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PROPOSED AGE AND ORIGIN OF GYPSUM NEEDLES OF CRYSTAL CRAWL, FORT STANTON CAVE, NEW MEXICO

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ABSTRACT—Crystal Crawl in Fort Stanton Cave near Capitan, New Mexico, was once covered with a forest of gypsum needles that has been almost entirely destroyed by over 100 years of frequent visitation and mineral collection. One of those needles was sketched and added to the Great Divide expedition report in 1891. We studied needles from three collections and noted regular-looking growth banding in many of them. The average band width of 10 measured needles (0.16 to 0.38 mm/band) is similar to growth rates of gypsum needles previously published (0.07 to 0.21 mm/year), supporting our interpretation that the banding was produced from annual growth of the gypsum needle. With that interpretation, we estimate that the individual needles of Crystal Crawl took 100 to 500 years to grow. We also measured the age of one needle based on two uranium-series analyses of needle 2 (3.3 ±2.7 and 4.3 ±3.9 ka) that show that it grew during the Middle or Late Holocene. Our interpretation is that the entire crystal forest grew during this time. It is likely that the needle forest grew during a time when the cave environment shifted to slightly more evaporative conditions, which could have been during onset of drier Early and Middle Holocene climate, or initiated due to collapse which created the large entrance of Fort Stanton Cave. Alternatively, the needles could have grown following mobilization of gypsum by the last flooding of the cave that reached the Crystal Crawl floor level. This suggested Holocene age and origin for the gypsum forest is also evidence that could support a similar hypothesis for deposition of the Snowy River calcite, also in Fort Stanton Cave.

INTRODUCTION

Fort Stanton Cave, located east of the north end of New Mexico's Sacramento Mountains (Fig. 1), was the second cave west of the Great Plains in the United States to be surveyed (Davis, 2004). New Mexico was a territory at that time. Twenty years before non-native Americans found Carlsbad Cavern, the Wheeler Survey explored and mapped Fort Stanton Cave. Before that, in 1855, soldiers from newly designated Fort Stanton signed their names in the cave (Davis, 2004). In 1872, Quartermaster Conrad and Lieutenant Boyd, both stationed at nearby Fort Stanton, had a boat built at the fort and used it to explore some of Fort Stanton Cave, which was partially flooded at that time (Daw, 1984). It was 1877 when the Wheeler Survey entered and surveyed Fort Stanton Cave (Davis, 2004), and they were somewhat disappointed that many grander features reported to be in the cave were not found (Morrison, 1878). Fort Stanton Cave was surveyed and explored as part of the great expeditions of the "West" led by Clarence King, John Wesley Powell, Ferdinand V. Hayden, and George Montague Wheeler, which were terminated soon after this first survey of Fort Stanton Cave, and reorganized as the U.S. Geological Survey in 1879 (Rabbitt, 1989).

Fort Stanton Cave has formed in the thin- to medium-bedded limestone/dolostone of the Permian San Andres Formation, which is gypsum-bearing locally (Kelley, 1972). In contrast to Carlsbad Cavern and other caves farther south in New Mexico, which are complex mazes developed by oxidation and hydrolysis of rising hydrogen sulfide, Fort Stanton is a more conventional cave with long horizontal passages developed by epigenic capture of aggressive surface waters (Davis and Land, 2006). Today, Fort Stanton Cave is known for its beautiful but rare velvety-textured speleothems, the Snowy River calcite channel, and globally important paleoclimate studies. The discovery of Snowy River in 2001 (see Peerman and Bilbo, 2013) has elevated the cave's importance.

