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Major Earthquakes Recorded by the Initiation and/or Regrowth of Speleothems in Midwestern US Caves: Final Technical Report

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ABSTRACT

A total of eight caves located in Illinois, Indiana, Missouri and Arkansas were sampled during this investigation. Forty nine stalagmites and cores of stalagmites, some containing multiple generations of stalagmites, were collected and dated using uranium-thorium age-dating techniques. Examination of these caves and others in these states revealed the common nature of the young white stalagmites that grow on bedrock, fine sediment and atop older stalagmites. The older stalagmites typically coincide with known and suspected New Madrid seismic zone (NMSZ) earthquakes.

Stalagmite ages ranged from 27 to 367,000 years BP. Only ten stalagmites were older than 13,000 years before present (BP) and were not used for comparison with known and suspected NMSZ earthquakes due to the paucity of evidence for NMSZ earthquakes of this age. Only Holocene-age stalagmites with analytical errors of less than +/- 250 years (31 samples) were used in our comparison with known and suspected NMSZ earthquakes. Times of stalagmite initiation for the Holocene-age stalagmites coincided well with known and suspected NMSZ earthquakes. A model using a 500-year recurrence period of NMSZ earthquakes was introduced and appears to be consistent with a mixture of stalagmite-initiation ages and known and suspected NMSZ earthquakes determined by other means.

The distribution of stalagmite-initiation times appeared to be uniform and not temporally clustered throughout the Holocene. Examination of stable isotopes of five selected stalagmites showed that $\delta\ ^{18}O$ and $\delta\ ^{13}C$ followed climatic variations in the Holocene. On the basis of these data, the distribution of stalagmite-initiation times did not appear to have been affected by climatic variations during the Holocene.

Our data suggest that most of the Holocene-age speleothems collected during this investigation were initiated by earthquake-induced opening/closing of fracture-controlled flow paths in the ceilings of cave passages. On the basis of these data and previously collected stalagmites, we conclude that the dates of initiation and regrowth, and perhaps changes in stalagmite growth rates (including cessation of growth) may be used as indicators of NMSZ earthquakes in the Midwestern US, and probably other seismic zones in the world.

INTRODUCTION

Caves have been recognized as potential repositories for records of major seismic events based on damaged speleothems (Kagan 2005; Gilli 2005). We have explored application of this method to U.S. Mid-continent by the study of speleothems from three southern Illinois Caves in close proximity to the NMSZ. Historic earthquakes generated by the NMSZ represent some of the

largest in the world, the most well known being the 1811-12 earthquake series (Figure 1). At that time, there was a series of some 200 light to great earthquakes, four exceeding surface-wave magnitudes (M_s) of 8.0 in the sparsely-populated region (Nuttli, 1987). Unfortunately, to date, only one historic and 8 prehistoric earthquakes have been identified. Seismic events associated with the NMSZ represent a significant threat to cities and towns within its vicinity (e.g., the St. Louis, MO metropolitan area, current population over 2 million). Our first investigation searched for new types of evidence for paleoseismic events in the Midwestern US. Results to date suggest that large earthquakes can affect the initiation/regrowth of speleothems and perhaps stop their growth. The results of this work ultimately could yield a more complete Holocene record of paleoseismic events in the Midwestern US or, at least, could provide support for dates of such events determined by others using different techniques (e.g. sand blows, fluvial deposits). In addition, the data from this investigation appear to have yielded additional dates of major seismic events that could be used to extend the paleoseismic record through and perhaps beyond the Holocene. The results of this investigation will be useful to workers characterizing and modeling potential ground-motion sources associated with the NMSZ, and local and regional authorities in identification of periods or location of seismic hazard for populated areas. Finally, the technique developed herein could potentially be used in other seismically-active parts of the U.S. and the world.

The answer to the question of "when is the next large NMSZ earthquake(s) (similar magnitude as those of 1811-12) likely to occur?" is currently unclear. Estimates of the recurrence interval of seismic activity along the NMSZ require an accurate reconstruction of paleoseismic history and strain rates indicated by crustal movement near the fault. GPS studies disagree about the seismic hazard indicated by strain rates (Smalley et al. 2005; Newman et al. 1999). Furthermore, because of the paucity of historic information about seismic events, there is uncertainty in the recurrence interval of NMSZ earthquakes. Studies utilizing liquefaction features and landslides suggest that a large earthquake on the NMSZ occurred at A.D.1450 ± 150 years (between 400 - 700 years BP) and A.D. 900 ± 100 years (between 1000-1200 years BP), indicating that the recurrence interval may be a little as 500 years (Tuttle et al., 1999; Tuttle et al, 2002). Recent work by Holbrook et al. (2006), using Holocene-age Mississippi River floodplain deposits, added additional ages of 1620 BC ± 220 years (3626 years BP) and 2244 BC ± 269 years (4250 years BP). This latter work suggested that the NMSZ earthquakes may not have a regular periodicity, but could be temporally clustered on a millennial scale. One of the older dates for a NMSZ earthquake, based on sand blows and sand dikes in southern Illinois, was identified by Tuttle et al. (2004) at 4520 BC ± 160 years (6520 years BP). Tuttle et al. (2006) recently identified a large sand blow near Marianna, Arkansas (80 km south of the southwestern bound of the NMSZ) that was dated at about 3500 BC (5500 years BP) that may be related to the NMSZ (Table 1). It is clear that retrieving as much information as possible about paleoseismicity in this area is necessary to refining estimates of a recurrence interval. Additional dates of paleoseismic events would enhance the ability of federal, state, and local agencies to make critical preparedness decisions.

Panno et al. (2009) found numerous, small white speleothems in three large caves in southwestern Illinois (Illinois Caverns, Fogelpole Cave and Pautler Cave). The stalagmites were made of starkly white calcite ranging from 2 to 6 cm in height, and about 3 cm in width. The white stalagmites were actively growing on older stalagmites, flowstone, breakdown, or on fine-

grained sediments stalagmites (Figure 2 in Panno et al. 2009). The stark whiteness of the calcite speleothems suggested that they contained very low concentrations of dissolved high molecular weight organic acids; humic acids typically are responsible for the tan, orange and brown colors of speleothems, whereas, fulvic acids can be incorporated into lighter colored or white speleothems (White, 1997). These speleothems were similar in color, texture, and mineralogy to those found by Postpischl et al. (1991) and Agostini et al. (1994) in close proximity to an earthquake-prone zone in Italy. These workers found that a second generation of stalagmites formed on dormant stalagmites in the Grottoa del Cervo in Italy following a major earthquake that occurred in 1456. The newer stalagmites were made of coarsely crystalline calcite, were white in color and poorly laminated. The description of the white stalagmites are similar to those found in caves in the Midwestern US in the vicinity of the NMSZ. Based on observation of hundreds of these small white stalagmites of similar size, Panno et al. (2009) speculated that flow of the drip water was initiated by the 1811-1812 NMSZ earthquakes. The water would relatively rapidly enter the bedrock limestone at the epikarst and, in the course of migrating toward the cave through reopened fissures and fractures, become saturated with respect to calcite. Entering the cave, the water would degas and precipitate calcite in the form of stalactites, stalagmites and flowstone. In addition, the darker colored stalagmites on which some of these white stalagmites are growing may have been initiated during known prehistoric seismic events.

The objectives of this phase of our investigation were to 1) Examine other caves in Illinois and adjacent states for earthquake-initiated stalagmites. 2) Date selected stalagmites from these caves to determine if the distribution of dates of initiation matched ages of known paleoseismic events based on other techniques. 3) Conduct an examination of stable isotopes along the growth paths of selected stalagmites to test the hypothesis that no climate change was involved in the initiation or cessation of stalagmite growth. This report is the results of research conducted from March 15, 2008 through March 14, 2009 involving stalagmite sample collection from eight caves in four state of the Midwestern US.

METHODS AND MATERIALS

Caves Sampled

A total of eight caves were sampled between June of 2008 and February of 2009 (Figure 1). Each cave was visited at least once, and several of the caves were visited multiple times. A total of 49 stalagmites were collected as whole samples and as core samples, with permission. Most of the stalagmites that were cored during this investigation were repaired with a mixture of hydrocement and crushed calcite. Many of the stalagmites collected contained multiple stages, separated by easily recognizable partings and/or color changes apparent both in the field and in the lab following cutting the stalagmites in half with a diamond saw. The initiation point of each stalagmite stage was sampled multiple times (2 to 3 times per location) and dated, resulting in a total of 106 separate U/Th analyses. Data from 2 or 3 locations sampled along a growth band on a stalagmite were combined into a single U/Th date. Further, several of the stalagmites sampled previously (from 2002 to 2006) (Panno et al. 2009) were resampled for U/Th dating in order to get more accurate ages with the University of Illinois' newer analytical equipment.

Illinois. Illinois Caverns, Fogelpole Cave, and Pautler Cave are located in southwestern Illinois' sinkhole plain. Illinois Caverns was visited on June 6, 2008, September 5, 2008, and December 11, 2008 (6 samples). Fogelpole Cave was visited on August 8, 2008 and February 10, 2009 (7 samples). Pautler Cave was visited on June 25, 2008 and September 17, 2008 (7 samples). Permission to sample these caves was obtained from the Illinois Department of Natural Resources and the Karst Conservancy of Illinois.

Indiana. Donnehue's Cave, Buckner's Cave and Ellers Cave are located in the cave-rich region of southern Indiana. Donnehue's Cave was visited November 10, 2008 and June 3, 2009 (6 samples). Buckner's Cave was visited on December 8, 2008 (5 samples). Ellers Cave was visited on December 9, 2008 and January 21, 2009 (4 samples). Permission to sample these caves was obtained from the Indiana Karst Conservancy.

Missouri. Mertz Cave is located in the cave-rich region of Missouri near Perryville and was visited on June 5, 2008 (4 samples). This cave is privately owned and was sampled with permission.

Arkansas. Blanchard Springs Caverns is located in north-central Arkansas, an area known for its show caves, and is owned by the U.S. Forest Service (USFS). The cave was visited on February 26, 2009 (7 samples). Only core samples were collected from this cave per a written agreement with the USFS.

Uranium/Thorium Dating

Speleothems were dated using the U-Th disequilibria dating techniques using mass spectrometry for the analysis (e.g., see Zhou et al. 2005 for method details). Stalagmites were microdrilled to collect multiple samples of about 100 mg along annual growth laminae; U-Th disequilibria ages of these laminae were measured by multi collector inductively coupled plasma mass spectrometry (MC-ICPMS) on the Nu plasma HR located in the Department of Geology, UIUC. Chemical separation procedures for U-series analyses were similar to those of Edwards et al. (1986) and Cheng et al. (1998). MC-ICPMS analysis consisted of aspirating a 10 ppb solution of purified U or Th through a desolvating nebuliser and measuring either ^{238}U, ^{235}U, ^{236}U and ^{234}U or ^{232}Th, ^{230}Th and ^{229}Th simultaneously on the mass spectrometer. Sensitivity for U and Th are routinely 400V/ppm at a nebulisation rate of 100 microliter/min. The instrument is fitted with a retarding potential lens providing abundance sensitivity of < 200ppb and an electron multiplier having a dead time of ~10 ns and dark current of < 6 cpm. Because of the young age of these samples, detrital Th corrections to the age are significant but generally less than 10%.

Because any incorporation by the older, underlying carbonate minerals of the bedrock and older speleothems could significantly bias the age of the white stalagmites, particular care was taken to maintain a buffer zone between the oldest sample from the white stalagmite and the underlying older carbonate minerals. In addition, because of the presence of dissolution pits near the apex of the stalagmites, U-Th disequilibria ages were determined from unaffected growth laminae along the flanks of the stalagmites.

Delta O-18 and Delta C-13

In addition to being dated, selected stalagmites were analyzed for stable isotopes along their

length to determine if they may have stopped and started growing because of changes in climate. Changes in $\delta^{18}O$ and $\delta^{13}C$ patterns relative to stalagmite ages relate to variability in average annual temperature and changes in vegetation as a direct result of climatic changes.

A total of 7 to 19 samples each from 5 stalagmites were collected for stable isotope analysis for a total of 71 samples. Samples for $\delta^{18}O$ and $\delta^{13}C$ were collected from top to bottom along the axis of selected stalagmites using a Dremmel tool fitted with a fine tip diamond studded drill bit. The drill bit was cleaned between each sample with an acid wash and de-ionized water and dried with a Kimwipe. The carbon and oxygen isotopes were measured using a Finnigan Mat 252 isotope ratio mass spectrometer with an attached Kiel III Individual Acid Bath Carbonate Device. Samples were reacted with 100% phosphoric acid at 70° C. The $\delta^{13}C$ and $\delta^{18}O$ values are reported relative to the Vienna Peedee belemnite (V-PDB) reference standard as calibrated through analysis of NBS-19 with values of 1.95‰ and -2.2‰, respectively (Coplen et al., 1983). Reproducibility for $\delta^{13}C$ and $\delta^{18}O$ is <±0.1‰ and < ±0.15‰ respectively. Typically six NBS 18 and 19 standards were run with each sample set, and duplicates were run every tenth sample.

RESULTS AND DISCUSSION

Initially, this investigation allowed us to collect additional stalagmites from caves in Illinois that supported early results regarding the relationship between stalagmite initiation and large earthquake activity. These results were published in the *Bulletin of the Seismological of America* in August of 2009 (Panno et al. 2009). These stalagmite and stalagmites collected and analyzed subsequent to the submission of our paper provided a more in-depth view of the distribution of stalagmite initiation times during the Holocene over a much larger area of the Midwestern US. All of the U/Th data collected to date are presented in Table 1 and show stalagmite ages that range from 77 year to 367,000 years BP. For our analysis of the data, we focused on the Holocene-age stalagmites because they were more easily related to dated liquefaction features determined by others (Figure 2). The stable isotope data are presented in Table 2 and Figures 3 and 4. All of these data will be discussed below.

Effects of Earthquakes on Speleothem Growth

Relatively young, white speleothems were present in all the caves sampled. Their presence, and the following observations suggests that seismic events were responsible for the initiation of the white speleothems: 1) the rejuvenation of stalagmites that had not grown for thousands of years, 2) the time-synchronous initiation of the growth of white speleothems throughout all caves, 3) their similarities to earthquake-initiated stalagmites of the Grottoa del Cervo, and 4) their ages based on growth laminae and U-Th disequilibria as described in more detail in Panno et al. (2009).

