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PREGLACIAL DEVELOPMENT OF CAVES AT STRUCTURAL DUPLEXES ON THE LEWIS THRUST, GLACIER NATIONAL PARK, MONTANA

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Abstract: Two significant caves in Glacier National Park are developed in Middle Proterozoic carbonate rocks. One lies within two large-scale duplex structures resting on the Lewis Thrust. The other is in the hinterland region of one of the duplexes. Both of the caves are aligned along bedding planes, joints, and faults. Poia Lake Cave has large segments that, in part, are aligned along low-angle thrust faults. Both Poia Lake Cave and Zoo Cave have uptrending, dead-end passages developed above the main passage along near-vertical normal faults. In Poia Lake Cave, three small maze sections also lie above the main passage. My previous speleogenic model involving a semi-confined aquifer, with mixing zones along faults and fracture zones now seems unlikely because the strata would be unable to simultaneously confine the aquifer and allow descending water to mix along fracture zones and faults. A second model involving a deep-looping system, while more feasible, also seems unlikely due to the short flow length of postulated cave passages. Recent studies suggest cave development occurred under confined aquifer conditions whereby long-traveled deep water ascends from an artesian aquifer near the Lewis Thrust. The aquifer developed after the hinterland region of the Lewis Thrust was uplifted during the Laramide Orogeny. It remained active until the system was disrupted by late Pleistocene glacial erosion. Since the original phreatic development of the caves, they have been subjected to some collapse, vadose entrenchment, and deposition of clastic sediment including rounded cobbles and glacial varves.

Introduction

The origin of alpine caves in previously glaciated areas has classically been attributed to increased run-off from melting glaciers, higher precipitation during interglacial periods, or events in the Holocene (Hill et al., 1976; Warwick, 1976; Campbell, 1975). More recently, glaciers have been postulated to inhibit cave development (Audra, 2004), and many caves in alpine settings have origins that predate glaciation. Some alpine caves began as deep-phreatic looping systems that probably developed soon after uplift (Worthington, 2005). Others began as middle Tertiary artesian systems (Audra et al., 2003; Bodenhamer, 2006), and some began in semi-confined aquifers beneath impermeable strata that were partly removed prior to glaciation (Fernandez-Gilbert et al., 2000). Following initial development, many alpine caves were modified or enlarged by phreatic and vadose systems associated with warmer late Tertiary climates and Pleistocene interglacials (Audra, 2000). Large parts of some alpine caves have been removed during downcutting or have been filled during glacial advances (Audra, 2000; Ford et al., 1983; Schroeder and Ford, 1983).

Alpine caves in Glacier National Park were first studied by Campbell (1975, 1978b). Campbell mapped four caves in the park. He also identified stratigraphic and structural controls within Poia Lake Cave and proposed a model of speleogenesis in which the cave was formed entirely by vadose water during the Pleistocene (Campbell, 1975). Beginning in the fall of 2004 and ending in the summer of 2005, I supervised a cave mapping and monitoring project in Glacier National Park (BHS-OLEC, 2005). Part of this project included a preliminary geologic map of Poia Lake Cave and a history of development that began in the Pliocene as a semi-confined phreatic aquifer (Bodenhamer, 2006). In addition, the spatial orientation of Zoo Cave and other nearby caves were investigated and an inclusive model for their speleogenesis developed. The completed study provided geologic maps and descriptions of Poia Lake Cave and Zoo Cave and two competing models for the origin of both caves. One model involves downward flowing water in an unconfined phreatic aquifer, and the other involves upwelling water from a long-flowed artesian aquifer.

Setting

The caves discussed in this article are on the eastern edge of the Lewis Range in Glacier National Park, Montana (Fig. 1). The highest peak in the Lewis Range reaches an altitude of about 3200 m, and the plains just to the east of the caves are at about 1700 m. The Lewis Range is topographically rugged as a result of several episodes of glacial erosion, the earliest of which dates into the late Pliocene (Karlstrom, 1991). The crest of the Lewis Range