A section of the cave referred to as the "Crystal Chamber" by the Wheeler expedition (Green, 1891) must have been extraordinary. The Crystal Chamber, now called Crystal Crawl (Fig. 1), is almost entirely denuded after more than 100 years of visitation and mineral collection. Left preserved, it would undoubtedly have been one of the great speleological wonders of the world, as Snowy River is today. Crystal Crawl is 5–10 meters wide and a few hundred meters long, and was floored or at least mostly floored with a "forest" of gypsum needles that grew from clayey cave sediment. Green (1891) referred to this crystal forest as follows: "The floor is a sparkling lawn of what appears to be

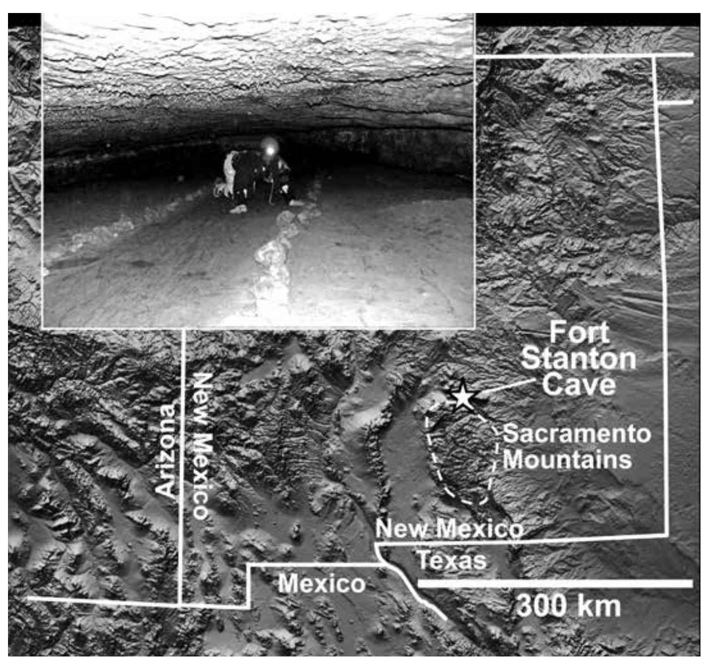

FIGURE 1. General location of Fort Stanton Cave and photograph showing Crystal Crawl as it looks today.

blades of crystal grass." Today only a few places in the passage, out of human reach, exhibit these needle forests (Fig. 2). One of these needles was sketched, and its crystal habit noted, by the Great Divide Expedition (Green, 1891), and a brief note about the crystallography of these needles was published in the Proceedings of the Colorado Scientific Society (Hills, 1891). Very few such needles have been found in other parts of Fort Stanton Cave, though a sparser growth of longer ones up to ~50 cm long was recently discovered in Needleton, a remote passage interpreted to be older than the Snowy River gallery.

Here we have studied a few of these crystals in order to help understand, preserve, and enhance the importance of Crystal Crawl and Fort Stanton Cave. We attempt to answer the following questions: when and how did they grow, how long did it take them to grow, and could they grow back?

RESULTS

Unlike dripstone speleothems such as stalagmites and stalactites, growth of gypsum needles originates from the base of the needle, not the tip (White, 2005). Therefore, the tip is the oldest part of the needle. They protrude from the clayey floor sediment, and Green (1891) reported that they originate from about 12 mm depth. Relative humidity (RH) data for the east end of the Devils Backbone for a year during 2007–2008 and for the entrance of Crystal Crawl during 2000 shows that the RH in the cave dips only slightly below 100% during the winter months (90–98%). Enrichment and crystallization of sulfate in the cave sediment due to slightly drier conditions is likely responsible for initiation and growth of gypsum needles.

We examined numerous needles from a private collection stewarded by the Fort Stanton Cave Science Project, the University of New Mexico Geology Museum collection, and the Denver Museum of Nature and Science collection. From old photographs, some tiny protected areas in the cave, and the museum samples, we observed that the needles grew mostly perpendicular to the cave floor sediment surface as individuals and as sprays or 'nests' where numerous needles seem to originate from a central spot similar to the gypsum nests described by Maltsev (1997; see Fig. 2). They undoubtedly covered most of the floor sediment in Crystal Crawl. In general, they are blade-shaped with blunt tips, flattened, wider at their bases and described as resembling "horseshoe nails" by Green (1891). The longer needles are <110 mm in length, although Green (1891) estimated their lengths between 25 to 150 mm. From 1854 to 1891, Green (1891) noted that only a narrow path made by the previous expeditions disrupted the needle lawn. By 1964 so many needles had been removed from Crystal Crawl that more of them were found at the cave entrance, most of them broken, than in Crystal Crawl (Hallinger, 1964).

