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RECENTLY DISCOVERED PASSAGES IN FORT STANTON CAVE, NEW MEXICO, AND IMPLICATIONS FOR SPELEOGENESIS AND REGIONAL GEOMORPHIC PROCESSES IN THE NORTHERN SACRAMENTO MOUNTAINS

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Abstract.—Fort Stanton Cave in Lincoln County, the third-longest surveyed cave in New Mexico at 18 km, was one of the earliest caves in the state to be noted in written records, but its development has received little study. Other large New Mexico limestone solution caves, such as Carlsbad Cavern, are of hypogenic origin. Fort Stanton Cave is hydrologically almost inactive today, but its passage structure and patterns, and ubiquitous allogenic sediment deposits, indicate that it was dissolved by epigenic meteoric water originating primarily in locations yet undetermined to the south and west. Discovery of the Snowy River complex, a major NNE-trending passage series located to the east of the original cave, provides new opportunities for further extension of the cave, and for age-dating, paleoclimatic study, and paleohydrologic analysis. These may shed light on the evolution of the landscape east of the northern Sacramento Mountains, and on the past behavior of groundwater and surface water in this region.

INTRODUCTION

Fort Stanton Cave (FSC), 18 km (11 mi) long, is formed in the Permian (lower Guadalupian) San Andres Limestone near the northern end of the Sacramento Mountains. Its existence has been on record since 1855, when the nearby U.S. Army Fort, whose name the cave bears, was established. Fort Stanton Cave is now administered by the U.S. Department of the Interior, Bureau of Land Management, which has gated the cave, and controls access via a permit system.

Geologic Setting

Fort Stanton Cave is located east of the igneous core of the Sacramento Mountains crest, on the south side of the Rio Bonito valley, which separates the Sacramentos from the Capitan Mountains batholith to the north (Fig.1). The cave is formed mostly in the lowermost Rio Bonito member of the San Andres Formation (Kelley, 1971), which, in this area, consists of thick-bedded limestone, dolomitic limestone containing some residual hydrocarbons, and rare tongues of Glorieta Sandstone near its base. Limestone bedrock within and near the cave has been extensively modified by localized brecciation resulting from intraformational solution collapse.

The Sacramento Mountains uplift is a large, east-tilted fault block with a prominent western escarpment (Fig. 2). Three episodes of deformation shaped the region: the late Paleozoic Ancestral Rockies orogeny; the Laramide orogeny (late Cretaceous-early Tertiary); and mid-to-late Tertiary extensional faulting associated with the Rio Grande Rift. There is abundant evidence for reactivation of older basement structures by Laramide and late Tertiary tectonism (Cather, 1991). The east flank of the Sacramentos grades into the Pecos Slope, a gentle homocline with regional eastward dip of less than 1° toward the Pecos Valley. The structural slope is modified by numerous fold belts, both crustal (Dunken-Tinnie Anticlinorium and Pecos Buckles) and superficial (Lincoln folds) (Pray, 1961; Kelley & Thompson, 1964; Kelley, 1971).

The dominant tectonic element of the Fort Stanton area is the Mescalero Arch, a broad structural divide separating the Pecos Slope to the east from structurally low areas of the Tularosa and

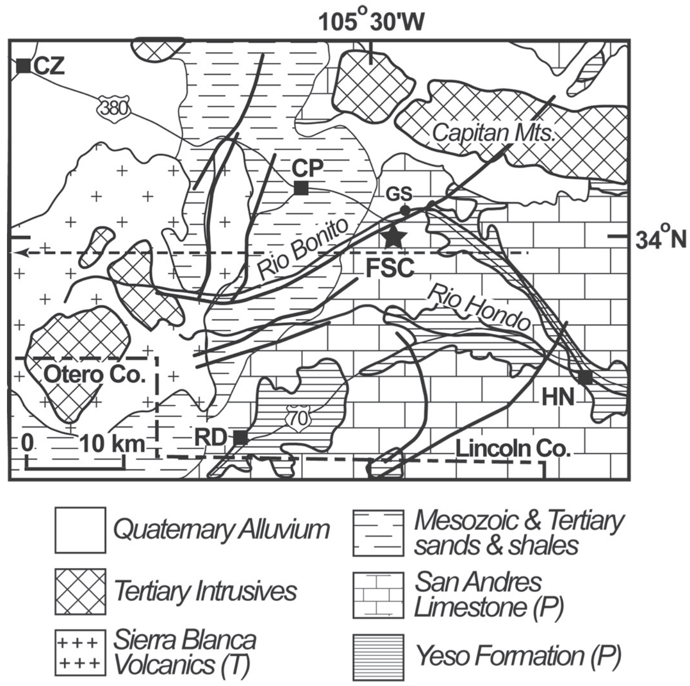

FIGURE 1. Generalized surface geology of northern Sacramento Mountains in the vicinity of Fort Stanton Cave. Heavy solid lines are major faults, although many lesser faults not shown on this map are also present. Dashed line shows location of cross-section in figure 2, which extends beyond the western boundary of the map. Cp = town of Capitan; Cz = Carrizozo; FSC = Fort Stanton Cave; GS = Government Spring; Hn = Hondo; Rd = Ruidoso