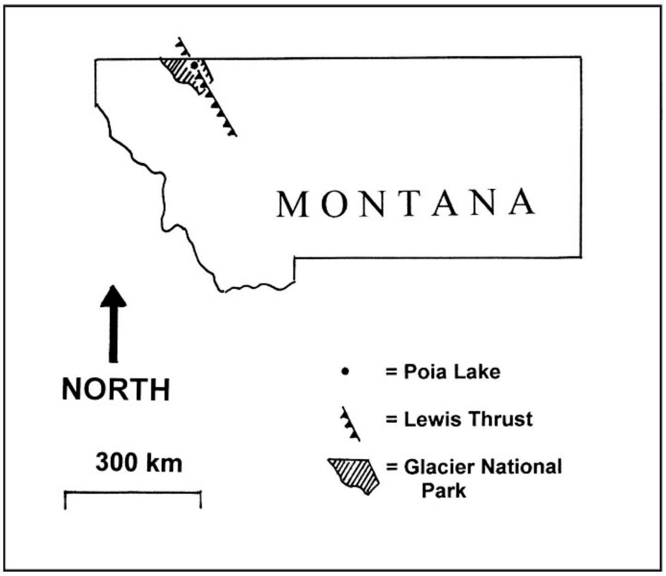

Figure 1. Location map of study area.

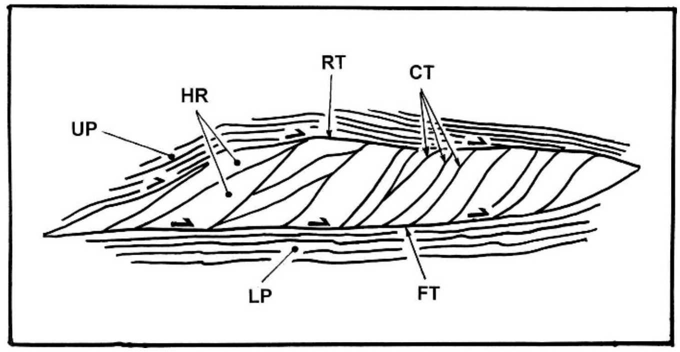

Figure 2. Diagram of a structural duplex. UP=Upper plate. RT=Roof thrust. HR=Horses. CT=Core thrust. FT=Floor thrust. LP=Lower plate (after Jardine, 1985; Bodenhamer, 2006).

follows the eastern limb of the Akamina Syncline which sits atop the Lewis Thrust. The axis of the Akamina Syncline and the strike of the Lewis Thrust trend N40°W (Whipple, 1992). At its widest, the Akamina Syncline spans nearly 25 km. The trace of the Lewis Thrust follows the eastern front of the Lewis Range for nearly 100 km and is estimated to have a displacement on the order of 100 km (Price and Montjoy, 1970). Above the Lewis Thrust, the Lewis Range is composed of Middle Proterozoic sedimentary and metasedimentary rock, which attain a thickness of more than 9000 m. As viewed from the east of Glacier National Park, the Lewis Thrust has driven massive Middle Proterozoic carbonates over Cretaceous shale and sandstone. Alt and Hyndman (1999) consider the Lewis Thrust one of the most spectacular examples of an overthrust fault in the world because of its excellent exposures in cliff faces on the south end and east side of the Lewis Range.

Two structural duplexes sit atop the Lewis Thrust in the vicinity of the caves. Structural duplexes are systems of faults in which two low angle faults bound a packet of rocks that are cut by a series of diagonal thrust faults. The structurally higher fault is called the roof thrust and the structurally lower thrust is called the floor thrust. Diagonal thrusts are called core thrusts and rock packets bounded by faults; in this case, the roof, floor, and core thrusts are called horses (Boyer and Elliot, 1982). A labeled diagram of a structural duplex is given in Figure 2. The two structural duplexes in the vicinity of the caves are named the Swift Current Duplex and the Yellow Mountain Duplex; the roof thrusts are named after the duplexes (Jardine, 1985). The Lewis Thrust is the floor thrust for both duplexes. Poia Lake Cave is in the hinterland region of the Yellow Mountain Duplex and may be within a smaller subsidiary duplex (Bodenhamer, 2006), and Zoo Cave is within a horse of the Swift Current Duplex. Figure 3 shows the position of Zoo Cave and Poia Lake Cave in relation to the Swift Current and Yellow Mountain Duplexes. This profile view is nearly perpendicular to the strike of the roof and floor thrusts and consequently only shows a few core thrusts.