FIGURE 2. The top photograph shows one of only a few small remnant patches of the needle forest that exists today. The bottom photograph is a sample of the gypsum needles protruding from the clay-rich sediment floor, which is exhibited in the Museum of Geology at the University of New Mexico.

Banding

One of the fascinating features exhibited by these gypsum needles is the presence of banding. The banding is uniform, but not well-exhibited in all needles (Fig. 3). Green (1891) noted that the gypsum needles were clear and transparent in the entrance area of "Crystal Chamber" (Crystal Crawl), and became more reddish brown farther into the chamber. It is the brown crystals that nicely exhibit the banding. There are two studies that report growth rate of gypsum needles in caves. Peck (1977) measured six gypsum needles that presumably grew over a period of 90 years (in an artificial trench dug in Webers Cave, Iowa, 90 years earlier). Peck's lengths varied from 9 to 19 mm, yielding a growth rate of 0.100 to 0.211 mm/year. Landis (1961) reported an average crystal growth of 0.07 mm/year (a trench dug by saltpeter miners in Cove Knob Cave, West Virginia 100 ±5 years before his measurements). Landis measured an average needle length of 7 mm. The average band thicknesses for each of our 10 needles measured for this study varied from 0.16 to 0.38 mm. Total number of bands measured was 2269. Assuming that the banding is annual, our measured growth rate of 0.16 to 0.38 mm/year is slightly higher than those measured by Landis (1961) and Peck (1977) (0.07 to 0.211 mm/year), but matches reasonably well.

The banding "time-series" (where each band represents a unit of time) for 10 crystals was measured using a HiRox digital microscope and Gatan's Digital Micrograph, a program designed to make measurements in microscopy. Needle 4 is a split crystal, where two needles branched from the same base. Figure 4 shows the growth history of these two needles and, with the exception

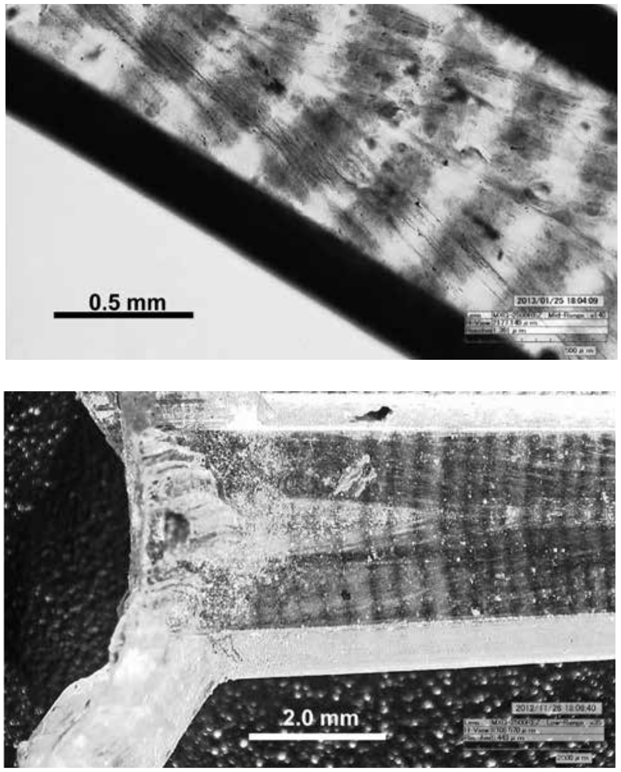

FIGURE 3. The top image is a micrograph of a segment of gypsum needle showing the banding at higher magnification. The material forming the bands seems to be clay. The bottom image shows the banding near the base of a gypsum needle. Some of the needles flare out at the base.