The youngest stalagmite ages fell into two age groups: about 90 years BP and about 200 years BP (Table 2). These ages coincide with the NMSZ earthquakes of 1811 and 1812 (Mueller et al. 2004), and the Missouri earthquake of April 9, 1917 (Finch 1917). Alternatively, it is also possible that some of the younger stalagmites were initiated by a NMSZ earthquake in 1895 (magnitude 6.6).

The effects of earthquakes on aquifers (perched or otherwise), as a result of sediment and bedrock deformation and ground shaking, include consolidation of sediment, fracturing of bedrock (including slippage along existing fractures), and movement (removal) of materials from within fractures and fissures. These changes are reported to occur within hundreds to thousands of km from the epicenter of an earthquake (Montgomery and Manga, 2003). Because of the proximity of the epicenter of the 1811-1812 NMSZ earthquakes and the Missouri earthquake of 1917 to the Illinois, Missouri, Indiana and Arkansas caves, we propose that these earthquakes (intensity ≥VI at the caves (Figure 1)) reopened vertical and horizontal conduits overlying the caves previously sealed by seismic activity, or simply clogged the flowpath. Local geology played a role as well with the relatively shallow soil zone (typically ≤ 10 m) and the near vertical, solution-enlarged fractures in the well-bedded Mississippian-age carbonate rocks. Evidence for dilation of bedding planes was found in Illinois Caverns where flowstone along the wall of the cave was fractured along at least one bedding plane in the limestone.

Other researchers, in the course of paleoclimatology studies, have recorded ages of Holocene stalagmite initiation in Missouri, all of which we found appear to be coincident with the ages of NMSZ paleoseismic events. Several Missouri caves (some commercial caves) also has small white speleothems, although we do not know if any have been dated at this time. Dates of the initiation of other stalagmites in Crevice Cave (Missouri) include 5460 ±224 years BP and about 7900 years BP (Lepley, 2004). Additional stalagmite initiation dates of the Middle Holocene from Missouri include about 5500 years BP (Ozark Caverns, MO), about 3900 years BP (Bridal Cave, MO) (Denniston et al. 2000) and 3500±100 years BP (Coldwater Cave, MO) (Denniston et al. 2007), which correspond with our dates. The initiation of new stalagmites and the regrowth of dormant stalagmites should reasonably be expected given the potential for large earthquakes to reopen existing pathways (fractures and bedding planes) within shallow bedrock per Montgomery and Manga (2003).

NMSZ Earthquake Model

A model of the results of this investigation was developed to show the historic and prehistoric NMSZ earthquakes, stalagmite initiation times on a time line from the present to 13,000 years BP (Figure 2). Only those stalagmite ages with less than 250 years analytical error are reported in order to avoid overlaps exceeding the 500-year recurrence interval of NMSZ earthquakes. A summary of paleoclimatic conditions along the time line was also included in order to examine possible effects of climate change on stalagmite initiation.

The distribution of the timing of stalagmite-initiation is fairly uniform until about 10,000 years BP (no temporal clustering) and coincides with known and suspected historic and prehistoric earthquake times. Stalagmite initiation times add additional ages that might be related to major NMSZ earthquakes. To test this, a model was prepared that is intended to use both the liquefaction data and the stalagmite data. Symbols were placed along the timeline that are between 350 and 700 years apart in an attempt to mimic the roughly 500 year recurrence interval of NMSZ earthquakes. Although the stalagmite-initiation ages seem to coincide with many of the predicted earthquake times, several gaps are still present. If additional research is funded, this model will be tested with stalagmite samples from all over the Midwestern US and we will attempt to reduce the analytical error on those stalagmites not used in the model.

Because of the paucity of liquefaction features older than 13,000 years BP, and the very wide range of uncertainty in those data, we did not use any of the ages of our stalagmites that exceeded this age. However, we did learn to identify Holocene-age stalagmites from very old stalagmites in the field based on their appearance and settings in our study area. Specifically, it was best to sample stalagmites that were capped with a relatively small (several cm tall) younger generation white stalagmite. Finally, the relatively wide error bars in both of the established NMSZ earthquake ages and the stalagmite initiation ages, plus the difficulties inherent in modeling and analyzing apparent patterns in data, has made a statistical analysis of these data impractical at this time.

Paleoclimate Effects

Stable isotopes ($\delta\ ^{18}O$ and $\delta\ ^{13}C$) from five selected stalagmites, each from a different cave, were combined into a single data set for each isotope and plotted versus the time-based age models derived from the U/Th ages determined on the various stalagmite samples (Figures 3 and 4). Similar patterns were seen in both data sets. The $\delta\ ^{18}O$ in stalagmites can serve as an indicator for temperature and precipitation rate. Isotopically heavier samples ranging from about 9500 years BP to about 7500 years BP suggest a progressively dryer, warmer period following the wet and cool period that marked the end of the Wisconsin Glacial Episode. Following a 2500 year gap in our data, the climate becomes more temperate like that of today. The $\delta\ ^{13}C$ can be used to identify changes in vegetation that indicate changes in climatic conditions, as well. The wet and cool period (from 14,000 to 10,000 years BP) is reflected by a shift to lighter $\delta\ ^{13}C$ values. A shift to dryer conditions is observed between 10,000 and 6500 years BP. Isotopic values for today's climate are mostly lighter as would be expected for a temperate climate; however, the $\delta\ ^{13}C$ of the stalagmite from Eller's Cave is relatively heavy suggesting the influence of C4 plants (corn).

In general, the stable isotopes in the stalagmite samples appear to respond to relatively subtle climatic changes of the Holocene. The fairly uniform distribution of stalagmite-initiation ages along the timeline in Figure 2 suggests that these changes in climatic conditions had little effect on the initiation of stalagmite growth in the study area. For example, the Middle Holocene dry period did not have fewer stalagmites than the wetter period that followed.

CONCLUSIONS

Stalagmite ages for all samples collected during this investigation ranged from 27 to 367,000 years BP. Only Holocene-age stalagmites with analytical errors of less than +/- 250 years (31 samples) were used in our comparison with known and suspected NMSZ earthquakes due to the paucity of evidence for NMSZ earthquakes older than 13,000 years BP. Times of stalagmite initiation for the Holocene-age stalagmites coincided well with known and suspected NMSZ earthquakes. A model using a 500-year recurrence period of NMSZ earthquakes was introduced and appears to be consistent with a mixture of stalagmite-initiation ages and known and suspected NMSZ earthquakes determined by other means. Further, the distribution of stalagmite-initiation times appeared to be uniform throughout the Holocene and not temporally clustered. Examination of stable isotopes showed that $\delta^{18}O$ and $\delta^{13}C$ of five selected stalagmites followed

climatic variations in the Holocene. However, the distribution of stalagmite-initiation times did not appear to have been affected by climatic variations during the Holocene.

On the basis of these data, the dates of initiation and regrowth, and perhaps changes in stalagmite growth rates (including cessation of growth) may be used as indicators of NMSZ earthquakes in the Midwestern US, and probably other seismic zones in the world. On the basis of our data, we concluded that the speleothems collected for this and an earlier investigation were initiated by earthquake-induced opening/closing of fracture-controlled flow paths in the ceilings of cave passages. Future research will focus on additional U/Th dating and stable isotope analyses of already collected stalagmites and stalagmite cores. Caves in the states surrounding the epicenters of the NMSZ earthquakes will be examined for the young white stalagmites in order to determine their aerial extent. If possible, additional stalagmites from Iowa, Missouri, Arkansas, Kentucky and Tennessee will be collected and analyzed.

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Table 1. All U/Th ages for stalagmites collected during this investigation. Exceptions are indicated as "GL" for counting of annual growth laminae in thin section. Stalagmites dated previous to this investigation are indicated with an asterisk.

Sample Number	Description	U/Th Age (Years BP)	Comments
	Fogelpole Cave, Burksville, IL		
FC 94-1A*	Multi-stage	200 ± 36 (GL)	White (FC-4) (youngest)
FC 94-1B*	Multi-stage	4600 ± 130	Base of oldest part
FC 1 A*	Multi-stage	10,300 ± 70	Middle part
FC 1 B*	Multi-stage	11,500 ± 70	Base of middle part
FC 1 C*	Multi-state	17,780 ± 120	Center of oldest part
FC 1 D*	Multi-stage	83 ± 8	White (youngest part)
FC 1efg	Multi-stage	19,250 ± 250	Dark (base of oldest part)
FC 3*	Multi-stage	200 ± 36 (GL)	White (youngest part)
FC 3A*	Multi-stage	4,560 ± 100	Oldest part
FC 9*	Single-stage	196 ± 36 (GL)	White
FC 30ab	Single-stage	83,000 ± 12,500	Oldest part
FC 30cd	Single-stage	68,000	Central part
FC 30ef	Single-stage	29,900 ± 3800	Youngest part
FC 34abc	Multi-stage	5100 (isochron)	Oldest part
FC 35	Multi-stage	90 ± 73	White
FC 36abc	Multi-stage	8900 (isochron)	Oldest part
FC 37	Multi-stage	No data	
FC 38abc	Multi-stage	77 ± 1	White
FC 39	Multi-stage	No data	
	Mertz Cave, Perryville, Missouri		
MC 1	Single-stage on old slanted flowstone	No data	White
MC 2	Single-stage on floor	4600 ± 2500	White
MC 3	Single-stage on breakdown	9600 ± 860	Buff
MC 4	Single-stage on wall main passage	4400 ± 660	White
	Pautler Cave, Wartburg, IL		
PC 1	Single-stage	5,700 ± 1,800	White
PC 2a	Two-stage (younger stalagmite)	1,200± 260	Oldest part
PC 2b	Two-stage (older stalagmite)	3,050 ± 355	Oldest part
PC 3	Single-stage	620 ± 110	White
PC 6	Single-stage	196 ± 63	White
PC 7	Single-stage	210 ± 75	White
PC 10abc	Single-stage	443 ± 22	White
	Illinois Caverns, Burksville, IL		
IC 1*	Single-stage	191 ± 34 (GL)	White
IC 2*	Flowstone on which IC 1 grew	No data	

IC 4*	Single-stage	100 ± 18 (GL)	White
IC 5*	Single-stage	206 ± 37 (GL)	White
IC 6*	Single-stage	350 ± 420	White/Undateable
IC 9*	Single-stage	254 ± 15	White
IC 10*	Single-stage	88 ± 16 (GL)	White
IC 12*	Single-stage	84 ± 15 (GL)	White
IC 20	Stump	No data	
IC 21	Stump	125,200 ± 5900	Buff
IC 22	Single-stage	240 ± 56	White
IC 23abc	Single-stage	36,500 ± 1700	White
IC 24	Multi-stage	Undateable	White (sediment-rich)
IC 25	Multi-stage	Undateable	Mostly buried in sed.
	Donnehue's Cave, Bedford, IN		
DC 1a	Single-stage (top)	91,000 ± 800	Very old stalagmite
DC 1b	Single-stage (bottom)	164,700 ± 1800	Very old stalagmite
DC 2a	Single-stage (top)	367,000 ± 30,000	Very old stalagmite
DC 2b	Single-stage (middle)	332,000 ± 22,000	Very old stalagmite
DC 2c	Single-stage (bottom)	351,000 ± 28,000	Very old stalagmite
DC 3a	Single-stage (top)	224,000 ± 6200	Very old stalagmite
DC 3b	Single-stage (middle)	236,000 ± 6000	Very old stalagmite
DC 3c	Single-stage (bottom)	244,000 ± 7000	Very old stalagmite
DC 4	Single-stage	No data	Very old stalagmite
DC 5	Single-stage	No data	Very old stalagmite
DC 14abc	Multi-stage (white)	27 ± 50	Youngest part
DC 14fgh	Multi-stage	1500 ± 300	Middle of oldest part
DC 14jki	Multi-stage	1780 ± 240	Oldest part
DC 20a	Single-stage (top)	15,800 ± 2450	Buff
DC 20b	Single-stage (middle)	48,000 ± 630	Buff
DC 20c	Single-stage (bottom)	50,800 ± 600	Buff
	Buckner's Cave, Bloomington, IN		
BC 1abc	Multi-stage	114,000 ± 7050	Oldest part
BC 2	Multi-stage	No data	
BC 3	Multi-stage	4720 ± 220	Oldest part
BC 4abc	Multi-stage stump	8000 (isochron)	Oldest part
BC 4def	Multi-stage stump	2470 (isochron)	Youngest part
BC 5abc	Multi-stage stump	No data	
BC 5def	Multi-stage stump	No data	
	Eller's Cave, Bloomington, IN		
EC 1abc	Multi-stage	6740 ± 80	Oldest part
EC 1def	Multi-stage (white)	7220 ± 260	Youngest part
EC 2ab	Multi-stage (white)	82 ± 24	Youngest part

EC 2cd	Multi-stage	9,550 ± 165	Oldest part
EC 4	Filling of broken column	Undateable	
EC 5	Filling of broken column	Undateable	
	Blanchard Springs Caverns, Mountain View, AR		
BSC 1abc	Flowstone	19,000 ± 16,500	Buff (Base of Flowstone)
BSC 2	Base of "Redwood Stump"	Undateable	Recrystallized
BSC 3ab	Multi-stage	Undateable	
BSC 3cd	Multi-stage	Undateable	
BSC 4ghi	Multi-stage	6000 (isochron)	Youngest part
BSC 4def	Multi-stage	5700 ± 1400	Center part
BSC 4abc	Multi-stage	9200 ± 2650	Oldest part
BSC 5abc	Multi-stage	7000 (isochron)	Oldest part
BSC 6ab	Multi-stage	2950 ± 250	Center part
BSC 7ab	Multi-stage	Undateable	Youngest part

Table 2. Stable isotope data for five selected stalagmites and an age model based on U/Th dates.