Both caves are developed in the lowermost carbonate rocks of the Middle Proterozoic Belt Series. These carbonates are commonly referred to as dolomite and limestone, but some researchers have suggested they would better be described as carbonaceous siltstones or dolomitic siltstones, because they contain less than 50% carbonate (Smith and Barnes, 1966). The high silicate content of these rocks has resulted in some depositional features that are not typically seen in carbonates. These include cross bedding and ripple marks, which can been seen at a few locations in the bedrock of the walls and floors of the caves (BHS-OLEC, 2005). Other bedrock features found within the caves include chert lenses, stromatolites, stylolites, and thin gypsum beds (Campbell, 1975; Bodenhamer, 2006). Poia Lake Cave is thought to be in the middle member of the Altyn Formation (Campbell, 1975; Bodenhamer, 2006) and Zoo Cave is thought to be in the middle member of the Waterton Formation (BHS-OLEC, 2005). A surficial geologic map with an overlay of Poia Lake Cave and other cave entrances in the area is shown in Figure 4.

Poia Lake Cave

The entrance to Poia Lake Cave is at an altitude of about 1860 m on the south-facing side of a steep-sided glacial valley about 140 m above Poia Lake. A spring issues about 30 m below the entrance. This spring drains a stream that runs through the lower part of the cave. Estimated discharge at the spring ranges from 0.15 $m^3\ s^{-1}$ in the late winter to 2.3 $m^3\ s^{-1}$ in the early spring (BHS-OLEC, 2005). Poia Lake Cave is the longest cave in the study area with slightly over 1650 m of passage. The main passage of the cave ascends from the entrance toward the

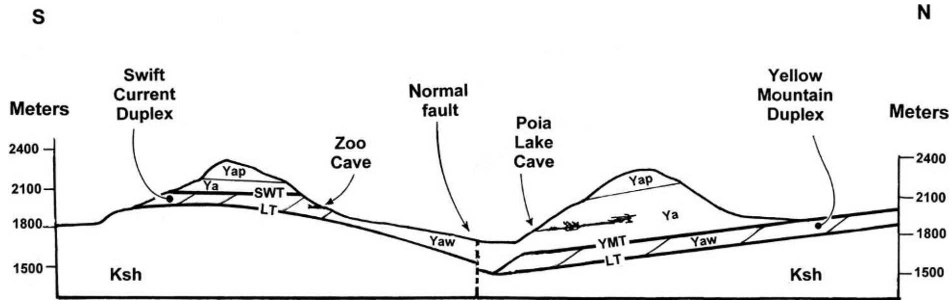

Figure 3. Structural profile along a line from Zoo Cave to Poia Lake Cave (looking west). LT = Lewis Thrust. SWT = Swift Current Thrust. YMT = Yellow Mountain Thrust. Yaw = Middle Proterozoic Altyn and Waterton Formations, undifferentiated. Ya= Middle Proterozoic Altyn Formation. Yap = Middle Proterozoic Appekunny Formation. Ksh = Cretaceous shale and sandstone.

north at a slope of about 12°. This slope approximates the local dip of the Altyn Formation. The entrance is the lowest point of the cave, and the highest is in a small maze above the known terminus of the cave, 112 m above the entrance. At three places in the cave, passages are developed in multiple tiers. In general the lowest tier is an active stream passage, the middle and upper tiers are dry walkways, crawlways, and rooms, and connecting the tiers in a few places are small, multilevel mazes.

Passages in Poia Lake Cave can be divided into six morphogenic types that correlate with variations in guiding fractures and lithology (Fig. 5). Guiding fractures include