Sierra Blanca Basins to the west (Fig. 2). The Mescalero Arch coincides with the crest of the Sacramento Uplift and plunges gently NNE, passing ~10 km east of Ruidoso and intersecting the mid-point of the Capitan batholith. The position of the Arch also roughly corresponds to the axis of the late Paleozoic Pedernal Uplift (Kelley & Thompson, 1964; Kelley, 1971; Cather, 1991). The west limb of the Arch is much steeper and more irregular than the east limb, descending across several NE-trending faults into the Sierra Blanca Basin, an asymmetric structural depression of late Laramide age which subsequently became a locus for late Eocene-Miocene plutonism and volcanism (Cather, 1991). Fort Stanton Cave is located on the steeply-dipping west limb of the Mescalero Arch, ~3 km west of the crest. The main cave passages are aligned generally north-northeast, sub-parallel to regional northeast-trending faults.

Fort Stanton Cave

Carlsbad Cavern, Lechuguilla Cave, and other caves in the Guadalupe Mountains to the south, are hypogenic caves developed by sulfuric acid generated by oxidation of hydrogen sulfide rising from depth (Palmer and Palmer, 2000). Such caves tend to have short but large chambers and passages, locally extensive mazelike complexity, often large vertical relief, and may contain extensive deposits of isotopically-light gypsum and sulfur. FSC (Fig. 3), in contrast, appears to be a "conventional" epigenic cave, developed by descending meteoric water. This is indicated by its long, sinuous, relatively narrow horizontal passages of relatively uniform diameter and limited interconnection, by extensive deposits of allogenic clastic sediment, and by evidence of energetic shallow-phreatic and vadose conduit flow. FSC resembles a smaller, simplified version of Mammoth Cave in western Kentucky.

Unfortunately, FSC is more cryptic in its relationship to regional geomorphology and hydrology than Mammoth Cave, whose catchment areas and spring outlets are relatively well defined. FSC is only minimally active today, and it has thus far not been possible to follow any of its passages up-flow to a demonstrable speleogenetic-water input source. The San Andres Limestone is a relatively weak rock, and where large galleries are developed, collapses have in many places obstructed the passages. Strong airflow through the breakdown blockages of the southern Lincoln Caverns and Bat Cave termini suggests extensive unexplored passage beyond. Even near the known passages, our knowledge of the full pattern is incomplete because many conduits are sediment-filled or completely hidden by breakdown or sediment banks. Active-resistivity testing in the area over and around the known cave has revealed many anomalies that probably represent passages yet unexplored (McLean and Luke, 2006). Study of FSC is also handicapped by the lack of other comparable long epigenic limestone caves in New Mexico. All other known long caves in the San Andres Formation are gypsum caves, mostly in the extensive evaporite karst in east-central New Mexico from Santa Rosa south to a few km north of Roswell. The Fort Stanton region may have other long limestone caves, but if so, decades of search have not yet revealed them. We know of FSC itself only because of its single sinkhole entrance above the mouth of Cave Canyon, which seems to be a fortuitous collapse of an unusually wide near-surface chamber at the intersection of several passages. This entrance may be no more than a few hundred years old.

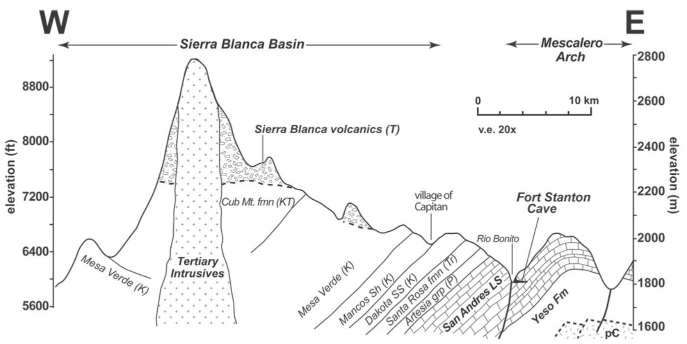

FIGURE 2. Diagrammatic cross-section of a portion of the northern Sacramento Mountains, showing generalized structural and stratigraphic relationships in the vicinity of Fort Stanton Cave. Vertical exaggeration 20x. Formation thicknesses are approximate.

PREVIOUS WORK

Mapping of the cave began with the Wheeler Survey in 1877 (Morrison, 1878), but systematic exploration and extension began only in the late 1950s with the arrival of cavers affiliated with the National Speleological Society (NSS). Discoveries (made mostly by digging out breakdown and sediment chokes) continued episodically into the 1970s, by which time ~13 km (8 mi) of passage had been surveyed by a project led since 1965 by NSS caver John Corcoran of Albuquerque.

