵⁷ for example, studied the susceptibility of underground facilities to damage and found that damage decreases with depth, and increases with increasing peak ground acceleration (PGA). The latter variable increases as earthquake magnitude increases and as distance from the epicenter decreases. Sharma and Judd⁵⁷ also noted that openings in solid medium behaved better than those in unconsolidated material. They also suggested that their data set is biased towards damage occurring because "there must be literally hundreds of other instances where no damage occurred but observations were not documented"⁵⁷ (p. 275).

Dowding and Rozen⁵⁸ compiled damage reports for tunnels as a function of peak ground acceleration at the surface. Their data showed that no underground damage occurred at less than 0.2 g and little to moderate damage between 0.2 and 0.5 g. Commonly, when damage was reported, it was near the portal or in areas of shallow cover. Dowding and Rozen⁵⁸ also noted that tunnels displaced by fault movement usually incur severe damage.

Brown and others⁵⁴ provided six case histories for tunnels with fault movement during earthquakes that document damage and one example for a tunnel displaced by right-lateral creep on the Hayward fault (California). Even when faults move and cut a tunnel, total collapse seems to be rare. A drainage tunnel driven along side of the Tanna Railroad tunnel (on the main line between Tokyo and Kobe, Japan) was collapsed by a 1930 earthquake

(estimated magnitude 7.1), but the main tunnel, estimated to be 0.5 m east of the active shear zone, incurred only minor cracking in the walls.

Pratt and others⁵⁹ also examined data for subterranean structures and found few data indicating damage in the subsurface due to earthquakes, which they concluded attested to the lessened effects with depth. They also noted that wells and shafts are not as susceptible to damage from earthquakes as are surface facilities and that higher frequencies (50 – 100 Hz) are more likely to damage subsurface facilities than the lower (2 – 10 Hz) frequencies that cause most of the surface damage.

Power and others⁶⁰ compiled data from 204 tunnels that had experienced seismic shaking including some data from earthquakes for which modern instrumentation or more detailed information was available. They observed that for ground motion with PGAs less than 0.2 g, there was little or no damage in tunnels, and for PGAs of 0.2 to 0.6 g damage varied from slight to heavy; however, all the reports of heavy damage were from a single earthquake in 1923 for which the damage may have been due to landsliding or collapse of shallow portions of one tunnel. At accelerations greater than 0.6 g, the damage only ranged from slight to moderate, which suggests that the tunnel response to the 1923 earthquake was anomalous. Powers and others⁶⁰ also noted (1) that damage was most likely in unlined tunnels and that reinforced concrete prevented heavy damage; (2) some reported damage may be due to causes other than seismic shaking; and (3) well-constructed tunnels can survive large peak accelerations without incurring major damage. For example, well-constructed tunnels near Kobe, Japan, experienced PGAs of about 0.6 g, but suffered no major damage.

Carpenter and Chung⁶¹ summarized the available literature on damage to underground facilities from earthquakes and underground nuclear explosions (UNEs) for the U.S. Nuclear Regulatory Commission. They concluded that (1) damage is expected underground if fault displacement occurs, but that damage from shaking alone is limited to the epicentral region with damage to surface facilities more severe than that below ground; (2) amplitude generally decreases with depth; and (3) earthquake damage may be a more serious problem for shafts than for tunnels.

Phillips and Luke⁶² set up an experiment using an UNE as an analogue specific to the proposed geologic repository at Yucca Mountain. They noted that, although the host rocks for the UNE experiment and potential repository were different (nonwelded air-fall tuff versus welded tuff at Yucca Mountain), the Rock Mass Ratings (RMR) were similar: 57 versus 61 (RMR is an internationally recognized index, based on 6 parameters, to calculate the stability of discontinuous rock masses). They noted three differences between earthquakes and UNEs: (1) shear waves dominate over compressional waves in earthquakes, but the opposite is true for UNEs; (2) duration of shaking is longer in earthquakes; and (3) frequencies may be different between the two types of seismic sources. Phillips and Luke⁶² analyzed each of these variables and concluded that the UNE was an adequate analogue for an earthquake in terms of seismic effects on a tunnel. Therefore, Phillips and Luke⁶² concluded that a 6.5 magnitude earthquake 16 km from Yucca Mountain should cause only minor damage to repository emplacement tunnels.