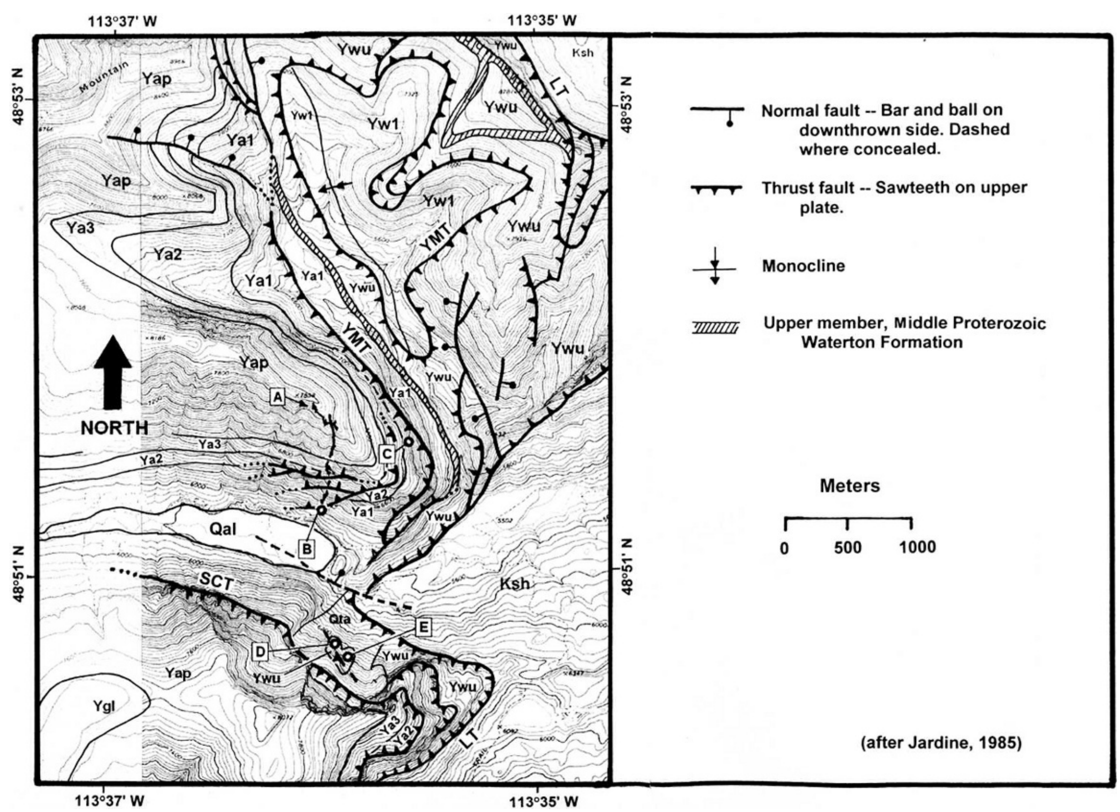

Figure 4. Geologic map of surface above caves near Poia Lake. A = Poia lake Cave passage. B = entrance to Poia Lake Cave. C = Entrance to Dancing Goat Cave. D = Entrance to Jens Cave. E = Entrance to Zoo Cave. LT = Lewis Thrust. SWT = Swift Current Thrust. YMT = Yellow Mountain Thrust. Yw1 = lower member of Middle Proterozoic Waterton Fortmation, Ywu = Middle Proterozoic Waterton Formation undifferentiated, Ya1 = lower member of Middle Proterozoic Altyn Formation, Ya2 = middle member of Middle Proterozoic Altyn Formation, Ya3 = upper member of Middle Proterozoic Altyn Formation, Yap = Middle Proterozoic Appekunny Formation, Ygl = Middle Proterozoic Grinell Formation. Ksh = Cretaceous shale. Qal = Quaternary alluvium, Qta = Quaternary landslide.