Despite this long-term exploration and survey work, surprisingly little formal geologic and hydrologic study of the cave is on record. Hallinger (1964) seems to be the only paper in professional literature that attempts to sketch the development of FSC. Hallinger, however, made no attempt to ascertain the source of the original cave-forming water, though noting that recent intermittent floodwater in FSC flowed northeast toward Government Spring in the Bonito valley.

The files of Corcoran's Fort Stanton Cave Project and BLM hold a few unpublished reports relevant to the cave's development. A paper by Roger Baer (unpubl. University of New Mexico class report, 1972) describes sediment sequences in the Main Corridor within several hundred m of the entrance. He recorded thick clay and silt deposits, overlain by poorly-sorted gravelly material that is probably relatively late floodwater influx from near the present entrance area.

Fred Luiszer and Ed Larson, of the University of Colorado (unpubl. report to BLM, 1992) describe paleomagnetic sampling of a 23-foot interval of clay and silty sand in the Main Corridor at the Crystal Crawl junction with the cave's southern branch. All samples were of normal polarity and were interpreted as indicating that the sediment was less than ~750 ka old.

Researchers at the University of New Mexico's Radiogenic Isotope Lab have made a preliminary U-series analysis of a stalactite midsection from the Main Corridor. This yielded an age greater than 400 ka (V. Polyak and Y. Asmerom, personal commun., 2005)—consistent with the paleomagnetic data, but perhaps surprisingly old for a passage so near base level.

THE SNOWY RIVER DISCOVERY

In the northern part of the cave, strong airflow from a breakdown mass east of the junction of Skyscraper Domes with Snowflake Passage led cavers in 1970 to begin a dig called Priority 7 (Fig. 3). This was soon abandoned because digging through the collapsed rubble mass, which might extend upward as far as the surface, was difficult and dangerous. Nevertheless, work at this dig was reactivated by the Fort Stanton Cave Project in 2001, leading to a breakthrough to an intersection with a large, unexplored gallery trending NE and SSW. BLM administrative requirements suspended further exploration until 2003.

This newly-discovered corridor was named Snowy River because its most notable feature is a unique channel, lined with white calcite, that meanders along the passage floor in both directions (Plate 14). This deposit is strong and firm enough to support walking, and plans were developed to explore along it with minimal damage to the surface, by changing to clean clothes and footgear before walking on the calcite. In 2003, FSC Project survey teams mapped the southerly branch, named Snowy River South, for nearly 2 km in the SSW direction, following the strike of the San Andres underneath the surface ridges roughly parallel to the main trend of the original FSC but several hundred m to the east of it. One mud-floored tributary, the Mud Turtle passage, wound westward to an end in breakdown ~10 m beneath the east wall of Don Sawyer Hall in the original cave, with air passing through the untraversable connection.

The northerly branch, Snowy River North, was also surveyed more than 1 km NE in 2003, converging toward the Rio Bonito valley in the direction of Government Spring. In addition, a major branch forked from Snowy River North. This went up a steep slope more than 30 m and intersected a large abandoned phreatic conduit, named the Metro (Plate 14). Its main branch, the South Metro, went SSW, sub-parallel to Snowy River South nearby, for half the length of Snowy River South until blocked by a massive collapse choke. A smaller northward continuation from the upper junction crossed over Snowy River North, toward the Bonito valley, before pinching into a squeeze too tight to explore without digging. In all, ~5 km (3 mi) were added to the original FSC length, bringing it to more than 18 km (11 mi).

The Snowy River passage is more level and unobstructed than any preceding passage found in FSC, probably because it is at a lower stratigraphic level where the strata are unbrecciated and stronger, so that little breakdown interrupts the passage gradient. When exploration ended in 2003, open passage was still going at both ends of the Snowy River conduit. In Snowy River South, the ceiling had lowered to less than 1 m high (it had averaged about 6 m through most of the conduit), but the passage was still about 6 m wide, with a wind estimated at several km/hr blowing from beyond. The white-calcite-lined floor channel continued indefinitely southward. Snowy River North, which became larger after the down-flow segment of the Metro conduit united with its upper part, was about 12 m high by 6 wide where its floor dropped ~1 m and a small stream appeared from an underlying bedding plane. The explorers named this Crystal Creek (not to be confused with Crystal Crawl in the original cave). In this area the Snowy River calcite crust thins and gives way to mud and bedrock. The survey team stopped at this point to await biological sampling of the untouched water, as called for in an agreement with BLM.

It was anticipated that exploration of Snowy River South would continue in 2004. However, questions were raised by BLM about safety of the Priority 7 breakdown entry route, and exploration was again suspended. One work trip to the Snowy River complex was again permitted in 2005, when radiolocation was done to confirm the close surveyed relation of the Mud Turtle tributary to Don Sawyer Hall. Plans have now been made to dig the connection open, to provide a shorter and safer route into Snowy River, after which exploration and survey are expected to resume.