Sample	$\delta^{13}C_{VPDB}$	$\delta^{18}O_{VSMOW}$	U/Th ages	Position mm	Age Model**
FC1-1	-5.46	26.24	19200	0	19200
FC1-2	-5.37	26.48		4	18490
FC1-3	-5.64	26.78	17780	8	17780
FC1-4	-5.03	26.12		14	11557
FC1-5	-5.75	26.30		19	11462
FC1-6	-6.37	26.32		25	11348
FC1-7	-7.22	26.41		31.5	11224
FC1-8	-7.06	26.51	11100	38	11100
FC1-9	-7.05	26.45		44	10986
FC1-10	-7.54	26.46		49	10890
FC1-11	-7.53	26.60		56	10757
FC1-12	-7.63	26.35		61.5	10652
FC1-13	-7.35	26.36		69	10510
FC1-14	-7.51	26.43		75	10395
FC1-15	-6.35	26.74	10300	80	10300
FC1-16	-7.71	25.34	83	86	83
FC1-17	-8.78	25.11		90	59
FC1-18	-8.73	24.99		95	30
FC1-19	-7.99	25.65		98	12
DC14-1	-9.37	—*	1780	0	1780
DC14-2	-8.67	25.30		9	1721
DC14-3	-8.38	25.59		14	1689
DC14-4	-9.02	25.33		18.5	1660
DC14-5	-8.90	25.38		30	1585
DC14-6	-8.61	25.66	1500	43	1500
DC14-7	-8.31	25.27		52.5	1438
DC14-8	-7.81	—		60.5	1386
DC14-9	-8.62	24.96		63	1370
DC14-10	-7.89	24.90		66	1350
DC14-11	-7.33	24.96		70	1324
DC14-12	-7.72	24.72		72	1311
DC14-13	-8.71	24.78		76.5	1282
DC14-14	-10.59	24.75	27	80	27
DC14-15	-10.18	24.91		84	16
DC14-16	-10.57	—		86.5	9
DC14-17	-10.18	24.70		89	3
EC2-1	-0.853	—	9550	0	9550
EC2-2	-0.911	26.648		8.5	9216
EC2-3	-1.307	26.555		14	9001
EC2-4	-0.975	26.977		20.5	8746
EC2-5	-1.205	26.678		26	8530
EC2-6	-1.405	26.754		36	8137
EC2-7	-1.904	26.632		42	7902
EC2-8	-1.535	27.391		51	7549
EC2-9	-0.094	27.736		56	7353

EC2-10	-0.104	27.919		60.5	7176
EC2-11	-1.601	28.682	6980^	65.5	6980
EC2-12	-1.152	27.684		71	6764
EC2-13	-0.188	26.072	82	76	82
EC2-14	-0.914	26.262		83	63
EC2-15	-1.614	26.037		87.5	51
EC2-16	-1.600	25.920		92	38
EC2-17	-1.424	26.338		97	25
EC2-18	-0.762	26.338		102	11
EC2-19	-2.746	25.753		105	3
BSC6-1	-4.340	26.189		1.5	4816
BSC6-2	-2.753	25.930		11	3672
BSC6-3	-2.986	25.831	2950	17	2950
BSC6-4	-4.533	25.573		23	2228
BSC6-5	-5.756	----		28.5	1565
BSC6-6	-4.981	25.568		35	783
BSC6-7	-5.434	25.660		40.5	120
PC2A-1	-7.231	25.863	1200	0	1200
PC2A-2	-8.365	25.628		9.5	1058
PC2A-3	-8.808	25.935		21.5	878
PC2A-4	-8.293	25.857		29	765
PC2A-5	-7.449	25.743		38.5	623
PC2A-6	-8.687	24.978		50.5	443
PC2A-7	-8.935	26.431		61	285
PC2A-8	-8.848	26.354		71.5	128
PC2A-9	-9.652	26.036		78	30

**---- insufficient signal for reliable d18O result.*

^ average age from EC1 located near EC2 with a similar laminar pattern at the top.

*** Ages were determined using linear extrapolation between U/Th dates.*

The tops of the stalagmites were still growing and assumed to be modern.

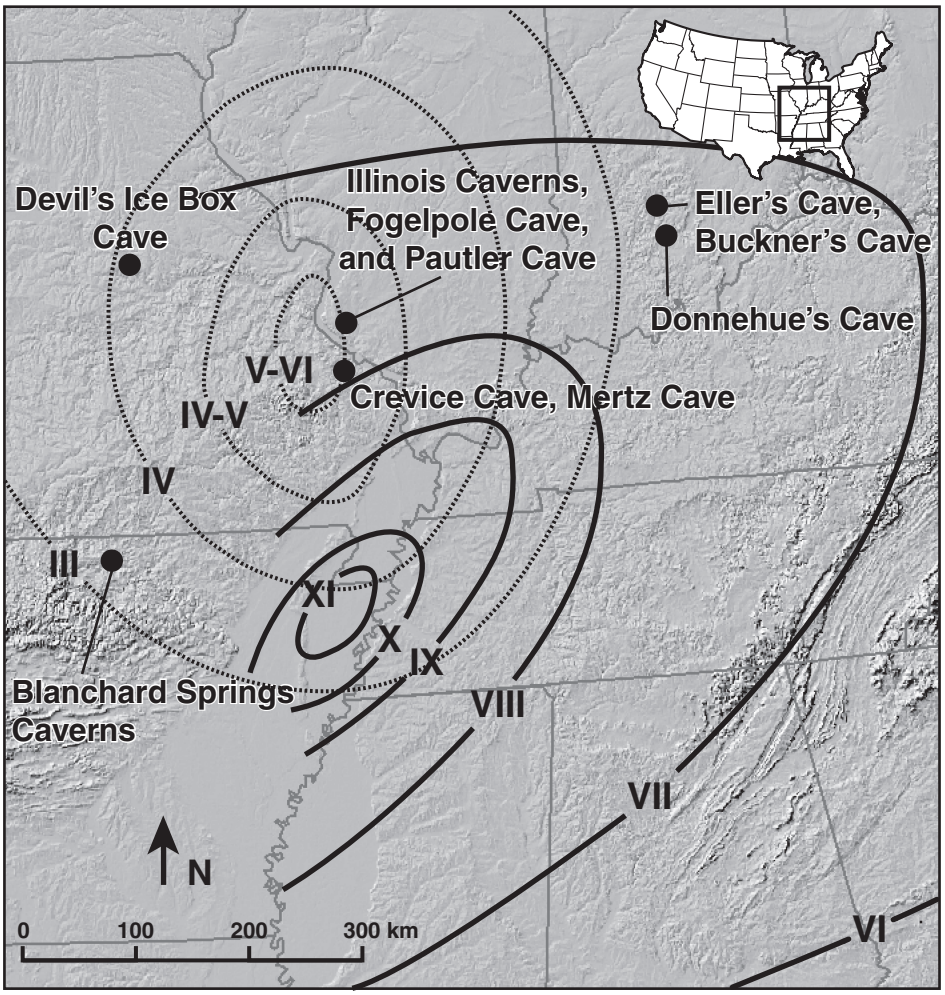


Figure 1. A composite isoseismal map of the New Madrid Seismic Zone earthquakes of 1811-1812 and the April 9, 1917 Missouri earthquake showing the Mercalli Intensity values felt across the Midwestern U.S. The study area location is identified on the inset map. Modified from Mueller et al., 2004 and Finch,1917.

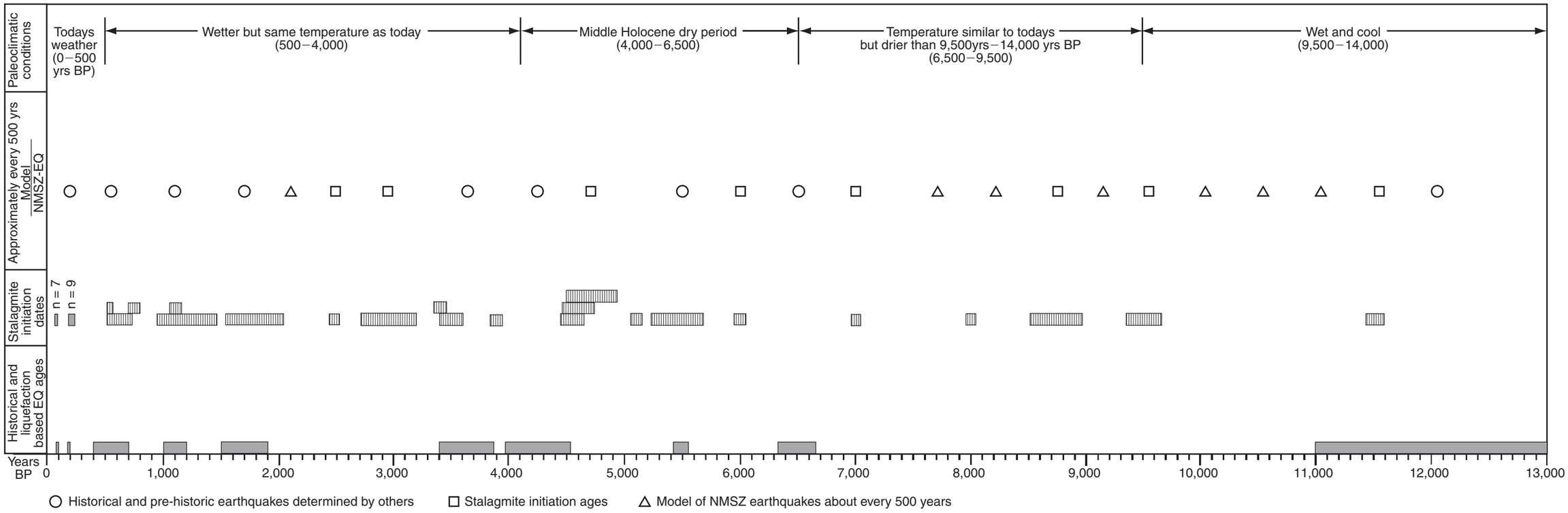
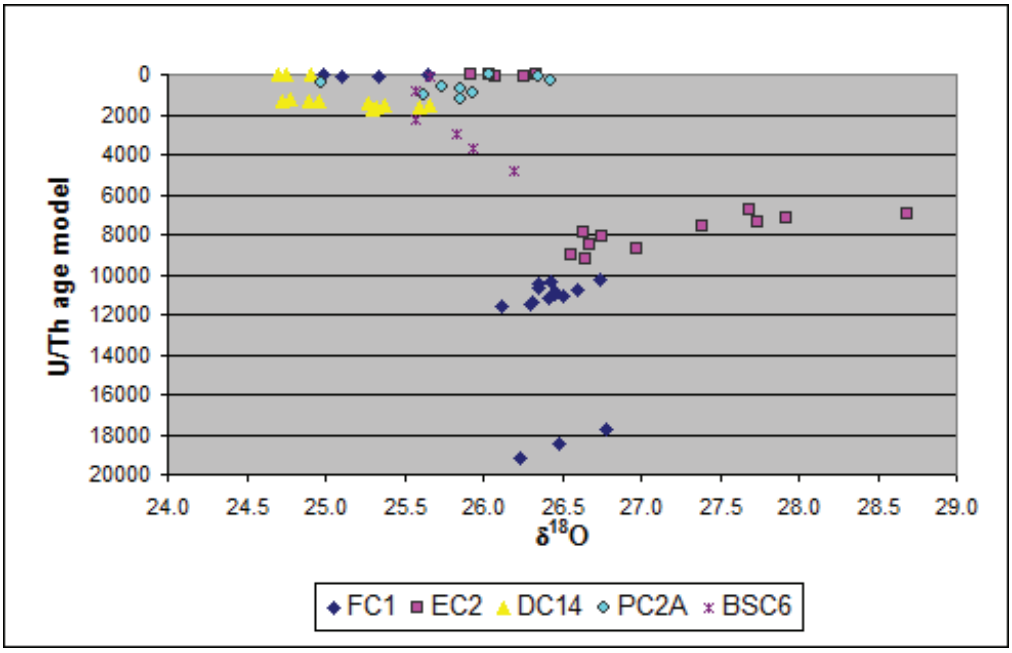
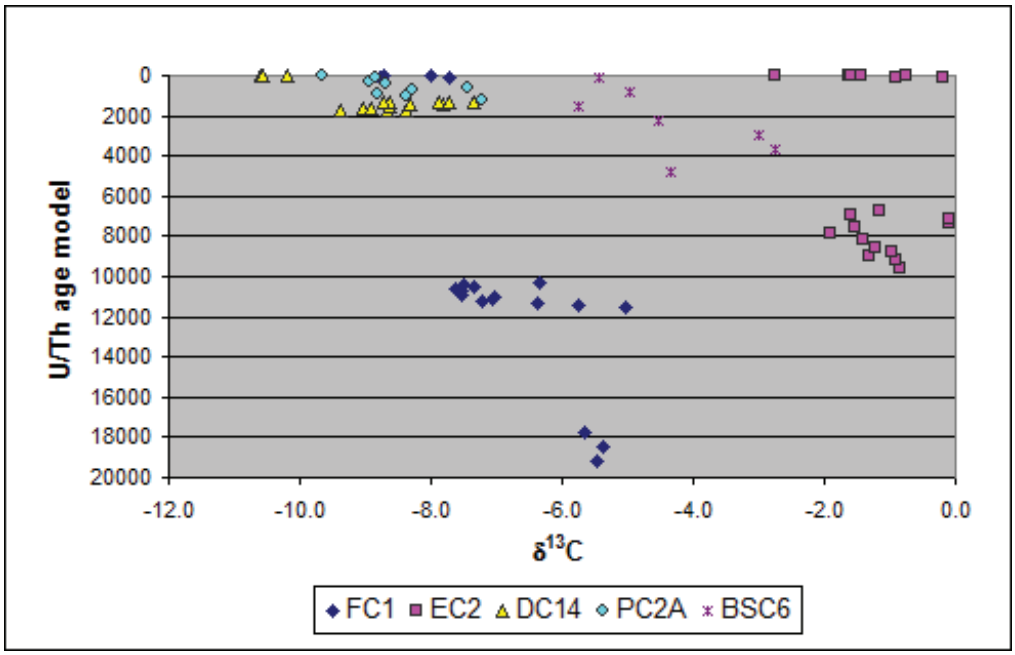


Figure 2. A composite of all known or suspected NMSZ earthquakes from historic records and liquefaction features, stalagmite-initiation dates with analytical errors less than 250 years, a model of Holocene-age NMSZ earthquakes assuming a recurrance interval of every 500 years, and Holocene paleoclimatic conditions.



d18O values swing to more positive values from 9500 to ~ 7500 yrs ago which agrees with other proxy data indicating change in climate during this period to dryer (warmer?) conditions.

Figure 3. Delta 18O values for five stalagmites from caves in Illinois, Indiana and Arkansas showing overall trends driven by paleoclimatic conditions. A change to isotopically heavier values occurs between 9500 and 7500 years BP in response to a drier (warmer?) conditions. This is followed by a shift to isotopically lighter values for today's more temperate conditions.