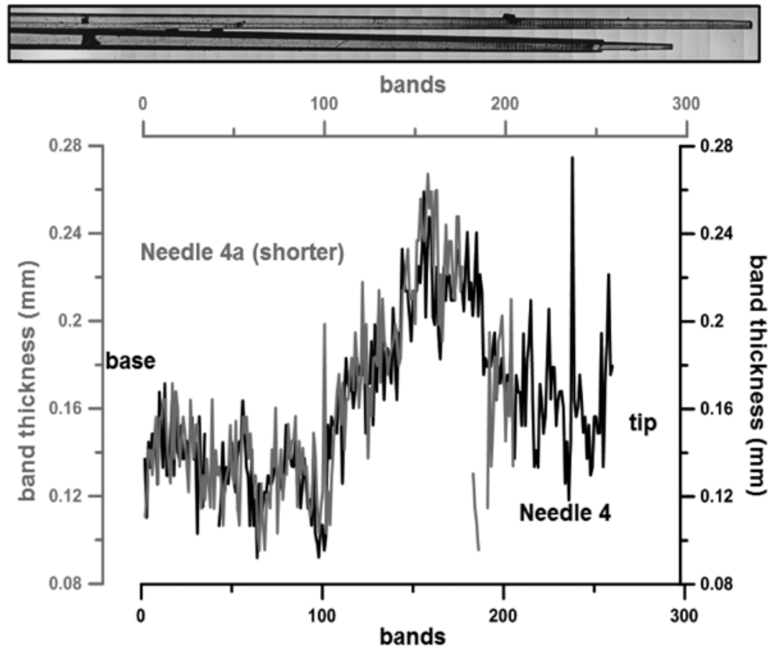

FIGURE 4. This graph shows the correspondence of banding records between two needles that are joined at the base (split crystal). Measurements made with a HiRox digital microscope and Gatan's Digital Micrograph imaging software.

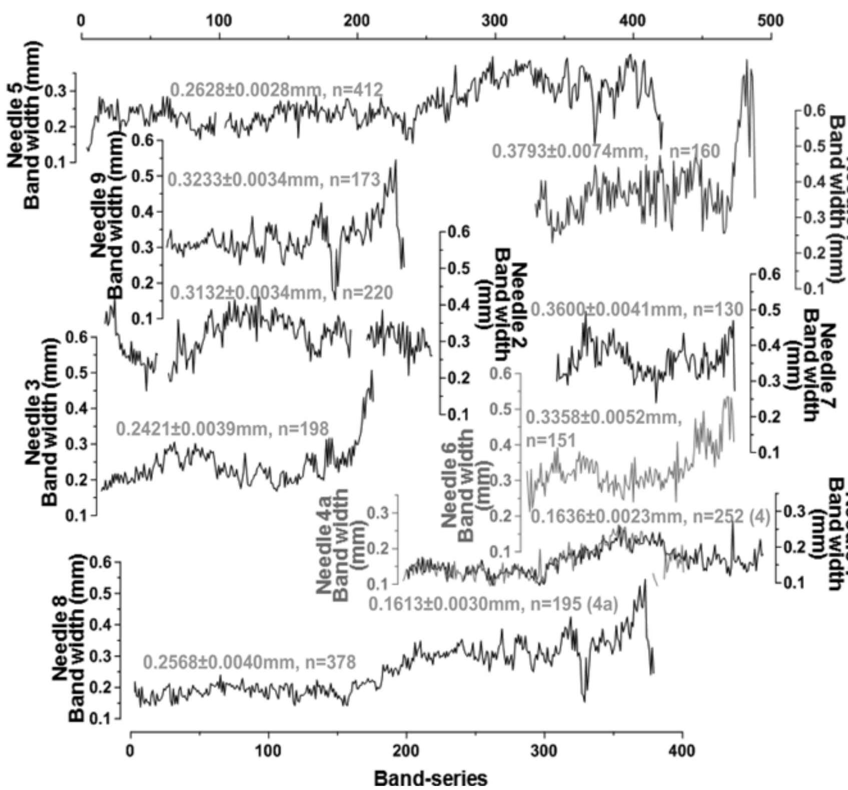

FIGURE 5. Band-series of ten needles are staggered but all are scaled the same, and show that growth (band thickness) is not as uniform over time as it appears at lower magnification. The mean band thickness and standard error of the mean in millimeters, and the number of bands measured for each needle are included in the figure. The top and bottom x-axes all have the same scale, and all y-axes are scaled equally as well. Some band-series show larger grow variations than others, but all of the variabilities are visibly consistent with decadal-like variability seen in speleothems and tree rings.