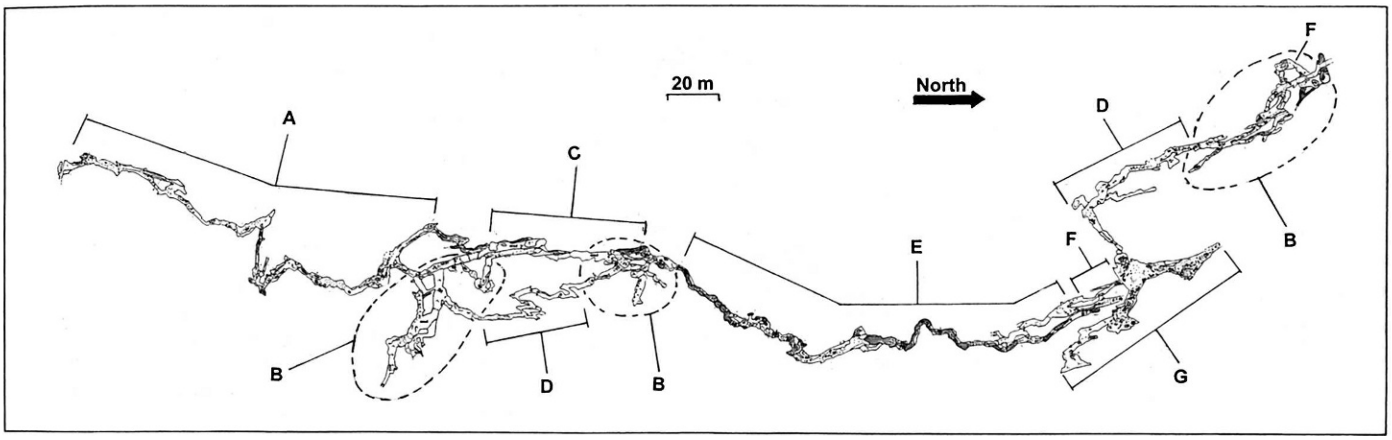

Figure 5. Morphogenic passage types, Poia Lake Cave. A=Abandoned vadose and modified phreatic passages near entrance, B=Multilevel phreatic mazes, C=Midlevel phreatic passages with vadose modifications above lower-tier stream passages, D=Upper-tier phreatic passages, Lower-tier stream passage, F=vertically developed phreatic passages, G=Middle-tier rooms and walkway (Bodenhamer, 2006).

bedding planes, joints, thrust faults, and normal faults. While remapping the cave geology, five thrust faults, six normal faults, and numerous vertical joints were identified (Figs. 6–10). Displacement on thrust faults mapped in the cave is estimated to be on the order of 10 to 100 m, and measured normal fault displacement ranges from 8 cm to 1.5 m (Bodenhamer, 2006). Described differences in the bedrock lithology of the cave walls are referred to by three letter abbreviations (Fig. 7). These abbreviations are roughly equivalent to Roman-numeral subunits, used in my previous study (Bodenhamer, 2006). Lithologic units in Poia Lake Cave are believed to be conformable, but in many places unit contacts are disrupted by thrust faults or covered by clay. Lithologic unit abbreviations and descriptions are provided in Table 1.

Zoo Cave

The entrance to Zoo Cave is south of the entrance to Poia Lake Cave on the opposing wall of the Kennedy Creek Valley at an altitude of about 1970 m (Fig. 3). The entrance is at the base of a small cliff surrounded by talus slopes associated with undermining and mass wasting of horses near the foreland of the Swift Current Duplex (Fig. 11). The cave has slightly over 300 m of passage, all part of a small mostly filled-in multilevel phreatic maze. More than half of the floor surface in the cave is covered with thick deposits of wood rat droppings, in some places as much as 1 m deep. Where not covered by droppings, clay or breakdown mask the floor surface.

Nearly all passages in Zoo Cave are elliptical walkways developed along bedding planes, steeply dipping joints, normal faults, and thrust faults. Three normal faults (labeled NFa to NFb) and one thrust fault intersect passages in Zoo Cave (Figs. 12–13). Normal faults are believed to be the result of torsional forces that developed in horses during formation of the Swift Current Duplex (Jardine, 1985). The thrust fault is the lower core thrust of the horse that contains the cave. Lithologic units in the cave are described in Table 2. In comparison with Poia Lake Cave, variations in lithology and structure within Zoo Cave are more dramatic, but differences in the character of cave passages are more subtle. Passages within Zoo Cave consist of 1) vertically oriented elliptical walkways, 2) horizontal walkways with high rounded and domed ceilings, 3) high slanting domes, 4) a low rounded walkway, and 5) a low crawlway (Figs. 12–13).

Speleogenetic Models

Previous work on the geology of Poia Lake Cave proposed a speleogenetic model in which upper-tier passages developed in a semi-confined aquifer between inflow and outflow zones that were established as overlying strata were removed by downcutting (Bodenhamer, 2006). Palmer (2003) described the development of early conduits in caves that would have preceded the development of an upper tier and favored directing all of the inflowing waters toward a single resurgence. In Poia Lake Cave, it was speculated that the inflow zone was along normal faults in the overlying Appekunny Formation, or directly into the Altyn Formation, and the resurgence was in the upper Altyn Formation. It was also speculated that multilevel mazes were the result of mixing zones attributed to the semi-permeable nature of the thrust faults. Lastly, middle-tier phreatic passages developed as inflow and outflow zones were lowered by further downcutting. Additional work on the geology of Zoo Cave identified several problems with the initial speleogenic model for the origin of Poia Lake Cave. The most important of these problems are explained below.