DISCUSSION

Interpretation of the Snowy River Complex

It has seemed probable that the flow of water during development of FSC has generally been from SSW to NNE, because this is the direction from the hills toward the presumed Rio Bonito base level, and because the cave survey shows a slight downward slope toward the Bonito Valley (see profile, Fig. 4). This is also the direction that water has been observed to move when intermittent springs have entered the Main Corridor during historic wet periods. However, direct evidence for flow direction during the cave's earlier dissolution has been sparse. Much of the cave as known before 2001 has been altered by collapse, and even where solution-modified walls are intact, directional wall scalloping is scant and crude because the wall rock is not homogeneous. Furthermore, most visible surfaces of older sediment deposits in the original cave were either laid down by such low-energy flow that directional indicators such as ripple marks are lacking, or such detail has been wiped out by 150 years of human trampling.

Discovery of the Snowy River passage complex, which is much less altered by collapses and retains many sediment surface features intact, has provided clearer evidence of flow patterns. The survey, using hand-held Suunto instruments with backsights and foresights, indicates that the Snowy River conduit has about a 0.25% downslope gradient (0.4°) from the southern to northern ends of exploration. Point bars and ripple marks throughout much of Snowy River South have confirmed relatively high-energy flow, from a southerly source toward the Bonito Valley, when the last clastic sediment was deposited in the passage. However, evidence also exists for intermittent backflooding from the Bonito valley into these nearly horizontal passages. Near the valleyward end of the North Metro, tiny *Pupilla* land snail shells are stuck in ceiling pockets; these are not found farther south in the Metro, and were probably introduced by reverse flow of floodwater from

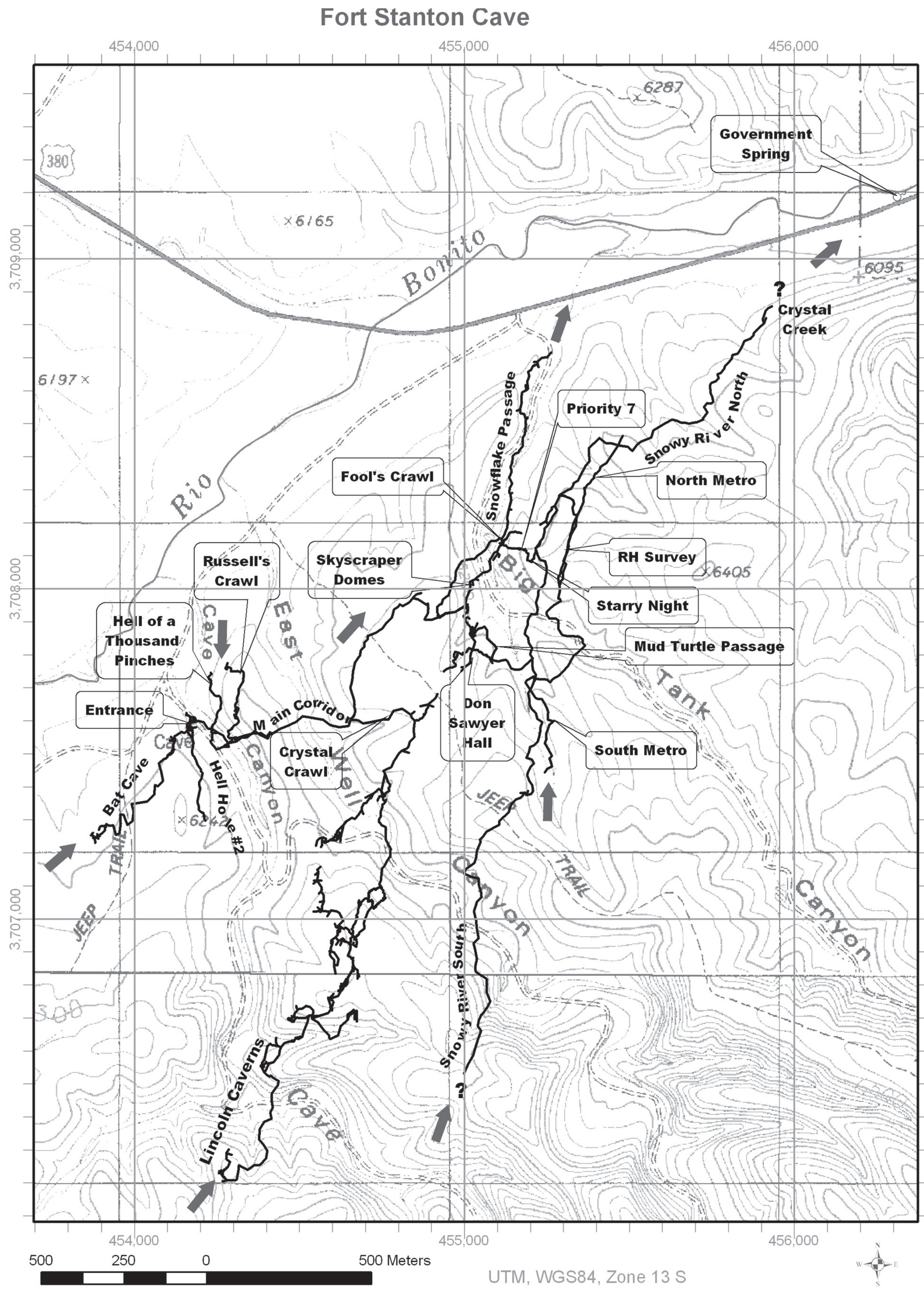

FIGURE 3. Plan view of Fort Stanton Cave, showing locations named in text, with topographic overlay. Arrows indicate apparent directions of water flow during speleogenesis; question marks indicate continuing unexplored passages. Courtesy of John Corcoran