that the longer needle started growing about 55 bands before the shorter needle, the match is remarkable. Even though the banding looks very uniform, all of the time-series show variable growth rates (Fig. 5).

Uranium-series analyses

Two pieces of needle 2 were used for uranium-series analyses. The pieces weighed 81.31 and 92.28 mg. These were powdered and dissolved in ~10 ml of 1N HNO_3 for 48 hours. The samples were spiked with a mixed Th-U spike (^{229}Th-^{233}U-^{236}U). The U and Th were co-precipitated with Fe solution and further separated using anion resin columns, similar to typical methods used for uranium-series work on stalagmites from Fort Stanton Cave (Asmerom et al., 2010). The ages determined from these two pieces are very sensitive to the ^{232}Th correction, because of the low U concentrations (19.0 and 20.0 ppb) and high Th concentrations (5.3 and 7.9 ppb), respectively. Ages calculated using ^{230}Th/^{232}Th (atomic ratio) correction of 6.6 ±50% ppm, based on those resolved for the Snowy River calcite samples, yielded ages of 3.3 ±2.7 and 4.3 ±3.9 ka. While these errors are large, the ages show that needle 2 grew during the latter part of the Holocene. There is not enough resolution in the age data to determine if the bands are due to yearly deposition.

Miscellaneous features

The crystals exhibit growth pits where crystal growth was inhibited by particles on the crystal surface. Figure 6 shows such crystal defects and a bat hair that presumably inhibited growth. In addition to the growth pits, crystallite terminations were observed on the crystal faces. Also, microbial-looking features, presumed to have grown/formed on the crystals sometime during their growth history, are present on the needle surfaces (Fig. 7). In addition to the banding, layers of clay-rich inclusions formed chevrons (Fig. 7). Scanning electron microscopy shows the gypsum to have a layered texture (Fig. 8A, B), which seemed to have been indicated on the sketch made for the Great Divide Expedition report (Green, 1891) that is redrawn and added to Figure 8 (Fig. 8E). Miller indices suggested for the needle faces are from Onac et al. (1995) and Onac (1997). Figures 8C and 8D show structure probably parallel with cleavage directions that was revealed by the electron beam.