The more positive d13C values from 9500 t0 7500 years ago also agree with dryer paleoclimatic conditions.

Figure 4. Delta 13C values for five stalagmites from caves in Illinois, Indiana and Arkansas showing a shift at around 10,000 years BP from a cool, wet climate to dryer climatic conditions (about 9500 to 7500 years BP). The isotopic values shift to today's more temperate conditions; however, the broad scatter of delta 13C values suggests the effects of intensive agricultural activities and C4 plants (corn).

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Panno, S.V., C.C. Lundstrom, K.C. Hackley, Z. Zhang. B.B. Curry, and B. Fouke 2008. Paleo-Seismic Activity from the NEW Madrid Seismic Zone Recorded IN Stalagmites. A NEW Tool for Paleo-Seimic History. Abstract in Geological Society of America Abstracts with Programs, v. 40, no. 6 (October 3-8, 2008), p. 151.

Panno, S.V., C.C. Lundstrom, K.C. Hackley, B.B. Curry, B. Fouke and Z. Zhang. 2009. Major earthquakes recorded by speleothems in Midwestern US caves. *Bulletin of the Seismological Society of America*, v. 99-4, p. 2147-2154.

Additional Publications Associates with this Research

The results of this research and earlier research was published by the *Bulletin of the Seismological Society of America* in August of 2009 (attached). The additional data will be examined and interpreted; papers resulting from this work will be submitted to this or other peer-reviewed journals and presented at professional meetings (e.g., Geological Society of America, American Geophysical Union).

Stories about this research have appeared in *The Economist*, *Science News*, *Soil Science Society of America*, was highlighted by the Geological Society of America (attached), and will be showcased on *Nova/Science Now* in an episode entitled "Earthquakes in the Midwest" that will be aired by the Public Broadcasting Service on September 1, 2009.

147-8 Paleo-Seismic Activity from the NEW Madrid Seismic Zone Recorded IN Stalagmites. A NEW Tool for Paleo-Seimic History

Sunday, 5 October 2008
George R. Brown Convention Center, Exhibit Hall E

*Samuel V. Panno[1], Craig C. Lundstrom[2], **Keith C. Hackley**[1], Zhaofeng Zhang[2], Brandon B. Curry[3] and Bruce W. Fouke[4], (1)Isotope Geochemistry, Illinois State Geological Survey, Champaign, IL*
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As the 200th anniversary of the 1811-1812 earthquakes of the New Madrid Seismic Zone (NMSZ) approaches, recent seismic activity in southern Illinois (magnitude 5.2) and a devastating earthquake of magnitude 7.9 in eastern Sichuan China have drawn attention to the need for additional techniques for studying seismic zones. Currently, the paleo-seismic history of the NMSZ is being reconstructed using sand blows and sand dikes, landslides, and Mississippi River floodplain deposits. A new technique being developed by the authors indicates that the time of initiation and/or regrowth of stalagmites in caves located within the magnitude 6 isoseismal line of a seismic zone may be dominated by seismic activity. Consequently, the paleo-seismic history of the NMSZ and any other seismic zone in the vicinity of active caves may be reconstructed using this technique.

We are currently sampling 60 stalagmites from caves in southern Illinois, and southeastern Missouri in order to determine the timing of their initiation. For dating purposes, we are using U/Th techniques and, for the very young stalagmites (200 years BP or less), a combination of U/Th dating and growth laminae counting. Preliminary results of this work and the available published dates of stalagmite initiation in Illinois and Missouri caves correspond to historic and prehistoric seismic events. The dates of initiation for stalagmites collected thus far occurred 200 +/- 50 (n = 5), 1178 +/- 17 (n = 2), 3500 +/- 100, 3,900, 4600 +/- 110 (n = 2), 5500 +/- 240 (n = 2), 11,284 +/- 70, and 17,840 +/- 120 years BP (n = 1 if not indicated). Each of these dates, within limits of analytical error, correspond with known earthquakes associated with the NMSZ determined by others using sand blows and landslides. Additional results from this investigation will be presented at the time of the meeting.

See more of: Structural Geology / Tectonics / Neotectonics/Paleoseismology (Posters)
See more of: General Discipline Sessions

Stalagmites May Predict Next Big One Along the New Madrid Seismic Zone

Released: 9/24/2008 1:00 PM EDT
Source: Soil Science Society of America (SSSA)

Newswise — Small white stalagmites lining caves in the Midwest may help scientists chronicle the history of the New Madrid Seismic Zone (NMSZ) " and even predict when the next big earthquake may strike, say researchers at the Illinois State Geological Survey and the University of Illinois at Urbana-Champaign.

While the 1811-12, magnitude 8 New Madrid earthquake altered the course of the Mississippi River and rung church bells in major cities along the East Coast, records of the seismic zone's previous movements are scarce. Thick layers of sediment have buried the trace of the NMSZ and scientists must search for rare sand blows and liquefaction features, small mounds of liquefied sand that squirt to the surface through fractures during earthquakes, to record past events. That's where the stalagmites come in.

The sand blows are few and far between, said Keith Hackley, an isotope geochemist with the Illinois State Geological Survey. In contrast, caves throughout the region are lined with abundant stalagmites, which could provide a better record of past quakes. "We're trying to see if the initiation of these stalagmites might be fault-induced, recording very large earthquakes that have occurred along the NMSZ," he said.

Hackley and co-workers used U-Th dating techniques to determine the age of stalagmites from Illinois Caverns and Fogelpole Cave in southwestern Illinois. They discovered that some of the young stalagmites began to form at the time of the 1811-12 earthquake.

Hackley is scheduled to present preliminary results of the study in a poster on Sunday, 5 October, at the 2008 Joint Meeting of the Geological Society of America (GSA), Soil Science Society of America (SSSA), American Society of Agronomy (ASA), Crop Science Society of America (CSSA), and Gulf Coast Association of Geological Societies (GCAGS), in Houston, Texas, USA.

Water slowly trickles through crevices in the ceiling of a cave and drips onto the floor. Each calcium carbonate-loaded drip falls on the last, and a stalagmite slowly grows from the bottom up. Time is typically recorded in alternating light and dark layers " each pair represents a year.

When a large earthquake shakes the ground, old cracks may seal and new ones open. As a result, some groundwater seeping through the cave ceiling traces a new pattern of drips " and, eventually, stalagmites " on the cave floor. Thus it is possible that each new generation of stalagmites records the latest earthquake.

The scientists use fine drills, much like those used by dentists, to burrow into the stalagmites to collect material for dating. In addition to the 1811-12 earthquake, their investigation has recorded seven historic earthquakes dating as far back as almost 18,000 years before the present. Understanding the NMSZ's past, including whether quakes recur with any regularity, will help the scientists predict the potential timing of future quakes.

In coming months, Hackley and his colleagues plan to expand the study, collecting stalagmites from caves across Indiana, Missouri and Kentucky. They hope that the new data will help to fill in more of the missing history of the NMSZ.

WHEN & WHERE

Sunday, 5 October, 8:00 AM " 4:45 PM (authors scheduled from 3:00-4:45 PM)
View abstract, Paper 147-8: "Paleo-Seismic Activity from the New Madrid Seismic Zone Recorded in Stalagmites. A New Tool for Paleo-Seismic History" at
http://a-c-s.confex.com/crops/2008am/webprogram/Paper47945.html
George R. Brown Convention Center: Exhibit Hall E (poster, booth 136).

Courtesy of K. Hackley

In the August 29 Issue:

Earthquake history recorded in stalagmites

Caves could yield insight into how often major Midwestern quakes have happened

By Sid Perkins

November 8th, 2008; Vol.174 #10 (p. 16)

Text Size

Enlarge

STALAGMITES ON THE WALLThese stalactites and stalagmites were formed in Illinois Caverns, east of St. Louis. The ages at which they began to form could help researchers chronicle when major earthquakes hit the region. Full story. Hackley and colleagues

HOUSTON — The dates at which some Midwestern cave formations began to grow could help researchers chronicle the earthquake history of Missouri and surrounding states, according to work reported October 5 in Houston during the annual meeting of the Geological Society of America.

During late 1811 and early 1812, a series of major quakes rocked the New Madrid Seismic Zone, a fault system named for a small town in southeastern Missouri near the center of those temblors. Scientists often can estimate the age of older, prehistoric quakes along those faults by analyzing wood or other organic debris trapped in pockets of sand and forced to Earth's surface during a quake, says Keith C. Hackley, a geochemist with the Illinois State Geological Survey in Champaign. But many such features have long been plowed or otherwise disturbed by farming, rendering results of analyses ambiguous.

Hackley and his colleagues have now used geochemical techniques, including uranium-thorium dating, to analyze material at the base of stalagmites found in caves between 180 and 230 kilometers north of the epicenters of the 1811–1812 quakes. Many of those stalagmites started growing about 195 years ago, when the massive temblors — estimated to range around magnitude 8 — may have cracked rocks overlying the caves. When these rocks cracked, mineral-rich groundwater seeped into the caverns from new locations and started generating new stalagmite formations. Other stalagmites that the team analyzed began growing about 90 years ago, about the time that a magnitude-5 quake shook a region just east of the caves, says Hackley.

These results hint that stalagmites could provide useful information about ancient quakes in the area, Hackley says. Preliminary analyses of about 60 formations found in caverns throughout southern Illinois, Indiana and Missouri suggest that major quakes occur in the region about once every 500 years or so. If correct, that frequency would confirm similar results obtained by less-accurate analyses of material gathered from sand blows or trenches dug during previous field studies.

Dating earthquakes

Written in stone

Oct 2nd 2008
From The Economist print edition

A new way of detecting ancient earthquakes

ON DECEMBER 16th 1811, the residents of New Madrid, Missouri, were startled out of their beds by a huge earthquake, which was quickly followed by a second. Those who survived the catastrophe reported that cracks opened in the earth's surface, that the ground rolled visibly in waves and that large areas of land sank downwards. The crew of the New Orleans, the first steamboat to ply the Mississippi, told locals that they had moored on an island the evening before the earthquake only to discover that it was gone in the morning. People in places as far away as Boston declared that they heard church bells ringing at the time the earthquake happened.

That huge earthquakes occur in parts of North America outside their traditional habitat on the Pacific margin is well known from accounts like those from New Madrid. Such records, however, have been kept only since Europeans arrived, so it has been hard to work out how active the faults that cause them are. Now it is a little easier. A study carried out by Samuel Panno of the Illinois State Geological Survey and his colleagues has revealed that nearby caves store the dates of past earthquakes in stone.

Dr Panno and his team found their recording angel in the form of stalagmites, the conical projections that grow on the floors of limestone caves. (The structures that hang down above them are called stalactites.) They made their discovery when they were using a radioactive dating technique to check the ages of small stalagmites occupying a number of caves in the Midwest. Many of these stalagmites, they found, had come into existence at about the same moment, and that moment coincided with the New Madrid earthquake.

This makes sense. Stalagmites form when water trickles through crevices in a cave's ceiling and drips to the floor. Each drop carries with it a quantity of dissolved calcium carbonate (the defining ingredient of limestone) that it has picked up while flowing through the rock above. When a drop lands, some of this mineral is deposited at the landing site, where it accumulates, forming a stalagmite. A paper to be presented at a meeting of the Geological Society of America in Houston on October 5th by Dr Panno's colleague Keith Hackley suggests that when large earthquakes shake the ground, new cracks in cave ceilings open. The result is the formation of a new generation of stalagmites.

Like trees, stalagmites are often composed of concentric layers that represent annual growth periods. Counting the layers is one way of assessing how old a stalagmite is. But radioactive dating provides a second, and sometimes more accurate, assessment. In this case the geologists drilled into the stalagmites and estimated their age from the way that uranium decays into an isotope of thorium. Many, they found, dated back to 1811, while others began life in 1917, the date of another nearby earthquake.

Subsequent investigation has confirmed a further seven big earthquakes previously suspected to have happened over the course of the past 18,000 years. An average interval between quakes of 2,500 years is a hopeful sign for New Madrid's immediate future. But if the technique can be tried out in other places it might reveal areas now thought safe, precisely because there has not been a recent earthquake, that are actually under threat.

An isotope geochemist is using stalagmites to track the history of earthquakes, and potentially predict future quakes in the New Madrid Seismic Zone, reports Sarah Day.

Geoscientist Online 29 September 2008

The area where the caves are found, in South West Illinois, lies on the New Madrid Seismic Zone (NMSZ), which recorded earthquakes of magnitude 8 in 1811-12, altering the course of the Mississippi River and ringing church bells in major cities along the east coast.

Little else is known about the seismic zone's pre-historical activity because the region was previously uninhabited, except by native Americans - who produced no written records. Scientists have relied instead on finding small mounds of liquefied sand that squirt to the surface through fractures when an earthquake occurs. Keith Hackley, an isotope geochemist with the Illinois State Geological Survey, believes the stalagmites provide a far more accurate record.

Stalagmites are formed when mineralised water trickles through crevices in cave ceilings and drips onto the floor. As the drips land on top of one another, they deposit calcium carbonate which gradually builds up to form a column. When an earthquake hits, old cracks can be sealed and new ones opened, promoting a new pattern of stalagmites on the cave floor.

Hackley and his colleagues have been using U-Th dating techniques to determine the ages of stalagmites from Illinois Caverns and Fogelpole Cave in South West Illinois. 'We're trying to see if the initiation of these stalagmites might be fault-induced, recording very large earthquakes that have occurred along the NMSZ,' he said. So far, results suggest that some of the younger stalagmites began to form at around the time of the 1811-12 earthquakes.

The stalagmites are dated by using fine drills to burrow into them and collect material, which is analysed to find the ratios of the radioactive isotope thorium-230 and its parent radioactive isotope uranium-234. Whilst uranium is soluble in natural water, thorium is not, which means that when the stalagmites are first precipitated, they contain no thorium. Over time, the uranium-234 in the precipitated material decays to thorium-230. By knowing the half life of both radioactive elements, the scientists are able to estimate how long the uranium has been decaying, and thus how old the stalagmites are.

As well as finding stalagmites that formed at around the time of the 1811-12 earthquakes, they have identified seven other potential historic earthquake events, dating back as far as 18,000 years. By developing a history of seismic events along the NMSZ, possible timings of future earthquakes can be better estimated.