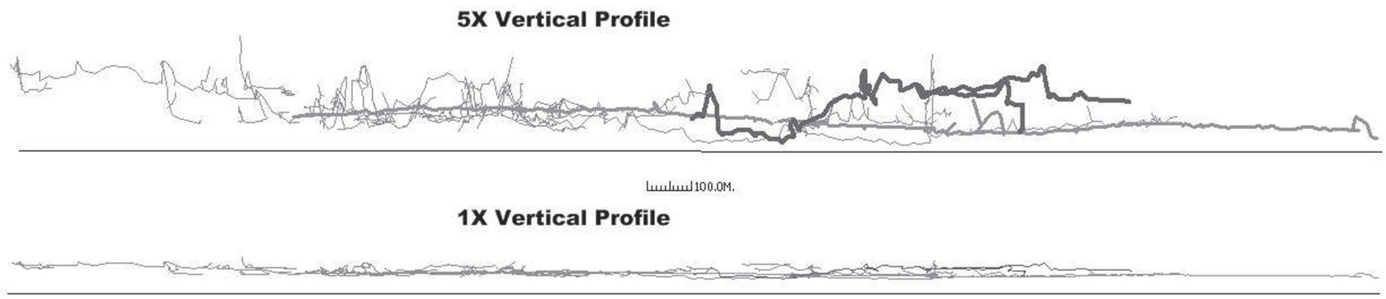

FIGURE 4. Line-plot profiles of Fort Stanton Cave, looking 60°→240°, showing passage slopes and elevations. Lower profile: true dimensions (no vertical exaggeration). Upper profile: 5x vertical exaggeration to clarify relations of Snowy River passage complex with original cave. Heavy black line, Metro; heavy gray line, Snowy River; all others, original Fort Stanton Cave. Courtesy of John Corcoran.

the valley before it had been cut down to the present level.

In Snowy River, the mud on the walls is extensively coated with black manganese minerals. On ledges, where thicker mud accumulated and subsequently cracked, it can be seen that at least four thin manganese layers are sandwiched into the deposit, indicating multiple brief episodes of manganese deposition. Much of this material dried and peeled off the walls before the Snowy River calcite deposit accumulated, and no later manganese has grown on these bared surfaces. The most probable explanation is intermittent manganese deposition from sluggish organic-rich backflood water from the Bonito valley. This manganese extends as far up Snowy River South as exploration has gone, but only ~30 m into the Mud Turtle tributary, which has a steeper gradient and may also have sent an opposing current flowing into Snowy River when the latter was backflooding. Similar manganese-rich coatings, probably also of backflooding origin, occur in the original FSC in Snowflake Passage, which, like Snowy River, approaches the Bonito valley.

The Snowy River complex shows the following sequence of events:

(1) When the Rio Bonito base level was more than 30 m above the present level, the Metro was dissolved as a phreatic tube, roughly following the strike, and undulating gently below the contemporary potentiometric surface through about 45 m of vertical relief. The undulations were controlled primarily by insoluble beds and lenses of yellowish claystone and siltstone in the ceiling, which inhibited upward dissolution (Plate 2). The segment approaching the valley formed a precursor of the valleyward section of Snowy River North.

(2) The water table descended below the highest segment of the Metro. A vadose stream slot (the RH survey; see map, Fig. 3) developed as a bypass below the uppermost Metro as that was abandoned; Metro North developed at this level as a short-lived spring outlet into the downcutting Bonito Valley.

(3) The water table descended. The Metro conduit developed increasing lateral hydraulic head in the downdip direction. As the water table stabilized near subsequent Snowy River passage elevation, water was pirated westward, downdip from the Metro beyond its present terminal breakdown and beyond the limit of exploration of Snowy River South. The Metro conduit down-flow from the piracy point was abandoned, and replaced by Snowy River, which soon became a free-surface vadose stream gallery near the new water table level. (Alternatively, surface erosion beheaded the Metro source, while a lower-elevation recharge point began feeding water to the Snowy River trend.) Snowy River North was then incised below the valleyward end of the ancestral Metro conduit.

(4) Large amounts of clay- to small-gravel-sized allogenic sediment washed through Snowy River, facilitating localized meander undercutting. Multiple cycles of aggradation and flushing may have occurred. Some water flowed from the Mud Turtle tributary.

(5) The free-surface stream eroded the sediment to the present floor level; finer sediments in the main channel were winnowed out to leave gravel bars and banks.

(6) One or more refloodings to ceiling level deposited brown mud on the walls and ceiling. Mud stalagmites, on ledges just below the ceiling, may have developed as such floods receded.