VI. CONCLUSIONS

Underground openings described in this paper are analogues for the stability of the emplacement tunnels at the proposed high-level nuclear waste repository at Yucca Mountain, Nevada. Natural and anthropogenic openings, in a variety of rock types, have stood open for thousands to millions of years, even in seismically active areas. These analogues support the reasonableness of predicted drift stability calculated for the drift degradation analysis report¹, which concluded that (1) even without ground support, there will be little collapse of the emplacement tunnels in either lithophysal or nonlithophysal units of the Miocene volcanic rocks under either static or thermal conditions; and (2) seismic events would cause (a) only minor tunnel damage in the nonlithophysal sections, and (b) only slightly more collapse in the lithophysal units. These conclusions cannot be tested directly with analogues, but their reasonableness can be assessed.

Caves in many rock types, but mostly in carbonates and lava, are known to stand open for tens of thousands to millions of years in regions where no seismic activity has been documented (although there may have been pre-historic activity). Caves also have been investigated in areas where strong ground motion has occurred many times. Damage to speleothems has been widely reported, but roof collapse is rare. If general collapse has occurred in response to seismicity, it is unreported or perhaps unrecognizable.

The record for anthropogenic underground openings spans a much shorter period of time, but it also attests to remarkable stability even in areas of strong seismicity. A few prehistoric mines that were not destroyed by subsequent mining are known to have stood open for as much as 5,000 years. There are thousands of tombs in limestone and volcanic rock that are more than 2,000 years old. There are several kilometers of tunnels in these same two rock types located in areas of strong seismicity, and these have not collapsed in more than 2,500 years. Even tunnels in partly indurated alluvium have survived in earthquake-prone areas with only partial collapse. This is not to say that mined openings do not collapse; even some fairly modern mines have collapsed. Subterranean excavations, however, can remain open for thousands of years, even in areas of strong seismicity.

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REFERENCES

1. BSC (BECHTEL SAIC COMPANY, L.L.C.), "Drift Degradation Analysis," ANL-EBS-MD-000027, REV 03, ACC: DOC.20040915.000027, 976 p., Bechtel SAIC Company, L.L.C., Las Vegas Nevada (2004). Accessed February 15, 2006, at <http://www.ocrwm.doe.gov/technical/amr.shtml>.
2. V.J. POLYAK, W.C. MCINTOSH, N. GUVEN, and P. PROVENCIO, "Age and Origin of the Carlsbad Cavern and Related Caves from $^{40}\text{Ar}/^{39}\text{Ar}$ of Alunite," *Science* **279**, 1919 (1998).
3. V.J. POLYAK and P. PROVENCIO, "Summary of the Timing of Sulfuric-Acid Speleogenesis for the Guadalupe Caves Based on Ages of Alunite," *Jour. Caves and Karst Studies* **62**, 2, 72 (2000).
4. V.J. POLYAK and Y. ASMEROM, "Late Holocene Climate and Cultural Changes in the Southwestern United States," *Science* **294**, 148 (2001).
5. V.J. POLYAK, J.B.T. RASMUSSEN, and Y. ASMEROM, "Prolonged Wet Period in the Southwestern United States through the Younger Dryas," *Geology* **32**, 1, 5 (2004).
6. T.J. GRIFFIN and I. MCDUGALL, "Geochronology of the Cainzoic McBride Volcanic Province, Queensland," *Jour. Geol. Soc. Australia* **22**, 4, 387 (1975).