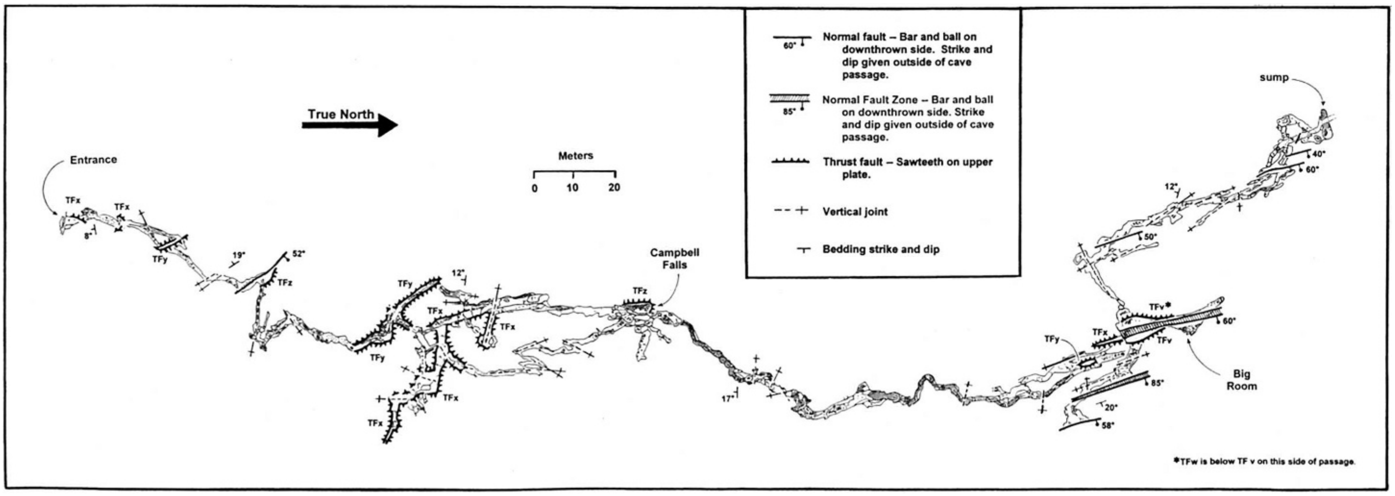

Figure 6. Structural map of Poia Lake Cave. Thrust Faults (TFv to TFz) are labeled to correlate with geologic profile in Figure 7 and Figure 8. Thrust faults extend sheet-like through the area of the cave. They are mapped where they crop out on cave walls (modified from Bodenhamer, 2006).

Lack of Upstream Branching Passage

If the upper tier of Poia Lake Cave had developed as a result of multiple inflow zones directed toward a single favored resurgence cave, the passages would probably branch upstream. Instead the cave is relatively linear with no major branches. Passages possibly branched in a headward part of the cave that is inaccessible or has been removed by erosion, but the deeply incised canyon to the east of the cave suggests that an inflow zone should have existed there, and passages in the known cave should branch toward this potential inflow zone.

Steeply Sloping Phreatic Passage

Most phreatic passages in the cave slope over long distances at an angle of about 12° following bedding. This relatively steep slope is unlikely to have developed below a piezometric surface in a highly fissured karst, as the lower parts of the cave would have formed over 100 m below the piezometric surface. Development of phreatic caves at great depths below an unconfined piezometric surface is well documented (Worthington, 2005), but the earlier model suggested a resurgent zone much lower than the piezometric surface (Bodenhamer, 2006). This suggests that the surface, like the upper-tier passage, also sloped steeply. This situation may have been possible if the upper tier passage developed as a drawdown vadose cave (Ford, 2000). Drawdown vadose caves initiate phreatically under an upwardly convex piezometric surface that is high near the inflow, but bends downward and slopes steeply near the resurgence. After phreatic passage development, a drawdown vadose cave evolves into vadose passages that lower the piezometric surface. If the upper-tier passage in Poia Lake Cave had developed as a drawdown vadose model, subsequent lowering of the piezometric surface would have