The preliminary results of the study will be presented in a poster at the 2008 Joint Meeting of the Geological Society of America, Soil Science Society of America, American Society of Agronomy, Crop Science Society of America, and Gulf Coast Association of Geological Societies, in Houston, Texas. Hackley and his colleagues plan to expand the study in the coming months, and will collect stalagmites from caves across Indiana, Missouri and Kentucky. They hope that the inclusion of new data will help to develop a more accurate history of the NMSZ.

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Bulletin of the Seismological Society of America, Vol. 99, No. 4, pp. 2147–2154, August 2009, doi: 10.1785/0120080261

Ⓔ

Major Earthquakes Recorded by Speleothems in Midwestern U.S. Caves

by Samuel V. Panno, Craig C. Lundstrom, Keith C. Hackley, Brandon B. Curry, Bruce W. Fouke, and Zaofeng Zhang

Abstract Historic earthquakes generated by the New Madrid seismic zone represent some of the largest recorded in the United States, yet prehistoric events are recognized only through deformation in late-Wisconsin to Holocene-age, near surface sediments (liquefaction, monoclinal folding, and changes in river meanders). In this article, we show that speleothems in caves of southwestern Illinois and southeastern Missouri may constitute a previously unrecognized recorder of large earthquakes in the U.S. midcontinent region. The timing of the initiation and regrowth of stalagmites in southwestern Illinois and southeastern Missouri caves is consistent with the historic and prehistoric record of several known seismic events in the U.S. midcontinent region. We conclude that dating the initiation of original stalagmite growth and later postearthquake rejuvenation constitutes a new paleoseismic method that has the potential for being applied to any region around the world in the vicinity of major seismic zones where caves exist. Use of this technique could expand the geographical distribution of paleoseimic data, document prehistoric earthquakes, and help improve interpretations of paleoearthquakes.

Online Material: Photos of stalagmites, estimated ages of major NMSZ earthquakes, and data used in dating of the stalagmites.

Introduction

Caves and their deposits have long been recognized as naturally well-preserved repositories of long-term proxy records of paleoclimatic conditions (e.g., Dorale *et al.*, 1998). Recent studies indicate that they may also record major seismic events based, in a large part, on speleothem (stalactite and stalagmite) damage (Gilli, 2005; Kagan *et al.*, 2005). Kagan *et al.* (2005) state that extreme seismic activity is needed to initiate speleothem damage (moment magnitude **M** 7.5–8.0). In 2001, we began investigating potential paleoseismic records in three caves within 300 km of the New Madrid seismic zone (NMSZ). The NMSZ, located in the midwestern United States, has been the site of some of the largest earthquakes in U.S. history, the most recent of which occurred in the winter of 1811–1812 when a series of some 200 minor to very large earthquakes shook the sparsely populated region (Nuttli, 1987) (Fig. 1). Although the magnitudes of the largest earthquakes were a matter of controversy, the three largest likely had between **M** 7.3 and 8.1 (Johnston, 1996; Hough *et al.*, 2000; Bakun and Hopper, 2004). As the two-hundredth anniversary of the 1811–1812 NMSZ earthquake series approaches, the population of the affected region is much larger, and an equivalent seismic event most likely would lead to a high casualty rate and extensive property damage.

The identification of recurrence intervals of strong to great earthquakes produced by the NMSZ requires an accurate reconstruction of paleoseismic history. Studies utilizing deposits (mainly sand blows) resulting from earthquake-induced liquefaction of subsurface sediments and fault-related folding indicate that large earthquakes occurred in the NMSZ between 400 and 700 yr B.P. (A.D. 1450 ± 150 yr), between 1000 and 1200 yr B.P. (A.D. 900 ± 100 yr), and between 1500 and 1900 yr B.P. (A.D. 300 ± 200 yr), indicating a recurrence interval of approximately 500 yr (Kelson *et al.*, 1996; Tuttle, Collier, *et al.*, 1999; Tuttle *et al.*, 2002), as well as an earlier event near 4340 yr B.P. (2340 yr B.C.) (Tuttle *et al.*, 2005). Recent work by Holbrook *et al.* (2006), using Holocene Mississippi River floodplain deposits, suggests an additional age of 3626 yr B.P. (1620 ± 220 yr B.C.) and an age of 4250 yr B.P. (2244 ± 269 yr B.C.) that lies within the range of one identified by Tuttle *et al.* (2005). However, Holbrook *et al.* had data from only one of the three fault segments of the NMSZ; based on these limited data, the authors suggest that NMSZ earthquakes may cluster on a millennial scale instead of having a regular periodicity. Tuttle *et al.* (2006) recently identified large sand blows near Marianna, Arkansas (80 km south of the southwestern bound of the NMSZ), dated at about 5500 yr B.P. (3500 yr B.C.) and 6800 yr B.P.

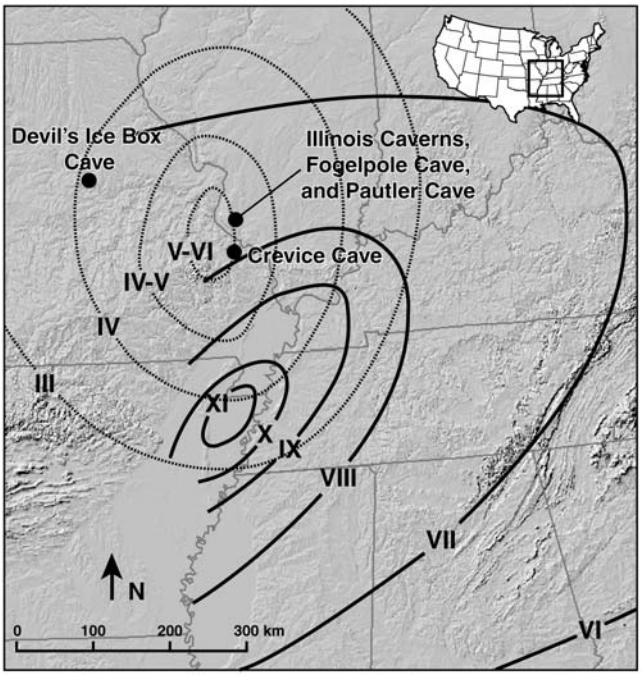

Figure 1. A composite isoseismal map of the NMSZ earthquakes of 1811–1812 (solid lines) showing modified Mercalli intensity values estimated across the central United States for the 16 December 1811 earthquake (Johnston and Schweig, 1996) and the Missouri earthquake of 1917 (dashed lines) from Finch (1917) showing modified Mercalli intensity values that have been converted from Rossi–Forel intensity values. The study area location is identified on the inset map.

(4800 yr B.C.) (Ⓔ Table S1, available in the electronic edition of *BSSA*) that the authors think may be related to sand blows and sand dikes in southwestern Illinois, 6520 yr B.P. (4520 ± 160 yr B.C.) (Tuttle *et al.*, 2004). Paleoliquefaction features were found by Vaughn (1994) in southeastern Missouri and were estimated to have occurred between 23,000 and 17,000 yr B.P. and between 13,340 and 9000 yr B.P. The latter date is similar to that of Munson *et al.* (1997) and Tuttle, Chester, *et al.* (1999) of 12,000 ± 1000 yr B.P.

Fogelpole Cave, Illinois Caverns, and Pautler Cave (located in southwestern Illinois) are among the longest caves in Illinois and contain abundant speleothems. These caves are located relatively far from the epicenters of earthquakes generated by the NMSZ, and seismically caused speleothem damage seems unlikely. However, changes to the hydrogeologic conditions in bedrock overlying the caves (e.g., dilated or reopened fractures) might be affected by strong to moderate earthquake activity (Montgomery and Manga, 2003). Water migrating through fractures in bedrock leading from the surface and/or soil zone to underlying cave passage is responsible for the formation of speleothems within the caves. We discovered numerous small, white speleothems present within these caves (Ⓔ Figs. S1 and S2, available in the electronic edition of *BSSA*); our preliminary work showed that the white speleothems are present in caves of southern Illinois and the surrounding states (including Indiana, Missouri, and Arkansas). The white stalagmites are particularly striking in that they grow on older, typically darker-colored stalagmites, flowstone, cave breakdown debris, and fine-grained sediment, and a thin white coating is often draped across adjacent rock and flowstone (Ⓔ Fig. S1, available in the electronic edition of *BSSA*). The occurrence and relatively small size of the white speleothems suggested that they were relatively recent deposits in the caves. Preliminary dating of several of the white stalagmites supported this interpretation and suggested that their ages of initiation are coincident with the 1811–1812 NMSZ earthquakes.

In this investigation, we examine the origin of the white speleothems and present evidence for a new technique for dating strong to great earthquakes anywhere where caves are found near major seismic zones. This work is based on postearthquake initiation of stalagmites in caves within several hundred kilometers of the NMSZ. Stalagmite dating could potentially provide an additional technique for the investigation of prehistoric earthquakes.

Methodology

Fifteen actively growing, white stalagmites (several growing on older stalagmites) were collected from Fogelpole Cave, Illinois Caverns, and Pautler Cave in compliance with the Illinois Cave Protection Act. Some were collected as whole stalagmites and some as drill cores. The samples were dated using uranium/thorium (U/Th) disequilibrium techniques (for the white stalagmites and for the base of the older stalagmites on which they grew) in combination with counting of annual growth laminae (for the white stalagmites) observed using petrographic techniques in thin section (Table 1). Growth laminae are annual depositional forms that occur in speleothems growing in caves in areas with strong seasonal variations; typically, they grow continuously throughout the year. As described by Tan *et al.* (2006), "visible laminae require a regular (often seasonal) alternation of the arrangement in space of crystals with a well-defined morphology (texture or fabric)."

For most of the samples, the age of stalagmite concentric growth layers (laminae) were determined using a total dissolution single sample $^{238}U/^{234}U/^{230}Th$ dating technique with measurements made on a Nu Plasma Multicollector-Inductively Coupled Plasma Mass Spectrometer (MC-ICPMS) located in the Department of Geology at the University of Illinois. Analysis protocols are given in Sims *et al.* (2008). For these samples, a standard correction for the presence of detrital thorium was used, assuming the $^{230}Th/^{232}Th$ was that of the Earth's crust ($\sim 4.46 \times 10^{-6}$). However, if the majority of ^{230}Th measured came from the detritus for some samples, then the standard method for correction was no longer usable and the determined age can be meaningless. For example, sample IC-12 had a very large detrital Th content and yielded a U/Th age of 400 yr ± 900 yr

Table 1
Annual Growth Laminae and U/Th Ages from Stalagmites Collected between 2002 and 2008

Sample Number (Year Sampled)	Growth Laminae Age (Yr B.P.)	Uranium/Thorium Age (Yr B.P. Extrapolated)	Year of Initiation of Stalagmite
FC94-1 (2002)	$200 \pm 36^{*}$	$225 \pm 5,\ 240 \pm 5^{\dagger}$	A.D. 1822–1757
FC94-1A (2002)	ND	$4600 \pm 130^{\dagger}$	2730–2470 B.C.
FC-1 B (2006)	ND	$11,500 \pm 70^{\dagger}$	9570–9430 B.C.
FC-1C (2006)	ND	$17,780 \pm 120^{\dagger}$	15,900–15,660 B.C.
FC-1 D (2006)	ND	$83 \pm 8^{\dagger}$	A.D. 1931–1915
FC-3 (2002)	$200 \pm 36^{*}$	$173 \pm 5^{\dagger}$	A.D. 1834–1782
FC-3 A (2002)	ND	$4560 \pm 100^{\dagger}$	2660–2460 B.C.
FC-9 (2006)	$198 \pm 36^{*}$	153 ± 8	A.D. 1828–1788
IC-1 (2006)	$191 \pm 34^{*}$	$9 \pm 12^{\S}$	A.D. 1834–1796
IC-4 (2006)	$100 \pm 18^{*}$	ND	A.D. 1916–1896
IC-5 (2006)	$206 \pm 37^{*}$	$96 \pm 12^{\S}$	A.D. 1821–1779
IC-10 (2006)	$88 \pm 16^{*}$	$18 \pm 32^{\S}$	A.D. 1927–1909
IC-12 (2006)	$84 \pm 15^{*}$	$400 \pm 900^{\S}$	A.D. 1930–1914
IC-22 (2008)	ND	$240 \pm 56^{\ddagger}$	A.D. 1822–1712
PC 1 (2008)	ND	$5700 \pm 1800^{\dagger}$	5500–1900 B.C.
PC 2a (2008)	ND	$1200 \pm 260^{\dagger}$	A.D. 1460–940
PC 2b (2008)	ND	$3050 \pm 355^{\dagger}$	1406–695 B.C.
PC 3 (2008)	ND	$620 \pm 110^{\dagger}$	A.D. 1498–1278
PC 6 (2008)	ND	$196 \pm 63^{\dagger}$	A.D. 1875–1749
PC 7 (2008)	ND	$210 \pm 75^{\dagger}$	A.D. 1873–1723

FC, Fogelpole Cave; IC, Illinois Caverns, PC, Pautler Cave; ND, not determined; if U/Th ages were determined from samples collected above the base of the stalagmite, those ages were extrapolated to the base of the stalagmite. Counting of growth laminae assumes continuous growth because initiation of the stalagmite is based on the absence of any apparent hiatus.

*Laminae from the flank of the stalagmite were projected to the apex and used to estimate the time of initiation based on the distance from the base. Counting error for annual laminae was estimated to be about 18% (Ⓔ details are available in the electronic edition of *BSSA*). The U/Th ages for FC94-1 are an average of the ages determined from the flank and from the apex of the stalagmite in Figure 2.

†Stalagmite ages are from U/Th single point dating techniques.

‡Stalagmites ages are from U/Th isochron dating techniques.

§U/Th age is meaningless due to problems associated with detritus within the samples.

(Table 1). Consequently, the error can greatly exceed the age, rendering the age unusable. For some samples rich in detritus (Ⓔ Table S2b, available in the electronic edition of *BSSA*), we performed an isochron analysis method whereby we drilled two spatially close samples having visibly different amounts of detritus. Each sample was completely dissolved and then measured for $^{238}U/^{234}U/^{230}Th/^{232}Th$ and a two point isochron age calculated.