7. A. ATKINSON, T.J. GRIFFIN, and P.J. STEPHENSON, "A Major Lava Tube System from Undara Volcano, North Queensland," *Bulletin Volcanologique* **39**, 266 (1975).
8. K.L. ROGERS, C.A. REPENNING, F.G. LUISZER, and R.D. BENSON, "Geologic History, Stratigraphy, and Paleontology of SAM Cave, North-Central New Mexico," *New Mexico Geology* **22**, 4, 89 (2000).
9. J.C. CARRACEDO, M. PATERNE, H. GUILLOU, F.J. PÉREZ TORRADO, R. PARIS, B. RODRÍGUEZ . y A. HANSEN, "Dataciones Radiométricas (^{14}C y K/Ar) del Teide y el Rift Noroeste, Tenerife, Islas Canarias," *Estudios Geológicos*, **59**, 15 (2003).
10. J.C. CARRACEDO and S. DAY, *Classical Geology in Europe 4 – Canary Islands*, 294 p., Terra Publishing, Harpenden, England (2002).
11. J.C. CARRACEDO, B. SINGER, B. JICHA, H. GUILLOU, E.y HANSEN A. RODRÍGUEZ BADIOLA, J. MECO, F.J. PÉREZ TORRADO, D. GIMENO, and S.y LÁINEZ A. SOCORRO, "La Erupción y el Tubo Volcánico del Volcán Corona (Lanzarote, Islas Canarias)," *Estudios Geológicos* **59**, 277 (2003).
12. O. BAR-YOSEF, M. ARNOLD, N. MERCIER, A. BELFER-COHEN, P. GOLDBERG, R. HOUSLEY, H. LAVILLE, L. MEIGNEN, J.C. VOEGEL, and B. VANDERMEERSCH, "The Dating of the Upper Paleolithic Layers in Kebara Cave, Mt. Carmel," *Jour. Archaeol. Sci.* **23**, 297 (1996).
13. O.K. DAVIS, "Caves as Sources of Biotic Remains in Arid Western North America," *Palaeogeography, Palaeoclimate, and Palaeoecology* **76**, 331 (1990).
14. J.S. STUCKLESS, "Archaeological Analogues for Assessing the Long-Term Performance of a Mined Geologic Repository for High-Level Radioactive Waste," *U.S. Geological Survey Open-File Report 00-181*, 27 p. (2000).
15. J.M. CHAUVET, E.B. DESCHAMPS, and C. HILLAIRE, *Dawn of Art – The Chauvet Cave*, 135 p., Harry N. Abrams, Inc., New York, New York (1996).
16. J. CLOTES and J. COURTIN, *The Cave Beneath the Sea – Paleolithic Images at Cosquer*, 200 p., Harry N. Abrams, Inc., New York, New York (1996).
17. M. RUSPOLI, *The Cave of Lascaux*, 208 p., Harry N. Abrams, Inc., New York, New York (1986).
18. P.A. SAURA RAMOS, *The Cave of Altamira*, 180 p., Harry N. Abrams, Inc, New York, New York (1998).
19. R.L. BREISCH, "The Conservation of European Cave Art," *National Speleological Society News*, 285 (1987).
20. M. DAY, *Sandstone Caves of Wisconsin, Proc. 13th International Congress of Speleology, Brasilia, Brasil, July 15-22, 2001*, 1, 89, International Union of Speleology (2001).
21. R. MANNELL, "Nangwarry Sandstone Caves," *Labrynth* **3**, 10, New South Wales Institute of Technology Speleological Society, New South Wales, Australia (1973).