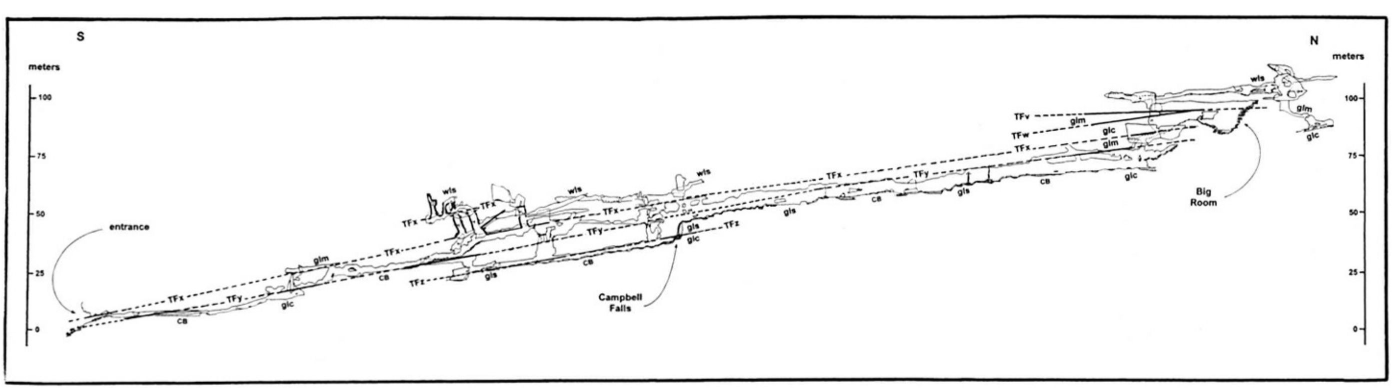

Figure 7. Geologic profile of Poia Lake Cave looking along strike of bedding. Thrust faults are dotted where inferred. Stratigraphic unit abbreviations: gls = medium gray thin bedded limestone with sand layers. glc = light gray limestone with dark chert lenses. glm = light gray massive limestone, wls= tan, white stylolitic limestone, CB= rounded cobble deposits (Bodenhamer, 2006).

