Caves, Speleothems and Excavations in Seismically Active Areas

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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 and 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. They apparently all tipped in the same direction in response to the first motion, and their orientation on the ground still retains that record of that direction.

Brune and Whitney (2000) have shown that precariously balanced rocks, such as those at Yucca Mountain, Nevada, can act as natural strong-motion detectors. Strongly varnished rocks piled atop one another or perched at the edge of ledges attest to long periods of seismic stability. Additionally, sparse occurrences of large boulders at the base of Yucca Mountain suggest a lack of events that might have dislodged precariously balanced rocks for extended periods of time. Yucca Mountain provides a second type of natural analogue for seismicity. On the west side of Busted Butte erosion has exposed the Paintbrush fault where it cuts a series of nearly continuously deposited sediments. This exposure records the timing and amount of vertical displacement for each rupture during the last 760,000.

Anecdotal information suggests that effects of earthquakes are much greater for surface structures than for subsurface ones. In general, amplitudes of surface motions are about double those at depth, and effects die out with increasing depth, and thus openings at the surface are more affected than areas at depth. Mines and tunnels intersected by faults are usually damaged. Close proximity to an epicenter yields more damage, and larger earthquakes cause more damage. Damage is least in competent rock. Anecdotal information is likely bias in that null effects may be under-reported.

Raney (1988) summarized the effects on western US mines from 28 historic earthquakes of intensity 8 or greater. Most mines (24) reported no damage at depth; a few reported minor (3) to major (3) damage. Damage to surface structures was ubiquitous. Dowing and Rozen (1978) and Powers et al. (1998) compiled damage reports for tunnels as a function of peak ground acceleration at the surface. Both compilations showed no underground damage 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. Powers et al. (1998) also noted that damage was most likely in unlined tunnels and that reinforced concrete never suffered heavy damage.

Natural analogues can be used to extend the seismic record even further back in time. Five examples of tunnels in seismically active areas and apparently undamaged by multiple earthquakes include:

1) Naples tunnel (Italy) 400 m in length, excavated in the 4th century B.C.
2) Nemi tunnel (near Rome, Italy) 1653 m in length, excavated in the mid 4th century B.C.

3) Albano tunnel (near Rome, Italy) 1450 m in length, excavated in the 5th century B.C.

4) Eupalinus tunnel (Samos, Greece) 1045 m in length, excavated in the mid 6th century B.C.

5) Hezakiah tunnel (Jerusalem) 553 m in length, excavated in the 8th century B.C.

Other examples of man-made underground structures surviving for extended periods of time include the dozens of Egyptian tombs across the Nile River from Luxor which are excavated in limestone, dozens of pre-Roman mines, and hundreds of Roman mines. Buddhist temples in north western India, excavated in basalt, have withstood seismic activity for 1400 to 2200 years. As a finally, there is a large (70 x 40 m) cistern under Istanbul that was built in 602 A.D. The roof is a series of masonry arches supported by 336 columns all, of which have withstood several large earthquakes including the 1999 Izmet earthquake (M=7.4).

The inclusion of caves in natural analogue studies extends the time record by orders of magnitude and greatly increases the geographic area covered. Caves do record seismic activity, as shown by Mitchell Caverns in southern California which had to be closed for a few weeks after the Hector Mine Earthquake (M=7.1) in 1999 for which surface rupture was located about 60 miles to the west. Damage, however, was restricted to one entrance; delicate structures deeper in the cave were undamaged. Southerland Peak Cave in southern Arizona was within intensity zone IX of the Southerland Peak earthquake in 1887. One stalagmite fell (probably due to failure of its clay base), and several soda straws broke and stuck in the clay floor. A larger, but otherwise similar stalagmite in nearby Kartchner Cavern apparently was unaffected. The base of the Kartchner stalagmite is known to be 60 m below land surface. Depth below land surface is likely an important variable for speleothem damage, but that datum is rarely reported.

Several caves in Europe have been studied extensively as recorders of paleo-seismology. For example, broken soda straws on the floor at the 60-m level of Observatoire Cave in Monaco can be correlated with an 1887 earthquake of intensity VIII. Gilli et al. (1999) concluded that such breakage required an acceleration of 7 m/sec^2 or greater. Drilling of the flow stone on the cave floor revealed other episodes of soda-straw breakage including one more than 35,000 years old. Male and Cervo caves in central Italy record at least five major seismic events that caused collapse or speleothem damage in the first 400 m of the caves:

1) 130 ± 20 ka
2) 100 ± 10 ka
3) 35 ± 5 ka
4) Pre 350 ka
5) 1456 A.D. earthquake

In northern Italy, seismicity has been accompanied by movement of the cave floor. In some cases this is indicated by breakage and regrowth of stalagmites. In Frassini Cave, one opening is offset nearly a meter along a joint plane. In Spipola and Buco dei Buoi Caves, stalagmites record multiple episodes of changes in growth axis, and these can be correlated with known seismic events from 1929 back to 770 A.D.

Caves cited to this point have all been developed in limestone. All appear to have remained open through even strong seismic events. The same must be true for caves of southwestern Europe that contain Paleolithic cave paintings that date from 15,000 to 30,000 years ago. The oldest continuously open cave found in the current survey is Lechuguilla in southern New Mexico where alunite formed on the cave floor yielded an age of 11.3 Ma.

Lava tubes are perhaps a better analogue for the welded tuffs of Yucca Mountain. These occur typically in of basaltic to intermediate composition, and they have cooling joints like those found in welded tuffs. Most lava tubes have stood open for thousands to hundreds of thousands of years, but ones as old as 4 million years are known. Some of the most spectacular are located in the Canary Islands, where Corona Volcano produced one tube 7.5 km long with diameters up to 35 m. The lava forming that tube has been dated at 21 +/- 6 ka.

The geologic and archaeological records lack clear evidence of extreme ground motion, or at least of motion sufficient to cause catastrophic collapse. Thus, such events are either extremely rare, or are poorly preserved or perhaps non-existent. Null evidence is never conclusive, but a large body of evidence could be assembled that might strengthen this conclusion.