22. D. COULSON AND A. CAMPBELL, *African Rock Art*, 256 p., Harry N. Abrams, Inc., New York, New York (2001).
23. H. CRAWFORD, *Subterranean Britain – Aspects of Underground Archaeology*, 201 p., St. Martin's Press, New York, New York (1979).
24. A. SILIOTTI, *Guide to the Valley of the Kings and to the Theban Necropolises and Temples*, 168 p., White Star S.r.l., Vercille, Italy (1996).
25. R. SHEPHERD, *Ancient Mining*, 494 p., Elsevier Applied Science, New York, New York (1993).
26. J.A. HARRELL, "Archaeological Geology of the World's First Emerald Mine," *Geoscience Canada* **31**, 2, 69 (2004).
27. U. RING, S. LAWS, and M. BERNET, "Structural Analysis of a Complex Nappe Sequence and Late Orogenic Basins from the Aegean Island of Samos, Greece," *Jour. Struct. Geol.* **21**, 1575 (1999).
28. T.M. APOSTOL, "The Tunnel of Samos," *Engineering and Science* **1**, 30 (2004).
29. V. CASTELLANI and W. DRAGONI, *Ancient Tunnels – from Roman Outlets Back to Early Greek Civilization*, *Proc. 12th Int'l Congress Speleology, La Chaux-de-Fond, Switzerland, August 10-17, 1997*, **3**, 265, International Union of Speleology (1997).
30. D. HOFSTADTER, "What Lies Beneath," *Smithsonian* **35**, 8, 100 (2004).
31. C.F. TOLMAN, *Ground Water*, 593 p., McGraw Hill Book Company, New York, New York (1937).
32. H.E. WULFF, "The Qanats of Iran," *Scientific American* **218**, 4, 94 (1968).
33. R. GORE, "The Eternal Etruscans," *National Geographic* **195**, 6, 696 (1999).
34. R.A. DAVIS JR., A.T. WELTY, J. BORREGO, J.A. MORALES, J.G. PENDON, and J.G. RYAN, "Rio Tinto Estuary (Spain) – 5000 Years of Pollution," *Environ. Geol.*, **10**, 10, 1107 (2000).
35. O. DAVIES, *Roman Mines in Europe*, 291 p. Clarendon Press, Oxford, England (1935).
36. B.K. BEHL, *The Ajanta Caves*, 256 p., Harry N. Abrams, Inc., New York, New York (1998).
37. R. WHITFIELD and S. OTSUKA, *Dunhuang – Caves of the Singing Sands, Buddhist Art from the Silk Road*, 356 p., Textile and Art Publications Ltd., London, England (1996).
38. V. TOPRAK, J. KELLER, and R. SCHUMACHER, *Volcano-Tectonic Features of the Cappadocian Volcanic Province, 1994, Proc. Int'l Volcanology Congress of the International Association of Volcanology and Chemistry of the Earth's Interior*, 58 p., Association of the International Union of Geodesy and Geophysics, Boulder, Colorado (1994).

39. D.A. SAWYER, R.J. FLECK, M.A. LANPHERE, R.G. WARREN, D.E. BROXTON, and M.R. HUDSON, "Episodic Caldera Volcanism in the Miocene Southwestern Nevada Volcanic Field – Revised Stratigraphic Framework, $^{40}\text{Ar}/^{39}\text{Ar}$ Geochronology, and Implications for Magmatism and Extension," *Geol. Soc. Amer. Bull.* **106**, 1304 (1994).
40. G.S. GOLANY, *Earth-Sheltered Habitat, History, Architecture and Urban Design*, 240 p., Van Nostrand Reinhold Company, New York, New York (1983).
41. G.S. GOLANY, *Urban Underground Space Design in China, Vernacular and Modern Practice*, 160 p., University of Delaware Press, Newark, New Jersey (1989).
42. F.F. POLLITZ, C. WICKS, AND W. THATCHER, "Mantle Flow Beneath a Continental Strike-Slip Fault -- Postseismic Deformation After the 1999 Hector Mine Earthquake." *Science*, **293**, 1814 (2001).
43. E. GILLI and R. SERFACE, "Evidence of Paleoseismicity in the Caves of Arizona and New Mexico (USA)," *Surface Geosciences* **329**, 31, Academy of Sciences, Paris, France (1999).
44. C.W. STOVER and J.L. COFFMAN, "Seismicity of the United States 1568-1989 (Revised)," *U.S. Geological Survey Professional Paper* **1529**, 418 p. (1993).
45. E. GILLI, A. LEVRET, P. SOLLOGOUG, and P. DELANGE, "Research on the February 18, 1996, Earthquake in the Caves of Saint-Paul-de-Fenouillet Area, (Eastern Pyrenees, France)," *Geodinamica Acta* **12**, 143 (1999).
46. E. GILLI, "Evidence of Palaeoseismicity in a Flowstone of the Observatoire Cave (Monaco)," *Geodinamica Acta* **12**, 159 (1999).
47. D. POSTPISCHL, S. AGOSTINI, P. FORTI, and Y. QUINIF, "Palaeoseismicity from Karst Sediments – The 'Grotta del Cervo' Cave Case Study (Central Italy)," *Tectonophysics* **193**, 33 (1991).
48. J.F. CADORIN, D. JONGMANS, A. PLUMIER, T. CAMELBEECK, S. DELABY, and Y. QUININ, "Modelling of Speleothems Failure in Hotton Cave (Belgium) — Is the Failure Earthquake Induced?" *Netherlands Jour. Geosciences/Geologie en Mijbouw* **80**, 3-4, 315 (2001).
49. A. BINI, Y. QUINIF, O. SULES, and A. UGGERI, "Les Mouvements Tectoniques Recent dan les Grottes du Monte Campo Dei Fiori (Lombardie, Italie)," *Karstologia* **19**, 23 (1992).
50. E. GILLI, "Effets des Seismes dans l'Endokarst – Application aus Etudes de Sismicite Historic," *Revue d'Analyse Spatiale Quantitative et Appliqué* **38-39**, 121 (1996).
51. Z. GARFUNKEL, I. ZAK, and R. FREUND, "Active Faulting in the Dead Sea Rift," *Tectonophysics* **80**, 1 (1981).