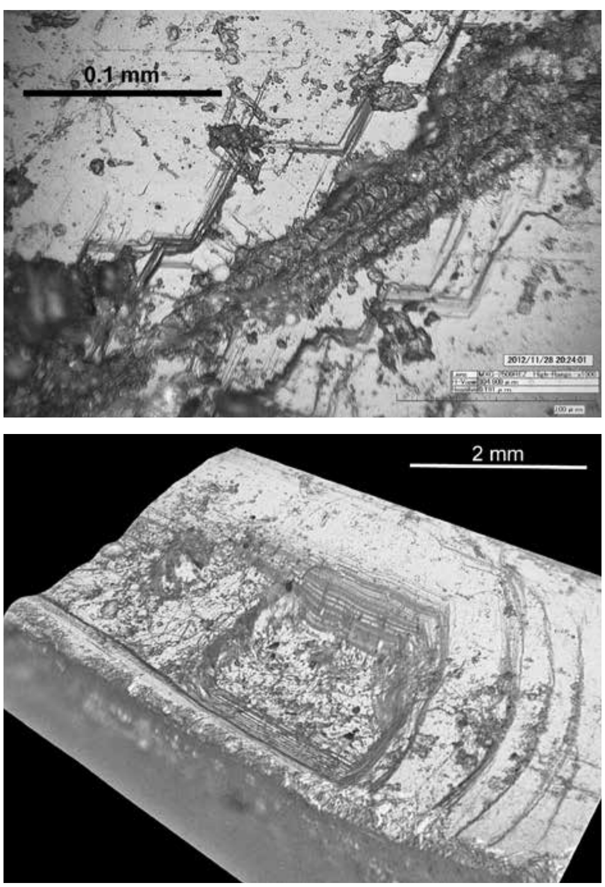

FIGURE 6. Top image shows what appears to be a weathered bat hair that has apparently disrupted growth of the gypsum, forming a shallow growth pit. The bottom image shows a larger, deeper growth pit.

DISCUSSION

The banding in these crystals is exceptionally uniform; too much so to be due to climatic periodicities other than annual. Two non-annual climatic periodicities that affect the southwestern United States that could produce banding are the El Nino Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Rasmussen et al., 2006). ENSO has a periodicity of 3–8 years, while PDO has a periodicity of ~25 years. ENSO- and PDO-driven banding would suggest that the needles grew over a period of 450–3200 years, and 3750–10,000 years, respectively. A PDO periodicity is therefore unlikely. Although ENSO periodicity is a possibility and may explain layer frequency in Snowy River calcite (Spilde and Boston, 2013), and the U-series ages could support this interpretation, we suspect that the banding represents annual deposition of gypsum instead. Similar banding in stalagmites has been shown to be annual (Polyak and Asmerom, 2001). We

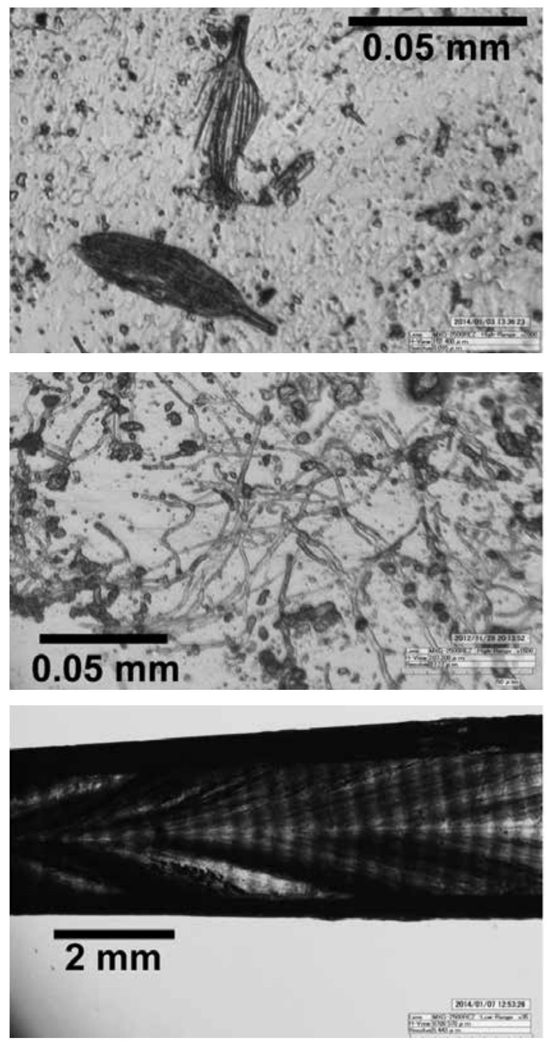

FIGURE 7. Top image shows small features attached to the needle surface that resemble moth scales. The middle image shows microbial-like features attached to or etched in the needle surface and the bottom image exhibits the chevron-like layers presumably composed of clay that infiltrated cracks in the needle.

interpret that the banding is too uniform to represent ENSO or PDO climatic oscillations. Also, and more importantly, the average band widths of 0.16 to 0.38 are consistent with growth rates determined by Landis (1961) and Peck (1977) of 0.07 to 0.21 mm/year. Our interpretation is that the banding represents annual growth bands, and based on band measurements of 10 needles, these needles had total ages of needle growth of 150 to 450 years. The U-series age of needle 2 suggests that the needles grew during the Holocene sometime between 500 and 7000 years ago.