(7) Occasional backflooding from the Bonito Valley deposited thin manganese-mineral coatings, interfingering with mud of stage 6, while the passage was mostly filled with quiet manganese-rich water, but not filled quite to the ceiling in higher parts.

(8) Clastic-bearing inflow along Snowy River ceased, possibly because of surface or subterranean piracy. Drainage was followed by localized breakdown, and partial peeling of the mud and manganese coatings. Inflow from the Mud Turtle tributary ceased.

(9) Intermittent smaller-scale influx of very slow-moving, nearly clastic-free, calcite-rich water, encrusted the Snowy River pool channel.

The Snowy River Calcite Deposit

The unique white pool deposit which gives Snowy River its name is itself a puzzling feature. It lines the deepest part of the stream channel on top of the underlying clastic sediment, and appears to mark the former presence of an elongated body of water, often 2 m or more wide and ~3 cm to more than 1 m deep. The deposit has been followed for about 3 km (2 mi) along the Snowy River gallery, and continues up-flow for an unknown distance. Nothing resembling it is found anywhere else in FSC: Indeed, as far as we are aware, the calcified bed of Snowy River is the longest continuous speleothem deposit known in any cave in the world. This floor deposit seems still more remarkable because it is virtually the only calcite speleothem in the Snowy River corridor, others being confined to rare patches of flowstone and inch-long soda-straw stalactites. The reason for this rarity of other speleothems is not understood; the nearby Metro and Mud Turtle passages are locally well-decorated with dripstone and flowstone (as are some sections of the original FSC).

The sharp division between underlying clay- to gravel-sized clastics and the overlying calcite suggests an abrupt change in hydrologic regime when calcite deposition began. Pronounced solutional pitting on bedrock and breakdown near stream level indicates that the stream water was strongly aggressive up until this change. If the calcite-rich water source which would later line the Snowy River channel was already contributing earlier, it was too dilute to allow precipitation. When the main aggressive source was cut off, the remaining flow became too low-energy to carry a significant clastic load, and turned from solutional to calcite-saturated. The disappearance of high-energy stream flow appears to have been too sudden to be due to drying climate alone; it suggests surface or subterranean piracy beheading Snowy River's stream. The calcite-depositing residual flow must have had a different locus and type of recharge—perhaps diffuse autogenic flow from exposed surface limestone above the passage somewhere beyond the present limit of exploration.

Snowy River's calcite surface is not smooth, but is made up of small nodules, which on close examination are seen to be composed of tiny acicular crystals, making the surface more porous than it appears from a distance. The material appears snow-white to those walking along it, but close up, a hint of tan suggests that a very small percentage of clay may be included. The morphology of the deposit is unusual. Cave-pool deposits elsewhere are usually divided into steps by rimstone dams, or have shelfstone overgrowths, neither of which are seen along Snowy River. In contrast, the Snowy River deposit, which must be several cm or more thick in its center, simply thins upward along its flanks, until it reaches nearly zero thickness at a distinct horizontal upper margin. For about eight cm above that margin, the adjacent sediment is thinly veneered with translucent calcite, indicating that the depositing water has very briefly stood higher than the normal upper limit.

These peculiarities seem best explained by assuming the Snowy River deposit's recharge was intermittent, and probably climate-controlled. In wet periods, flow fills the channel to a spillover point which controls the deposit's upper limit. However, the basin does not remain full long enough to start growing shelfstone along the margin. When the input rate falls below that necessary to maintain spillover, seepage into the permeable sediment below, and evaporation by the constant airflow through the gallery, cause loss in excess of recharge, and the surface gradually declines while the stagnant water becomes increasingly supersaturated with calcite. Thus the lower part of the channel is subject to longer and more effective deposition, accounting for the progressive downward thickening.

Before the Snowy River complex was closed to study, a single small sample of calcite from the upper edge of the Snowy river deposit was obtained, and subjected to U-series dating at the University of New Mexico's Radiogenic Isotope Lab, which yielded the extremely recent date of 152 ±61 years (V. Polyak and Y. Asmerom, personal commun., 2003). Also, very few stones or bank silt fragments have fallen onto the calcite surface since the last calcite-deposition episode. These observations suggest that the Snowy River calcite-deposition process is not extinct; the channel is probably only temporarily dry and could refill during the next sufficiently wet climatic period.

Interrelations within Fort Stanton Cave

It seems evident that the major dissolution of FSC was driven by northward-flowing water coming from sources beyond the present ends of Snowy River South, Lincoln Caverns, Hellhole #2, and Bat Cave (and perhaps from other unknown sources), and discharging into the Bonito Valley. However, detailed understanding of interconnecting flow patterns within the system, particularly the east-west elements, is problematic. A precision theodolite survey of the east-west, clay-floored Crystal Crawl, connecting the Main Corridor to the next north-south passage to the east, has been led by Jim Hardy of the FSC Project. This shows that Crystal Crawl's floor is so nearly level as to show no evidence of flow direction.