52. E.J. KAGAN, A. AGNON, M. BARMATTHEWS, and A. AYALON, "Dating Large Infrequent Earthquakes by Damaged Cave Deposits," *Geology* **33**, 4, 261 (2005).
53. R.G. RANEY, "Reported Effects of Selected Earthquakes in the Western North America Intermountain Region, 1852-1983, on Underground Workings and Local and Regional Hydrology – A Summary," U.S. Nuclear Regulatory Commission Report NNI-1988-3143, 114 p., U.S. Nuclear Regulatory Commission, Washington, DC (1988).
54. I. BROWN, T. BREKKE, and G. KORBIN, "Behavior of the Bay Area Rapid Transit Tunnels through the Hayward Fault," Report for U.S. Department of Transportation, UMTA-CA-06-0120-81-1, 208 p., U.S. Department of Transportation, Urban Mass Transportation Administration, Office of Technology Development and Deployment, Office of Rail and Construction Technology, Washington, DC (1981).
55. P.R. STEVENS, "A Review of the Effects of Earthquakes on Underground Mines," *U.S. Geological Survey Open-File Report 77-313*, 47 p. (1977).
56. E.B. ECKEL, "The Alaskan Earthquake March 27, 1964 – Lessons and Conclusions," *U. S. Geological Survey Professional Paper 546*, 57 p. (1970).
57. S. SHARMA and W.R. JUDD, "Underground Opening Damage from Earthquakes," *Engineering Geology* **30**, 263 (1991).
58. C.H. DOWDING and A. ROZEN, "Damage to Rock Tunnels from Seismic Shaking," *Jour. Geotechnical Engineering Division* **104**, GT2, 175 (1978).
59. H.R. PRATT, W.A. HUSTRULID, and D.E. STEPHENSON, "Earthquake Damage to Underground Facilities," 84 p., E.I. Du Pont de Nemours and Company, Savannah River Laboratory, Aiken, South Carolina, (1978).
60. M.S. POWERS, D. ROSIDI, and J.Y. KANESHIRO, "Seismic Vulnerability of Tunnels and Underground Structures Revisited," *Proc North American Tunnelingconference '98*, North Beach, Calif, 243, Balkema, Rotterdam, The Netherlands (1998).
61. D.W. CARPENTER and D.H. CHUNG, "Effects of Earthquakes on Underground Facilities – Literature Review and Discussion," U.S. Nuclear Regulatory Commission NUREG/CR-4609, 53 p., U.S. Nuclear Regulatory Commission, Washington, DC (1986).
62. J.S. PHILLIPS and S.A. LUKE, *Tunnel Damage Resulting from Seismic Loading, Proc. 2nd Int'l Conference on Recent Advances in Geotechnical Earthquake Engineering & Soil Dynamics, St. Louis, Missouri, March 11-15, 1991*, 1, 207 (1991).