Three possible interpretations for initiation of needle growth are: (1) the climate was drier during the middle Holocene; (2) the large entrance of Fort Stanton did not form earlier than a few thousand years ago, after which ventilation increased; and/or (3) water flooding the passages to a level close to the floor of Crystal Crawl soaked the cave fill with gypsum-bearing solutions, which then evaporated over a long period, causing the gypsum to grow as needles. All of these interpretations could involve conditions in the cave of sufficient dryness to initiate formation of these needles in Crystal Crawl. However, the origin of a large entrance would probably cause increased airflow throughout the cave, which could greatly affect the cave climate in Crystal Crawl. Fort Stanton Cave has only one known entrance for its more than 30 kilometers of passageways. Members of the Fort Stanton Cave Study Project have discussed the timing of the origin of the entrance, and a consensus is that the entrance is a recent feature to the cave, mainly based on scarcity of evidence of ancestral Americans at the entrance or in the cave, and the steep, youthful-looking slopes of the entrance sink. The Snowy River calcite channel lining in Fort Stanton Cave, perhaps the longest speleothem in the world, has formed over the last 1000 years (Land et al., 2011), and opening of a large entrance has been informally proposed as one of the possible causes of precipitation of the Snowy River calcite.

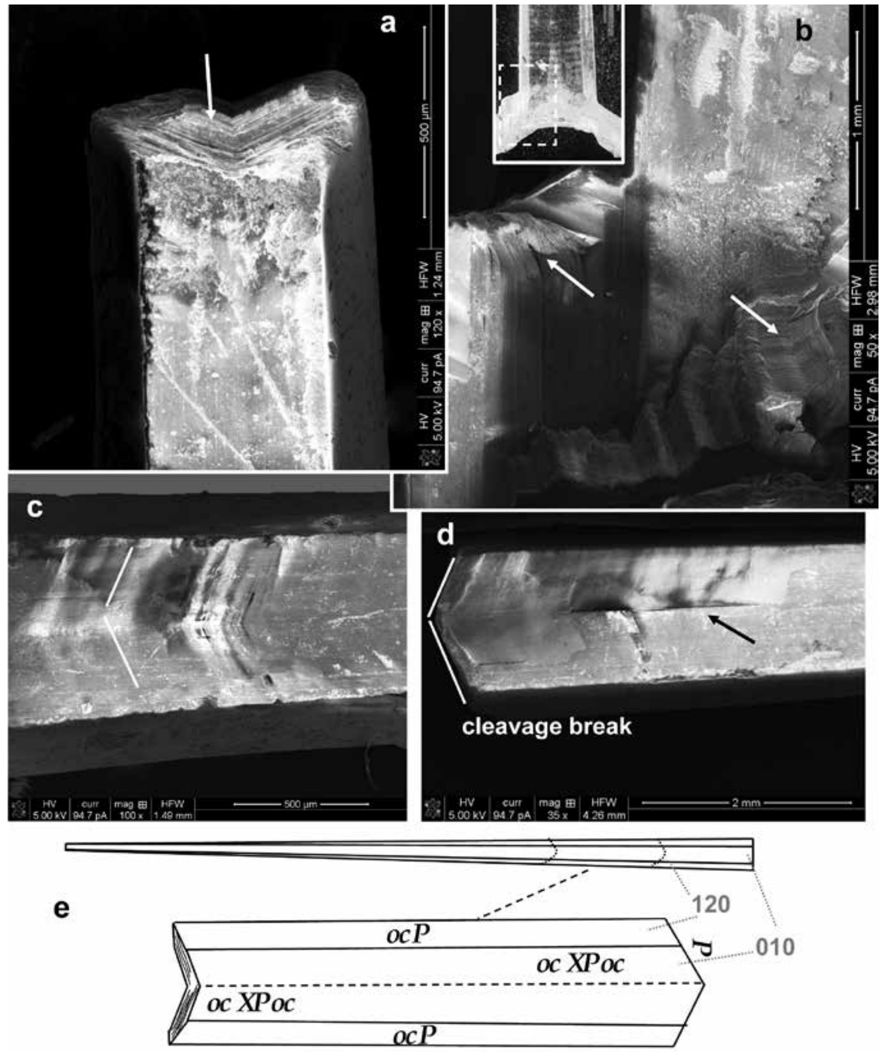

FIGURE 8. SEM images and primary crystallographic sketch of gypsum needles. A. Layered-like internal structure of gypsum at the tip of needle 1 (arrow). This is also nicely displayed in (B) at the very base of needle 1 associated with the tangs (arrows). C. Electron beam damage parallel with cleavage directions. D. A mirror plane projecting at the surface, probably as a result of beam damage (arrow). E. A sketch (redrawn) of the needle reported in Green (1891) with Miller indices of two crystal faces 010 and 120 added based on sketches from Onac (1997).

The Crystal Crawl - Snowy River connection hypothesis?

While each crystal is 150 to 450 years old, the crystal forest may have taken longer to form. It is possible that a collapse occurred about 1000 to 2000 years ago to form the large entrance to Fort Stanton Cave. The collapse drastically changed the cave climate, allowing slightly drier air to circulate through Crystal Crawl and Snowy River, particularly in the winter months. Sulfate was wicked from the cave sediment in Crystal Crawl due to the slightly drier conditions, resulting in the growth of the gypsum needles. This probably lasted more than 450 years, but the needle growth probably terminated naturally due to limited sulfate supply. At the same time, the intermittent stream in Snowy River became more sensitive to degassing of CO_2 and evaporative conditions, and calcite began precipitating from the stream waters. Admittedly, this hypothesis is based on preliminary results, and is presented to further stimulate research.