Uranium concentrations in stalagmites from Fogelpole Cave (U = 4.17–56.3 ppm) were anomalously high and greater than those in stalagmites from Illinois Caverns (U = 0.70–4.37 ppm) and Pautler Cave (U = 0.8–3.7 ppm), thus requiring smaller samples and yielding smaller analytical errors. Not all of the young, white stalagmites were datable because of the effects of postdepositional (digenetic) water–rock interaction suggested by vugs in the central portion of most of the stalagmites. Therefore, samples for U/Th dating were collected along the denser flanks of the stalagmites away from the central growth axis. In the case of stalagmite FC-3, the U/Th age of its flank was projected to the central axis of the stalagmite by following millimeter-scale concentric growth laminae (Fig. 2 and Ⓔ Fig. S3, available in the electronic edition of *BSSA*).

Thin sections of the stalagmites were examined under plain light (PL) and cathodoluminescence (CL) to identify the character and fabric of the growth laminae. Growth laminae were counted in accordance with principles and guidelines proposed by Tan *et al.* (2006). If laminae were obscured or not identifiable along a vertical transect, laminae along the sides of the stalagmites were counted and traced back to the apex of the stalagmite. Clusters of continuous growth laminae were counted at multiple locations within each stalagmite thin section yielding an average number of growth laminae per millimeter thickness for all but one white stalagmite. Laminae were most easily identifiable near the sides of the stalagmites (Fig. 3) where they could be counted and the upper and lower bounds of the laminae could be traced to the axes of the stalagmites. Assuming a linear growth rate, that value was multiplied by the height of the stalagmite to get the approximate age B.P. of the stalagmite.

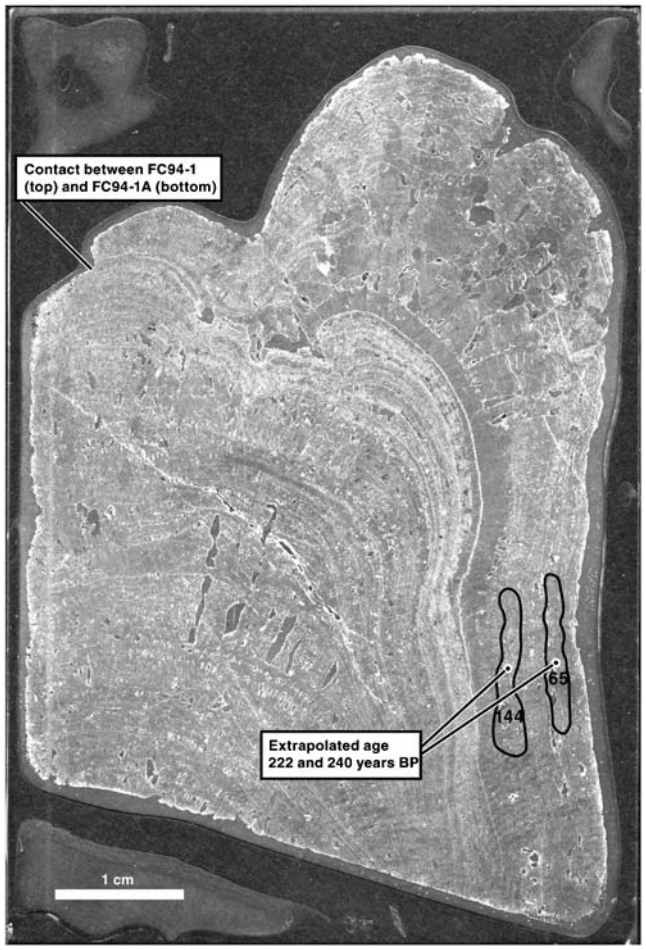

Figure 2. Section of stalagmite FC94-1 showing the locations of dated samples. The age of initiation of stalagmite FC94-1 was calculated from the ages of samples collected along its flank relative to the thickness of the flank and by projecting U/Th ages from the flank of the stalagmite to its apex, along the growth laminae, and calculating the age of initiation based on stalagmite thickness.

Counting error was estimated to be ±18% based on the variation in thickness of annual growth laminae.

Results

All age-related data from U/Th dating and annual growth laminae counting and comparisons of stalagmite-initiation dates with the timing of historic and prehistoric seismic events determined by other means are presented in Table 1 and Ⓔ Tables S1 and S2a,b (available in the electronic edition of *BSSA*). Stalagmite-initiation and stalagmite-regrowth dates from other sources (Dennison *et al.*, 2000; Lepley, 2004; Dennison *et al.*, 2007) are presented in Ⓔ Table S1 (available in the electronic edition of *BSSA*).

The white stalagmites were made of variable dense to porous, white, low-Mg calcite and typically ranged from 2 to 6 cm in height and 2 to 4 cm in width; those from Pautler Cave were often taller (Ⓔ Figs. S1 and S2, available in the electronic edition of *BSSA*). When forming on fine-grained sediment, drip water from stalactites initially created erosional craters. Within those craters, stalagmites formed with an appearance of having rootlike structures at their bases (Ⓔ Fig. S2, e.g., IC-4, IC-5, FC-1, available in the electronic edition of *BSSA*). Those samples growing on sediment were collected only from locations high in the caves where it had been determined that flooding had not occurred in at least the last few hundred years. Most of the stalagmites contained vugs along the long axis of the stalagmites that crosscut some of the centimeter-scale concentric growth laminae (Ⓔ Fig. S2, e.g., FC-1 and FC-9, available in the electronic edition of *BSSA*).

The white stalagmites are similar in color, texture, and mineralogy to those found by Postpischl *et al.* (1991) and Agostini *et al.* (1994) in a cave near an earthquake-prone zone in Italy. They found that a second generation of stalagmites formed on dormant stalagmites in the Grotta del Cervo in Italy following a major earthquake that occurred in 1456 (based on historic accounts). They reported that the newer portion of each stalagmite was made of coarsely crystalline calcite, was white in color, and was poorly laminated. The preearthquake older portion of the stalagmites was microcrystalline, dense, gray, and well laminated. As discussed in detail subsequently, these Italian cave observations suggest that the white speleothems from Fogelpole Cave and Illinois Caverns resulted from seismic events in the central midwestern United States, based on (1) concurrent initiation and rejuvenation of stalagmites that were dormant for thousands of years, (2) morphological similarities to earthquake-initiated stalagmites of the Grotta del Cervo, and (3) ages based on growth laminae and U/Th disequilibria that are concordant with known seismic events in the region.

The stark whiteness of the calcite speleothems (Ⓔ Figs. S1 and S2, available in the electronic edition of *BSSA*) suggests that they contain very low concentrations of dissolved high molecular weight organic acids and/or fine-grained sediment; humic acids and fine-grained sediments typically are responsible for the tan, orange, and brown colors of speleothems (White, 1997). We postulate that macropores in the porous sediments, dissolution crevices, bedding planes, and fractures in the bedrock, through which source drip water typically migrates, were opened/reopened by seismic events. It is not clear why the older stalagmites, temporally related to NMSZ earthquake activity, are often (but not always) darker in color. It might be possible that flooding associated with extreme prehistoric rainfall events could repeatedly coat the older stalagmites with fine sediment. For example, one multistage stalagmite (FC-1) collected well above the present effects of flooding has a roughly 10,000 yr old white stage that is separated from a more recent 83 yr old stage by a thin layer of fine-gained sediment (Ⓔ Fig. S2, available in the electronic edition of *BSSA*). This is further supported with work by Panno *et al.* (2004) who found evidence that flood waters have not risen higher than 2–3 m above present stream levels in Fogelpole Cave since 4000 yr B.P. (all samples were collected at cave levels higher

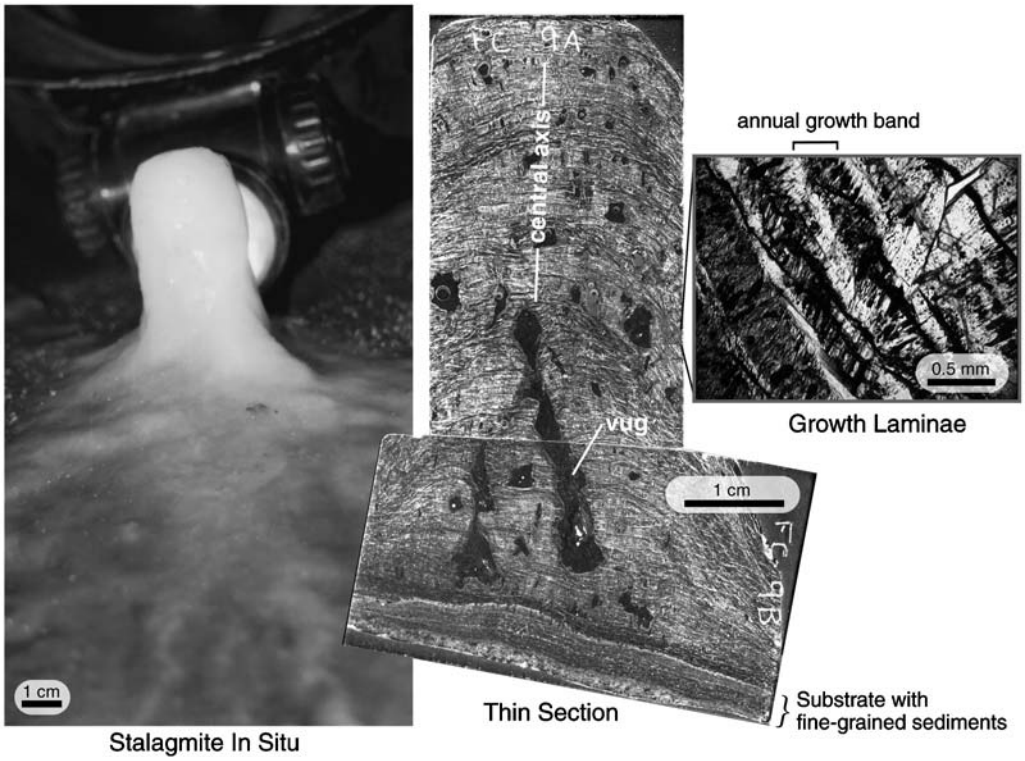

Figure 3. Stalagmite FC-9 *in situ* (left-hand panel), in thin section (middle panel), and under a PL microscope (right-hand panel) showing annual growth laminae. The dark laminae are interpreted to be more organic-rich spring and summer deposition and the clear laminae, fall and winter deposition.

than 3 m above stream levels). The longevity of these white stages, and hence their fracture pathways, are unclear at this time, but very preliminary data suggest a limited lifetime of less than 1000 yr.

The time of initiation of the stalagmites were inferred from U/Th dates and growth laminae (Table 1). The age of stalagmite FC94-1 (Fig. 2), estimated based on the midpoints of the sample locations along the flank, yielded an initiation age of 240 ± 2 yr B.P. for the sample closest to the stalagmite's surface (A.D. 1765–1760) and an initiation age of 222 ± 5 yr B.P. for the sample location closest to the stalagmite's base (A.D. 1784–1775). Stalagmite FC-3 was sampled across most of the growth bands (Ⓔ Fig. S3, available in the electronic edition of *BSSA*); extrapolation of the sample age to the apex of the stalagmite yielded an age of 173 ± 5 yr B.P. (A.D. 1834–1824). Stalagmite FC-1D yielded nearly identical U/Th (83 ± 8 yr B.P.; 84 yr if one considers the sample location on the stalagmite) and growth laminae ages (83 ± 8 yr B.P. or A.D. 1931–1915). Two of the older parts of multistage stalagmites (stalagmites with multiple stages of growth, hiatus, and regrowth) yielded ages of initiation of 4560 ± 100 yr B.P. (2560 B.C.) and 4600 ± 130 yr B.P. (2600 B.C.). Another multistage stalagmite (FC-1B, FC-1C, and FC-1D) grew for a short time about $17,840 \pm 120$ yr B.P., began regrowing about $11,284 \pm 70$ yr B.P., stopped again about 10,000 yr B.P., and began regrowing about 83 ± 8 yr B.P., respectively (Ⓔ Fig. S2, available in the electronic edition of *BSSA*).

The U/Th ages of several stalagmites were used to corroborate ages determined by counting growth laminae (Ⓔ Fig. S4, available in the electronic edition of *BSSA*). The crystal faces appeared (in PL) as thin, dark, spiky features that highlight the boundaries; under CL, they appeared lighter colored suggesting a more organic-rich content (Ⓔ Fig. S5a,b, available in the electronic edition of *BSSA*). In other stalagmites, the crystal faces were often wider with thinner, clear calcite bands separating them (Fig. 3). Along the FC 94-1 transect, the thickness of laminae ranged from 0.045 to 0.080 mm, with a mean, standard deviation, and median thickness of 0.055, 0.01, and 0.053 mm, respectively. The thickness of laminae along the flanks of the stalagmites is thinner, by almost an order of magnitude, than that along the central axes of the stalagmites. Eighty-three growth bands were estimated to be present between areas dated using U/Th dating techniques (65 ± 2 and 144 ± 5 calendar yr). The total number of laminae between the two dated locations was based on the thickness of 32 identifiable laminae; the counts were within analytical error of the U/Th ages. Using a value of two standard deviation about the mean, the growth laminae between the two U/Th ages yielded a time period between the samples of 81 ± 30 yr. Growth rates in all white stalagmites range from between 0.2 and 0.3 mm/yr along the vertical axes; this growth rate

appears to have remained constant from the base to the top of each stalagmite. Counting of the annual laminae has a conservative estimated error of ±18% (Ⓔ details are available in the electronic edition of *BSSA*).

Thin sections of the white stalagmites were examined for growth and dissolution patterns and inclusions of fine-grained sediment (Fig. 3). The stalagmites are composed of columnar calcite with their long crystallographic axes normal to the substrate on which the stalagmites were growing. All of the white stalagmites examined in thin section contain vugs, most commonly along their central axes, and typically contain little detritus except along their contacts with underlying substrates (Fig. 2 and Ⓔ Fig. S3, available in the electronic edition of *BSSA*). Linear features under PL in thin section (Fig. 3) consist of alternating clear and dark bands and are interpreted to be annual growth laminae based on corroborating U/Th dates. The clear laminae appear to be composed of clean, dense calcite, whereas the darker bands are characterized by crystal faces growing normal to the laminae boundaries.

Those stalagmites that did not have datable flanks (using U/Th techniques) were dated by counting annual growth laminae across the total thickness of the stalagmite. The number of laminae counted in reflected light images of thin sections are the same as those observed in PL (Fig. 3) and are assumed to constitute annual features based on the similar appearance of annual growth laminae identified by Baker *et al.* (1993) and based on a petrographic analysis of several stalagmites (Ⓔ details are available in the electronic edition of *BSSA*). There were two white stalagmites for which we were able to both count laminae and perform U/Th dating. The U/Th ages are consistent with ages determined by counting annual growth laminae for those two stalagmites (Table 1).