It is clear that aggressive eastward flow did take place at one time through the Mud Turtle passage from the Don Sawyer Hall breakdown into Snowy River. Whether there was similar flow from the Skyscraper Domes-Snowflake Passage corridor beneath the Priority 7 breakdown into Snowy River is not clear. Intermittent partial flooding that still affects the Main Corridor-Snowflake Passage route evidently does not spill over into Snowy River, since the muddy Main Corridor water would otherwise have stained or buried the Snowy River calcite deposit.

Earlier flow NNE through the Main Corridor and Snowflake Passage probably originally discharged directly into the Bonito Valley. However, the present low point in the survey of this conduit is in Fool's Crawl, not far west of the Priority 7 junction. It is possible that floodwater drainage from this part of FSC presently follows a hidden route, below the explorable cave level, beneath the Priority 7 breakdown and sub-parallel to Snowy River North toward Government Spring.

The role of the recently discovered Crystal Creek spring, in the NE part of Snowy River North, is also cryptic. It has the correct order of magnitude to be the source of the perennial flow of Government Spring, in the valley several hundred m farther NE. This can easily be clarified by dye tracing when the Snowy River complex is reopened to study. Whether or not its source conduits underlie known passages in the cave is undetermined. The known cave cannot be Crystal Creek's sole source, since it was flowing in 2003 after one of the driest multiyear periods on record, when the rest of FSC was quite dry.

Fort Stanton Cave in Geomorphologic Context

The 18 km of FSC, including the Snowy River extension, still occupy a "footprint" of only about 3080 m long by 1310 m wide—a small percentage of the potential extent of the system.

This extent is limited to the north by the nearby Rio Bonito valley. If Snowy River North is found to continue directly toward Government Spring, the explorable corridor will probably end within a few hundred meters in a hillside rubble choke. However, the flow path toward Government Spring may leave the original passage and follow a piracy route, in which case an abandoned segment of the larger passage may curve east, parallel to the valley's south side, for some distance beyond the present outlet. If so, it will probably not go much beyond the junction of the Rio Salado and Rio Bonito, since the base of the westward-dipping San Andres Limestone rises above the valley floor here, exposing the non-cavernous Yeso Formation.

To the south of the Bonito valley, the possible eastward extent of the cave is probably limited by the crest of the Mescalero Arch; shattering and gouge along a major fault there would prevent the Arch from being readily crossed by transverse cave passages. This structure lies up-dip, about 3 km east of the known cave. The cave's actual extent in that direction, however, depends on the type of karst recharge that has fed the cave system, and may fall well short of reaching the axis of the Mescalero Arch.

Active epigenic carbonate caves can have two types of recharge: autogenic, or infiltration from exposed soluble rock within the karst containing the cave; and allogenic, or sinking of water flowing off nonkarst terrain near its contact with soluble rock. Autogenic recharge, especially in semiarid climates such as have characterized the Fort Stanton region during much of the last few million years, is relatively ineffective in cave dissolution; much of the aggressiveness of autogenic water is neutralized by reaction with surface and subsurface limestone before it can participate in developing sizable passages. Allogenic recharge, in contrast, is more effective in cave development because it collects on non-carbonate terrain. This results in a solution that is undersaturated with respect to calcium carbonate, and is also more likely to enter the karst at point sources such as sinking streams, focusing dissolution along limited pathways.

The area east of FSC toward the Mescalero Arch crest consists of limestone ridges and canyons that show little evidence of epigenic karstification other than small-scale karren on outcrops. There are no sinkholes or blind valleys that would indicate significant autogenic solution, nor are there adjacent non-carbonate highlands that could provide allogenic runoff. Mixing of infiltrating seepage at depth could possibly develop sufficient aggressiveness via mixing corrosion to create small subterranean tributaries running down dip toward FSC, but it seems unlikely that recharge from this direction is responsible for much cave enlargement.

Localized clusters of small caves, some with strong airflow, have been found on limestone ridges east and south of FSC, and cavers have speculated that these could be up-slope entrances to FSC. However, none of these swallow significant water influx, nor do they demonstrate vadose features characteristic of recharge points for epigenic caves. None are associated with paleo-stream channels or other evidence of past allogenic recharge. We know of no good evidence that these caves are genetically associated with FSC. At least some of them may have been developed by dissolution of gypsum lenses in the San Andres (J. McLean, personal commun., 2005), or some may be hypogenic.

Immediately west of FSC is a NE-trending segment of the present Rio Bonito drainage which crosses from non-carbonate sedimentary rocks onto the San Andres Limestone. Today the river bed west of the cave is dry most of the time, but its gradient is steeper than that of the nearby cave passages, and during high runoff, it provides at least part of the floodwater that enters the Main Corridor. Some of this water flows north into the main cave from a nearly sediment-filled side passage known as Hell of a Thousand Pinches (HOTP) (Fig. 3), which, when dry, has been followed 230 m toward the Bonito. HOTP is essentially horizontal, and it is not clear whether it was originally an effluent or influent passage, but if the latter, it may be the youngest passage in FSC. The larger, older, and more southerly influent passages diverge increasingly from the Bonito's course, and it is unlikely that they were developed as simple piracy loops such as HOTP may represent.