The Crystal Crawl flood hypothesis

Cave mineralogist Carol Hill (personal commun. 2014) has suggested another mechanism. Crystal Crawl branches off the Main Corridor (a large gallery ~12 m high at the junction), which has repeatedly flooded 1–2 m deep in historic time (at an elevation 10 m below Crystal Crawl). Mud deposits indicate that the passage has flooded to the ceiling in the past. Hill hypothesizes that the last deep flood in the Main Corridor reached the level of the fill surface in Crystal Crawl, dissolving gypsum from sulfate in the San Andres bedrock, which soaked into the Crystal Crawl fill and took several hundred years to dry via capillary seepage toward the evaporative airflow, during which time the dissolved gypsum was re-precipitated as selenite needles. This explanation would account for the relatively uniform maximum length of the crystals, without requiring a growth period longer than the ages of individual needles. However, this explanation also requires flooding to have occurred in the Holocene.

CONCLUSION

Assuming that the U-series ages of needle 2 are representative of the timing of the gypsum crystal forest in Crystal Crawl, then a broader perspective may evolve from this study. Together with the U-series evidence for the Snowy River calcite, the age data indicate that something happened in the cave to initiate both the precipitation of Snowy River calcite over the last 1000 years, and growth of the crystal forest in Crystal Crawl probably during some brief period that occurred between ~500 to ~7000 years ago. An explanation common to both precipitating systems could be the formation of a large entrance, the current entrance to Fort Stanton Cave. A flood-soaking hypothesis to explain the timing of the needle-forest growth would need to occur in the Holocene, which seems unlikely, but given this hypothesis the inception of the Snowy River calcite may be unrelated.

Our study suggests that, if left undisturbed, and the first mechanism (drier Holocene climate) applies, these needles could grow back over the next 500 years. If the second mechanism (increased evaporation due to entrance opening) applies, needles could grow back if there is enough sulfate remaining in the sediment, and if conditions in the future are favorable for growth of gypsum needles. If the third mechanism (flooding mobilization of gypsum) applies, the needles will not grow back unless a flood of the necessary magnitude restores the gypsum-rich solutions to the Crystal Crawl fill.

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