Discussion

The ages of initiation of white stalagmites fell into two age groups (Table 1). The oldest ranged from 162 to 245 yr B.P. (A.D. 1802 ± 42 yr), and the youngest ranged from 69 to 118 yr B.P. (A.D. 1912 ± 24 yr). These older ages correlate well with the timing of the NMSZ earthquakes of 1811 and 1812. The younger ages correlate well with the timing of the Missouri earthquake of 9 April 1917 (Finch, 1917), a moderate (moment magnitude 4.9) Missouri earthquake whose epicenter was in the Ste. Genevieve–St. Marys, Missouri, area (Finch, 1917; U.S. Geological Survey [USGS], 2007) (Fig. 1). The effects of earthquakes on aquifers as a result of sediment and bedrock deformation and ground shaking include consolidation (volume reduction) of sediment, fracturing of bedrock (including slippage along existing fractures), and transport of materials into, out of, and within fissures. These changes are reported to occur as far as hundreds of kilometers from the epicenter of an earthquake (Montgomery and Manga, 2003). Based on the proximity of the epicenters of the 1811–1812 NMSZ earthquakes and the Missouri earthquake of 1917 to these caves (about 150 and 15 km, respectively), the proximity to NMSZ-generated sand blows located about 24 km to the east (Reynolds, 1887), and the historical 1811–1812 intensities in our study area (Fig. 1), we propose that shaking of an intensity of about 5 or greater (on the modified Mercalli intensity) is capable of dilating/reopening vertical and horizontal crevices overlying caves previously too tight for water movement or sealed by flowstone and/or fine-grained sediment. It is also possible that closure of these pathways may also occur as a direct result of such a seismic event.

The ages of the older stalagmites, on which the white stalagmites grew, correspond to the ages determined for a suspected earthquake-induced abandonment of a Mississippi River meander that occurred in 4250 yr B.P. (2244 B.C.) (Holbrook *et al.*, 2006) and earthquake-induced sand blows at 4350 yr B.P. (2350 B.C.) (Tuttle *et al.*, 2006). The latter two dates represent the findings of two independent studies that arrived at the same conclusion that one or more very large earthquake produced by the NMSZ about 4300 yr B.P. The significance of the oldest date of the multistage stalagmite that we dated (17, 780 ± 120 yr B.P.) could be coincident with a liquefaction date by Vaughn (1994) of 23,000–17,000 yr B.P. The second oldest date (11, 500 ± 70 yr B.P.) could be associated with the 12, 000 ± 120 yr B.P. earthquake event of Munson *et al.* (1997) and Tuttle, Chester, *et al.* (1999). Alternatively, speleothem dates may be associated with climate change coincident with the end of the Wisconsin glacial episode and the beginning of the Holocene.

An analysis of previously published stalagmite ages of initiation suggests that the basal ages of speleothems could provide critical geochronology on midwestern U.S. paleoseismicity. For instance, Crevice Cave, located in southeastern Missouri south and just across the Mississippi River from Illinois Caverns, Fogelpole Cave, and Pautler Cave, contains stalagmites (dated by Lepley [2004] for a paleoenvironmental study) whose dates of initiation correspond with known or suspected NMSZ earthquakes (Ⓔ Table S1, available in the electronic edition of *BSSA*). Dates of initiation of stalagmites of caves in southeastern Missouri near our study area include 5460 ± 224 yr B.P. (Crevice Cave) (Lepley, 2004), about 5500 yr B.P. (Ozark Caverns, Missouri), about 3900 yr B.P. (Bridal Cave, Missouri) (Dennison *et al.*, 2000), 3500 ± 100 yr B.P. (Devil's Ice Box Cave, Missouri) (Dennison *et al.*, 2007), and the regrowth of a stalagmite beginning 10, 190 ± 130 yr B.P. (Ⓔ Table S1, available in the electronic edition of *BSSA*) following a long hiatus (the stalagmite stopped growing 116, 930 ± 420 yr B.P. [Lepley, 2004]). The initiation of new stalagmites and regrowth of dormant stalagmites would reasonably be expected given the potential for large earthquakes to reopen existing pathways (fractures and bedding planes) within shallow bedrock (Montgomery and Manga, 2003). Because relatively small intensity earthquakes can apparently generate stalagmite growth, not all of the stalagmites are indicative of larger paleoearthquakes that are important to seismic hazard

assessment. However, a geographically broader-based investigation, coupled with other paleoseismic data might conquer this limitation. Accordingly, the techniques described herein could further constrain paleoearthquake records supplied by other paleoseismic techniques and have the potential to extend the paleoearthquake record into regions where other techniques (e.g., liquefaction and fluvial geomorphology) cannot be used. In addition, further development of the technique (e.g., a broader-based investigation) could provide information on locations and perhaps magnitude of paleoearthquakes similar to that of earthquake-induced liquefaction features.

An alternative explanation for the initiation of the white speleothems must be considered, which is that the initiation could be the result of changes in land use that might have altered the chemical composition of recharge water and affected recharge pathways into the caves. For example, the initial plowing of the prairie in the study area began in the 1840s (Anonymous, 1883) and the widespread use of artificial nitrogen-based fertilizers that began in the 1960s could have changed the acidity of recharge water entering the epikarst and ultimately the caves. The application of anhydrous ammonia is now common in the midwestern United States, and its conversion from ammonia to ammonium to nitrate results in a net gain of one proton as follows: $NH_3 + H_2O \rightarrow NH_4^+ + OH^-$ and $NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$. The biologic degradation of organic carbon from the plowing under of prairie plants should generate carbon dioxide and even more protons as follows: $2CH_2O + O_2 \rightarrow 2CO_2 + 4H^+$. These reactions would increase the acidity of the recharge water that could dissolve healed and/or new pathways into caves and could have resulted in the initiation of white speleothems. Examination of land use overlying cave passages where white speleothems occur revealed that the speleothems occur beneath both forested and cultivated areas. Further, the coincident nature of historic and prehistoric earthquakes in the study area with stalagmite-initiation ages (Table 1 and Ⓔ Table S1, available in the electronic edition of *BSSA*) suggests that seismic events are probably the dominant process. However, this does not preclude the possibility that the initiation of at least some speleothems might be associated with climate change and/or historic changes in land use.

Finally, we emphasized that this investigation involved a limited number of samples collected from a relatively small area. However, the results, in terms of coincidence of timing of the initiation of stalagmite growth with Holocene and possibly late-Wisconsin earthquake activity, strongly suggest a causal relationship.

Conclusions

Speleothems in caves in the vicinity of the NMSZ constitute a previously unrecognized recorder of large earthquakes in the U.S. midcontinent for at least the last 200 yr and potentially the last 100,000 yr. The timing of the initiation of stalagmites in caves of southwestern Illinois and southeastern Missouri is consistent with known historic and prehistoric seismic events in the midcontinent region. Seismic events could have opened, reopened, or altered pathways into caves that allowed for seepage of speleothem-forming fluids. Determination of timing of stalagmite initiation and later postearthquake speleothem rejuvenation has the potential to document prehistoric earthquakes, expand the geographical distribution of paleoseimic data, and help improve interpretations of paleoearthquakes.

Data and Resources

All U/Th and thin section data described herein are accessible in the table and figures of this article and Ⓔ in the tables and figures of the supplemental material available in the electronic edition of *BSSA*). This information is also available at http://www.isgs.illinois.edu/research/earthquake-hazards/panno/speleothems.shtml (last accessed June 2009).

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Major Earthquakes Recorded by Speleothems in Midwestern U.S. Caves

by Samuel V. Panno, Craig C. Lundstrom, Keith C. Hackley, B. Brandon Curry, Bruce W. Fouke, and Zaofeng Zhang

Introduction

These supporting online materials contain a detailed description of sample collection methods, techniques used for petrography and growth-laminae counting of thin sections, uranium-thorium age-dating techniques, and a description of the geology and hydrogeology of the study area. In addition, we have included two data tables and five figures. Table 1 provides a comparison of stalagmite initiation dates with dates of known paleoearthquakes determined by other means. Tables 2, 3 provide the analytical results of uranium-series dating for all of the stalagmites dated in this investigation. Six figures provide photographs of stalagmites as they appeared in place and after being cored or collected and cut in half (including sampling locations for uranium-series dating). They also show thin sections in plain light and under cathodoluminescence in order to illustrate growth-laminae counting methods and the correlation of uranium-series dates with growth laminae counts.

Materials and Methods

Sample Collection

We collected, with permission from the Illinois Nature Conservancy and from the Department of Natural Resources, in accordance with the Illinois Cave Protection Act, and over the course of seven years, 15 stalagmites from Fogelpole Cave, Illinois Caverns and Pautler Cave (Figs. 1, 2). Because at least the upper part of the stalagmites were young and actively growing, both growth laminae counting in thin sections and standard U-Th disequilibria dating techniques (described below) were used to date the speleothems.

Petrography and Growth Laminae Counting

Thin sections were made from the nine white stalagmites using standard techniques. Each stalagmite was cut in half vertically along its growth axis and thin sections were made from one of the halves of each stalagmite. Thin sections were prepared by Burnham Petrographics, Rathdrum, ID. Thin sections were made with slightly thicker than normal and polished. The thin sections were initially examined under both transmitted and reflected light using a petrographic microscope in order to identify the character and fabric of the growth laminae.

Stalagmite growth laminae were counted in accordance with principles and guidelines proposed by Tan et al. (2006). Laminae were often obscured by other features (e.g., dissolution) or not identifiable along a single transects; to compensate for this, laminae along the sides of the stalagmites were counted and extrapolated to the transect being counted. Thin sections of each stalagmite were examined with a petrographic microscope under plain light (PL) and cathodoluminescence (CL). Uranium/Thorium ages were used to corroborate ages determined by counting growth laminae. Thin sections of several stalagmites were examined in detail. A transect of a thin section taken from the flank of stalagmite FC 94-1 was examined using plain light and CL (Figs. 3, 4). Lineaments within the thin section that we interpreted as growth laminae were created by the alignment of thin crystal faces lying normal to laminae boundaries, and by dissolution features. The crystal faces appeared (in plain light) as thin, dark, spiky features that highlight the boundaries; under CL, they appeared lighter-colored suggesting a more organic-rich content (Fig. 5). In other stalagmites, the crystal faces were often wider with thinner, clear calcite bands separating them. Contacts between laminae were usually sharp and often associated with parallel fractures that probably formed during the making of the thin sections. Along the FC 94-1 transect, the thickness of laminae ranged from 0.045 mm to 0.080 mm, with a mean, standard deviation, and median thickness of 0.055 mm, 0.01 mm, and 0.053 mm. The thickness of laminae along the flanks of the stalagmites is thinner, by almost an order of magnitude, than those along the central axes of the stalagmites. Eighty-three growth bands were estimated to be present between areas dated using U/Th dating techniques (65 ± 2 and 144 ± 5 calendar years). The total number of laminae between the two dated locations was based on the thickness of 32 identifiable

laminae; the counts were within analytical error of the U/Th ages. Using two standard deviation about the mean, the growth laminae between the two U/Th ages yielded a time period between the samples of 81 ± 30 years.

In order to examine the entirety of each stalagmite, we used reflected light with the thin sections lying on a black background to bring out the growth laminae. Thin sections were scanned on an Epson flatbed scanner, and growth laminae were counted on 28 X 43 cm blow ups of the thin section scans. Because growth laminae were not visible everywhere on the thin sections (due to localized dissolution and recrystallization), clusters of continuous growth laminae were counted at multiple locations within each stalagmite thin section yielding an average number of growth laminae per mm thickness for each stalagmite. Laminae were most easily identifiable near the sides of the stalagmites where they could be counted and the upper and lower bounds of the laminae could be traced to the axes of the stalagmites. Assuming a linear growth rate, that value was multiplied by the height of the stalagmite to get the approximate age BP of the stalagmite. Counting error was estimated to be ± 18% based on the variation in thickness of annual growth laminae.

Uranium-Thorium Disequilibrium Age Dating

Speleothems were dated using standard U-Th disequilibria dating techniques (described below). Stalagmites were microdrilled in order to collect 100 mg samples along annual growth laminae. For most of the samples, the age of stalagmite concentric growth layers (laminae) were determined using a total dissolution single sample ^{238}U-^{234}U-^{230}Th dating technique with measurements made on a Nu Plasma MC-ICPMS located in the Department of Geology at the University of Illinois. Analysis protocols are given in Sims et al. 2008. Chemical separation procedures for U-series analyses were similar to those of Edwards et al. (1986) and Cheng et al. (1998). MC-ICPMS analysis consisted of aspirating a 10 ppb solution of purified U or Th through a desolvating nebuliser and measuring either ^{238}U, ^{235}U, ^{236}U and ^{234}U or ^{232}Th, ^{230}Th and ^{229}Th simultaneously on the mass spectrometer. Sensitivity for U and Th are routinely 400V/ppm at a nebulisation rate of 100 microliter/min. The instrument is fitted with a retarding potential lens providing abundance sensitivity of < 200ppb and an electron multiplier having a dead time of ~10 ns and dark current of < 6 cpm. Because of the young age of these samples, detrital Th corrections to the age are significant, but generally less than 10% (Tables 2). For these samples, a standard correction for the presence of detrital thorium was used, assuming the ^{230}Th measured came from the detritus for some smaples, then the standard method for correction was no longer usable and the determined age can be meaningless. For example, sample IC-12 had a very large detrital Th content and yielded a U/Th age of 400 years ± 900 years. Consequently, the error can greatly exceed the age, rendering the age unusable. For some samples rich in detritus (Table 2), we performed an isochron analysis method whereby we drilled to spatially close samples having visibly different amounts of detritus. Each sample was completely dissolved and then measured for ^{238}U-^{234}U-^{230}Th-^{232}Th and a 2 point isocron age calculated.

Because any incorporation of the older, underlying carbonate minerals of the bedrock and older speleothems could significantly bias the age of the white stalagmites, particular care was taken to maintain a buffer zone between the oldest sample from the white stalagmite and the underlying older carbonate minerals. In addition, because of the presence of dissolution pits near the apex of the stalagmites, U-Th disequilibria ages were determined along unaffected growth laminae along the flanks of the stalagmites. The growth laminae sampled were then followed up to the apex of the stalagmite and the total age was extrapolated by measuring the total thickness of the stalagmite. This technique was cross checked using multiple U/Th ages of stalagmite FC94-1.