A similar but inactive passage, Russell's Crawl, parallels HOTP not far to the east at a level about 5m higher (Fig. 3). This may have been a precursor to the HOTP route at a slightly higher base level. Other springs not associated with known passages have been reported along the Main Corridor when floodwater is entering the cave. Hummel (1983) reported a positive dye test connecting sinking water along the Rio Bonito to water which at that time flowed through the Main Corridor, but the precise points of sinking and reappearance were not specified.

As far as yet explored, the two largest up-flow passages, Lincoln Caverns and Snowy River South, extend SSW beneath increasingly high ridges (Fig. 3). This is also the direction from which past allogenic recharge might have been expected. Southwest of FSC, runoff from the Sacramento Mountains core formerly flowed east, depositing a blanket of igneous and sedimentary gravel across a broad outwash slope. The largest remnant of this material, mapped as Quaternary/Tertiary alluvium by Kelley (1971), caps Fort Stanton Mesa beginning ~5 km (3 mi) SW of FSC. Across the gap crossed by Highway 214, ~3 km (2 mi) south of FSC, discontinuous unmapped gravel outliers extend NE both along and across the ridges of the present terrain above and south of the presently mapped extent of FSC, marking paleochannels where water from noncarbonate terrain crossed San Andres Limestone. These channels shifted successively northwest and downward in several stages, the last of which is the present Bonito valley west of FSC.

It is not likely that paleochannel segments nearest FSC were the sources of cave-forming water, because the highest channels are about 125 m above the present base level. It is improbable that, since development of FSC, up to 125 m of limestone have eroded from the uplands, while the base-level Bonito valley, to which the cave is nearly graded, has been down-cut very little.

If the San Andres outcrop is followed farther SW where it changes to an eastward dip, allogenic paleo-input points become increasingly plausible. A particularly suggestive feature is a gravel deposit at a fork in the Little Creek valley near the west edge of sec. 23, T10S, R14E, about 10.5 km (6.5 mi) from FSC, south of and lower than Fort Stanton Mesa. This deposit shows that large flows from non-carbonate terrain incised valleys into the San

Andres limestone more than 60 m below the planar Fort Stanton Mesa outwash deposit and its outliers above FSC. Sinks in this area could have fed aggressive water NE toward FSC long after paleochannels on the mesa and ridge tops had been abandoned and had begun to be dissected, but before the present drainage pattern was fully established. Headward erosion of headwater tributaries of the Ruidoso and Bonito rivers could later have diverted much of the perennial flow from this higher inter-river area via surface or subterranean piracy, which would explain the abandonment of the largest FSC conduits by clastic-bearing flow.

FUTURE WORK

The best test for the original source or sources of FSC's speleogenetic water will be renewed exploration of the Snowy River South passage. Meanwhile, there is significant evidence to support a remote source. Strong winds through Snowy River South and Lincoln Caverns, far below the surface, are consistent with extensive passages beyond. In Snowy River South, the wind direction has been observed to reverse between two visits, although surface temperature was little different. This suggests a strong barometric component of the cave wind (for cave airflow mechanics, see Wigley & Brown, 1976), which would indicate an enclosed volume many times that of the presently known cave. (However, not all of this volume is necessarily of explorable size.) An air-temperature measurement of 14°C (58°F) in the inner part of Snowy River South, the highest on record in FSC, is also consistent with air which has traveled far below the surface. Finally, aside from a few roots penetrating the ceiling in two high parts of the Metro conduit, and the tiny snail shells previously discussed, no living or fossil macrobiota have been seen in the Snowy River complex. This suggests that there are no nearby entrances large enough to admit bats or other troglophilic animals, thereby limiting the probability of strong chimney-effect airflow from such sources.

It is clear that most of the clastic sediment in FSC is allochthonous. It is far too abundant for much to be internal limestone solution residue. However, no systematic analysis of sediment composition has been done. Such analysis could place constraints on possible source areas. It is particularly important to analyze the deposits in Snowy River South, where sediment has clearly traveled a long distance underground. Four Snowy River South pebbles which have been closely examined are composed of fine-grained, light-colored sandstone. This small sample is not very consistent with the composition of surface paleogravels derived from the Sacramento Mountains, which are mostly igneous.

Polyak and Asmerom's two dates provide the only absolute ages for materials from FSC. If more deposits from various parts of FSC can be dated, relationships among parts of the cave, and with the surrounding geomorphology, can be clarified. Exploration will add information about the evolution of the regional landscape and climate, which may not be possible from surface study. The Snowy River calcite deposit, in particular, could provide a relatively high-resolution record of climatic variations.

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PLATE 14: FORT STANTON CAVE - SNOWY RIVER PASSAGE

PLATE 14B. The "Metro" in Fort Stanton Cave.

PLATE 14B. The first three people on the Snowy River Formation in Fort Stanton Cave.