Geology and Hydrogeology of the Study Area

The study area includes three caves in the sinkhole plain of southwestern Illinois, Fogelpole Cave, Illinois Caverns and Pautler Cave. The sinkhole plain occupies parts of three counties and contains approximately 10,000 mapped sinkholes (with as many as 90 per km^2), numerous large springs, and the longest caves in Illinois (Weibel and Panno, 1997; Panno et al., 2004a, b, c). Climatic conditions in the area are temperate and the area receives an average rate of precipitation of between 102 and 107 cm per year (Spatial Climate Analysis Service 2000). Here, Mississippian-age St. Louis Limestone is exposed along the western margin of the Illinois Basin and gently dips eastward toward the center of the basin. This relatively soluble, calcite-rich formation has prominent bedding planes and is highly jointed. Bedrock is overlain by a Quaternary succession of loess and glacial till that is replete with cover-collapse sinkholes. These deposits are as much as 20 m thick, and includes weathered pre-Illinoian silt and residuum (Oak Formation), Illinois Episode diamicton and silt (Petersburg Silt and Glasford Formation) capped by Wisconsin Episode loess (Peoria and Roxana silts) (Panno et al., 2004a). The bottoms of many sinkholes revealed bedrock. The uneroded Quaternary deposits are about 10 m thick in the vicinity of Fogelpole Cave, Illinois Caverns and Pautler Cave (Panno et al., 1996).

Fogelpole Cave, Illinois Caverns and Pautler Cave are branchwork-type caves (Panno et al., 2004a, b) with over 22 km, 10 km and 10 km of passages, respectively. All three caves have perennial first- and second-order streams that flow the lengths of their passages. These subterranean streams eventually discharge from relatively large springs down gradient of the distal end of the cave passages. Located within 4.5 km of each other, Fogelpole Cave and Illinois Caverns trend from northwest to southeast, and act as drains for their respective groundwater basins. Recent work by the authors has shown the caves to have formed about 150,000 years BP due to glacial melting near the end of the Illinois Glacial Episode (Panno et al. 2004b). Pautler Cave is located about 12 km northwest of Illinois Caverns; however, little additional information about the cave is available.

Figures *Click an image to view full-size and/or view all images as a slideshow.*

Fig. 1. A gallery of white stalactites and stalagmites in Illinois Caverns, many of which are growing on older, darker stalagmites.

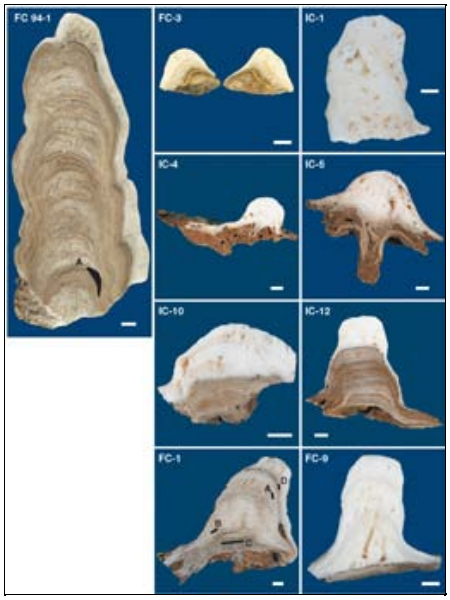

Fig. 2. A photo montage of all stalagmites (in cross section) collected and analyzed during this investigation. IC = Illinois Caverns and FC = Fogelpole Cave. All scale bars are 1 cm wide.

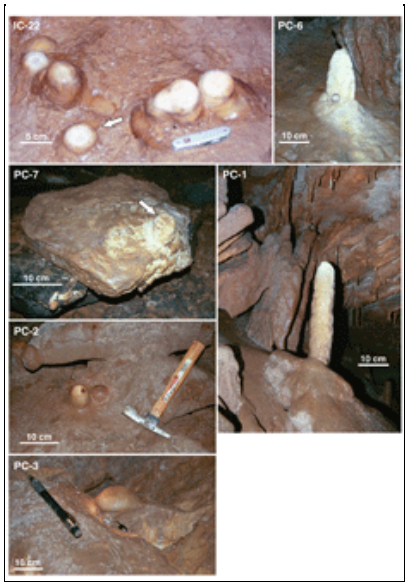

Fig. 3. A photo montage of all stalagmites (in the field) cored or collected and analyzed during this investigation. IC = Illinois Caverns and PC = Pautler Cave.

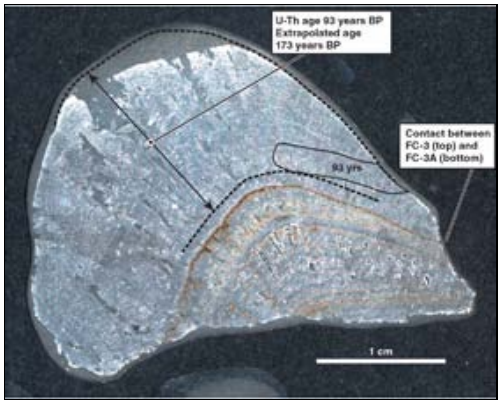

Fig. 4. Projection of U-Th ages from the flank of stalagmite FC-3 to its apex and its use in determining the age of initiation of the stalagmites. Note that part of the top of the stalagmite was lost during thin section polishing.

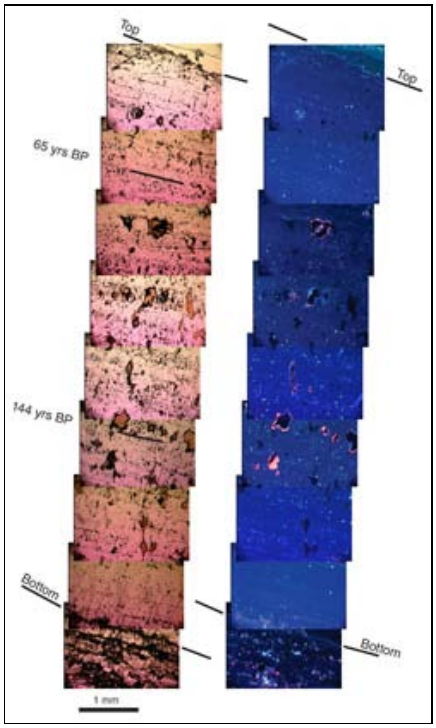

Fig. 5. Transect across the flank of stalagmite FC 94-1 in plain light (left) and CL (right) showing the locations of U/Th age dated layers, and annual growth laminae.

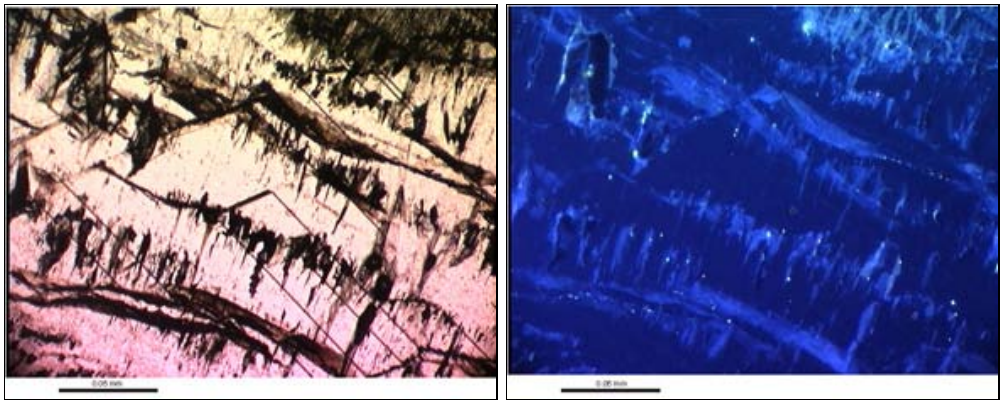

Fig. 6. Stalagmite FC-9 in PL (left) and CL (right) showing boundaries between growth laminae as termination of crystal faces. Cathodoluminescence shows the crystal faces to be lighter in color suggesting a greater organic content. A scalenahedron of calcite is seen cross-cutting annual laminae in PL.

Table 1.

Ages of major NMSZ earthquakes as determined from historic and geologic evidence and stalagmite initiation and regrowth from the study area.

Age (Years AD or BC)	Time BP (Years)	Source(s)	Evidence
AD 1917	100 ± 18*	Panno et al. (this study)	Stalagmite Initiation
	88 ± 16*	Panno et al. (this study)	Stalagmite Initiation
	84 ± 15*	Panno et al. (this study)	Stalagmite Initiation
	83 ± 8*	Panno et al. (this study)	Stalagmite Initiation
AD 1811-12		Nuttli (1987)	Historic Records
		Saucier (1989)	Liquefaction
	200 ± 36*	Panno et al. (this study)	Stalagmite Regrowth
	200 ± 36*	Panno et al. (this study)	Stalagmite Initiation
	191 ± 34*	Panno et al. (this study)	Stalagmite Initiation
	206 ± 37*	Panno et al. (this study)	Stalagmite Initiation
	198 ± 36*	Panno et al. (this study)	Stalagmite Initiation
	196 ± 63	Panno et al. (this study)	Stalagmite Initiation
	240 ± 56	Panno et al. (this study)	Stalagmite Initiation
	210 ± 75	Panno et al. (this study)	Stalagmite Initiation
AD 1450	550 ± 150	Tuttle et al. (1999a, 2002)	Liquefaction
	620 ± 110	Panno et al. (this study)	Stalagmite Initiation
AD 900	1100 ± 100	Tuttle et al. (1999a, 2002)	Liquefaction
	1200 ± 260	Panno et al. (this study)	Stalagmite Initiation
AD 300	1700 ± 200	Tuttle et al. (2005)	Liquefaction
1620 BC	3626 ± 220	Holbrook et al. (2006)	Miss. River Meander
	3500 ± 100	Dennison et al. (2000)	Stalagmite Initiation
	~ 3900	Dennison et al. (2007)	Stalagmite Initiation
	3050 ± 355	Panno et al. (this study)	Stalagmite Initiation
			Stalagmite Initiation
2244 BC	4250 ± 269	Holbrook et al. (2006)	Miss. River Meander
2350 BC	4350 ± 200	Tuttle et al. (2006)	Liquefaction
	4600 ± 130	Panno et al. (this study)	Stalagmite Initiation
3500 BC	~ 5500	Tuttle et al. (2006)	Liquefaction
	5460 ± 224	Lepley (2004)	Stalagmite Initiation
	5700 ± 1800	Panno et al. (this study)	Stalagmite Initiation
4520 BC	6502 ± 160	Tuttle et al. (2004)	Liquefaction

11,340 BC	13,340 - 9,000	Vaughn (1994)	Liquefaction
10,000 BC	12,000 ± 1000	Munson et al. (1997) and Tuttle et al. (1999b)	Liquefaction
	10,190 ± 420	Lepley (2004)	Stalagmite Regrowth
	11,500 ± 70**	Panno et al. (this study)	Stalagmite Initiation
21,000-15,000 BC	23,000 - 17,000	Vaughn (1994)	Liquefaction
	17,780 ± 120	Panno et al. (this study)	Stalagmite Initiation

*Based on growth laminae counting; stalagmites collected in 2006.
**Ages extrapolated to the bottom of the stalagmite.

Table 2. Data used in uranium-series dating of all stalagmites

Sample	U (ppm)	Th (ppb)	δ^{234}Ui	δ^{234}Up	(^{230}Th/^{238}U) A	Uncorrected ages (ka)	Corrected ages (ka)
FC94-1-high	12.62±0.02	4.984±0.008	-164.0±0.4	-163.9±0.4	0.0006033±0.0000060	0.079±0.001	0.065±0.002
FC94-1-low	11.70±0.02	11.79±0.02	-155.9±0.4	-155.8±0.4	0.001392±0.000012	0.179±0.002	0.144±0.005
FC-3	4.950±0.010	6.671±0.009	-47.15±0.11	-47.14±0.11	0.001178±0.000017	0.135±0.002	0.093±0.005
FC94-1A	8.902±0.026	162.5±0.53	-156.7±0.4	-153.9±0.3	0.03944±0.00044	5.20±0.07	4.56±0.10
FC-3A	14.24±0.11	54.27±1.09	-164.0±0.4	-161.6±0.4	0.03571±0.00078	4.74±0.13	4.60±0.13
FC-1A	6.614±0.015	12.20±0.03	-127.6±0.3	-123.9±0.3	0.07972±0.00038	10.40±0.07	10.33±0.06
FC-1B	10.68±0.03	8.338±0.019	-152.2±0.3	-147.4±0.3	0.08291±0.00040	11.16±0.07	11.13±0.07
FC-1C	10.49±0.03	19.91±0.04	-125.6±0.3	-119.4±0.3	0.1328±0.0006	17.85±0.12	17.78±0.12
FC-1D	11.24±0.03	6.813±0.015	-174.9±0.4	-174.9±0.4	0.0007413±0.0000224	0.098±0.003	0.076±0.004
IC1	1.742±0.004	14.62±0.03	411.0±0.9	410.6±0.9	0.002253±0.000084	0.174±0.013	0.009±0.017
IC5	4.398±0.010	22.52±0.05	137.1±0.3	137.0±0.3	0.002398±0.000065	0.230±0.006	0.096±0.017
FC9	4.167±0.009	4.250±0.009	-136.2±0.3	-136.2±0.3	0.001491±0.000051	0.188±0.006	0.153±0.008
IC10	1.333±0.003	35.37±0.08	173.8±0.4	173.5±0.4	0.006551±0.000093	0.609±0.009	0.018±0.037
IC12	0.7096±0.0016	53.40±1.19	549.3±1.2	529.1±1.2	0.1761±0.0009	13.22±0.08	0.4±0.9

Table 3. Data used in isochron uranium-series dating of stalagmites.

Sample	Isochron ages (ka,2σ)	Detritus (^{230}Th/^{232}Th) A	Sample Point Used
IC-22	240 ± 56	1.073	2
PC-1	5,700 ± 1,800	0.02	2
PC-2a	990 ± 260	0.76	2
PC-2b	3,050 ± 355	0.68	2
PC-3	620 ± 110	1.835	2
PC-6	196 ± 163	0.49	2
PC-7	4,300 ± 210	0.67	2

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