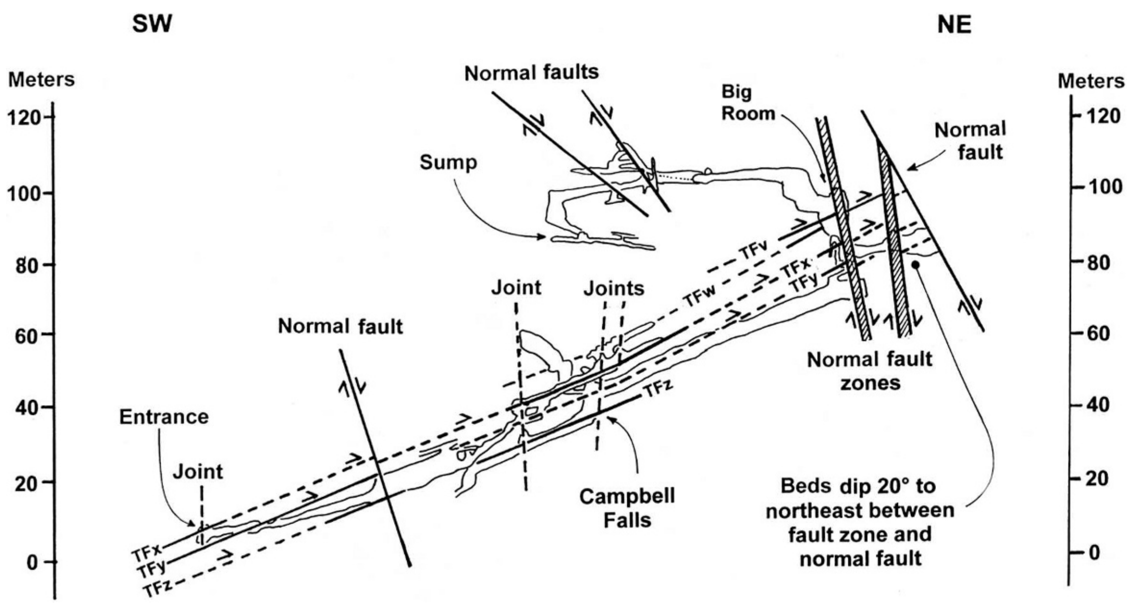

Figure 8. Structural Profile looking along the strike of thrust faults in Poia Lake Cave. Thrust Faults (TFv to TFz) are labeled to correlate with structural map in Figure 6 and geologic profile in Figure 7.

precluded development of middle-tier and other phreatic passages. Furthermore upper-tier passages would have probably been entrenched by vadose water during the drawdown phase.

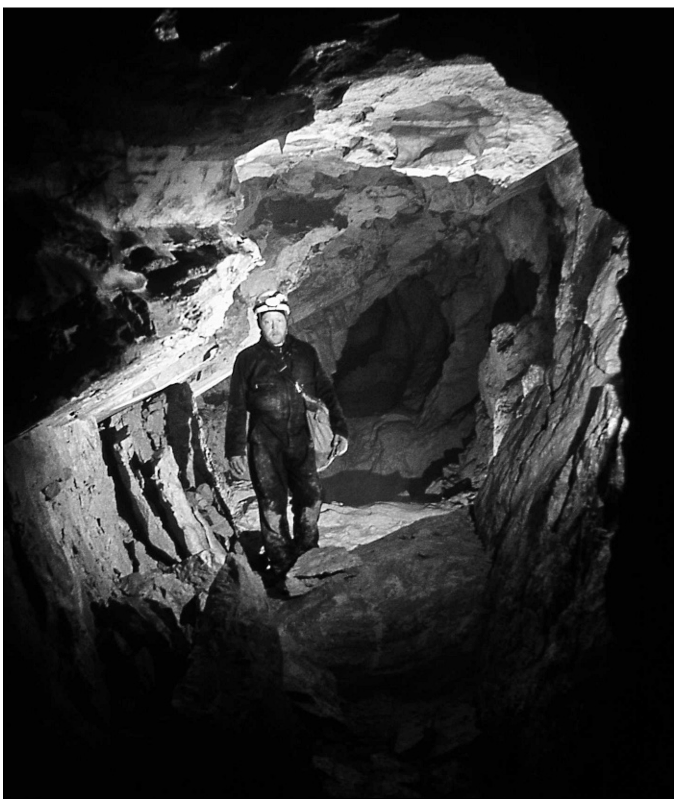

Figure 9. Thrust Fault X in upper-level passage in Poia Lake Cave. Fault cuts diagonally across center of photo.

Development of Multilevel Mazes at Mixing Zones

Passages in multilevel mazes are larger in cross section than nearby upper-tier passages. This assumes a more aggressive corrosion chemistry was at work in the formation of the mazes. The original model of down-flowing phreatic water suggested that phreatic water was able to mix with descending waters, except where they met in the vicinity of mazes. Because the mazes are developed along or near faults, it was thought that the faults acted to separate flows in some places while at others they permitted mixing (Bodenhamer, 2006). One problem with this notion is that fracturing is so prevalent throughout the strata it is unlikely that either thrust faults or normal faults could inhibit ground-water flow over any sizeable area. Furthermore, throughout phreatic parts of the cave, faults clearly are followed by conduits, and nowhere do they seem to have perched descending water.

Failure to Recognize Gypsum Beds

My previous study of Poia Lake Cave, did not recognize thin gypsum beds within the light gray silty limestone unit (glc). The gypsum beds are obscured by secondary calcite deposits in the first few hundred meters of the cave but are more obvious in less accessible upper-tier passages above the Big Room. Gypsum beds contributed greatly to the solubility of nearby dolomite layers. Ground water flowing through layers of gypsum and into adjacent layers of calcite and dolomite can result in a slight increase in precipitation of calcite, but a 150% increase in the dissolution of gypsum and a 500% increase in the dissolution of dolomite (Palmer, 2000). Recent identification of local gypsum layers means that initial cave

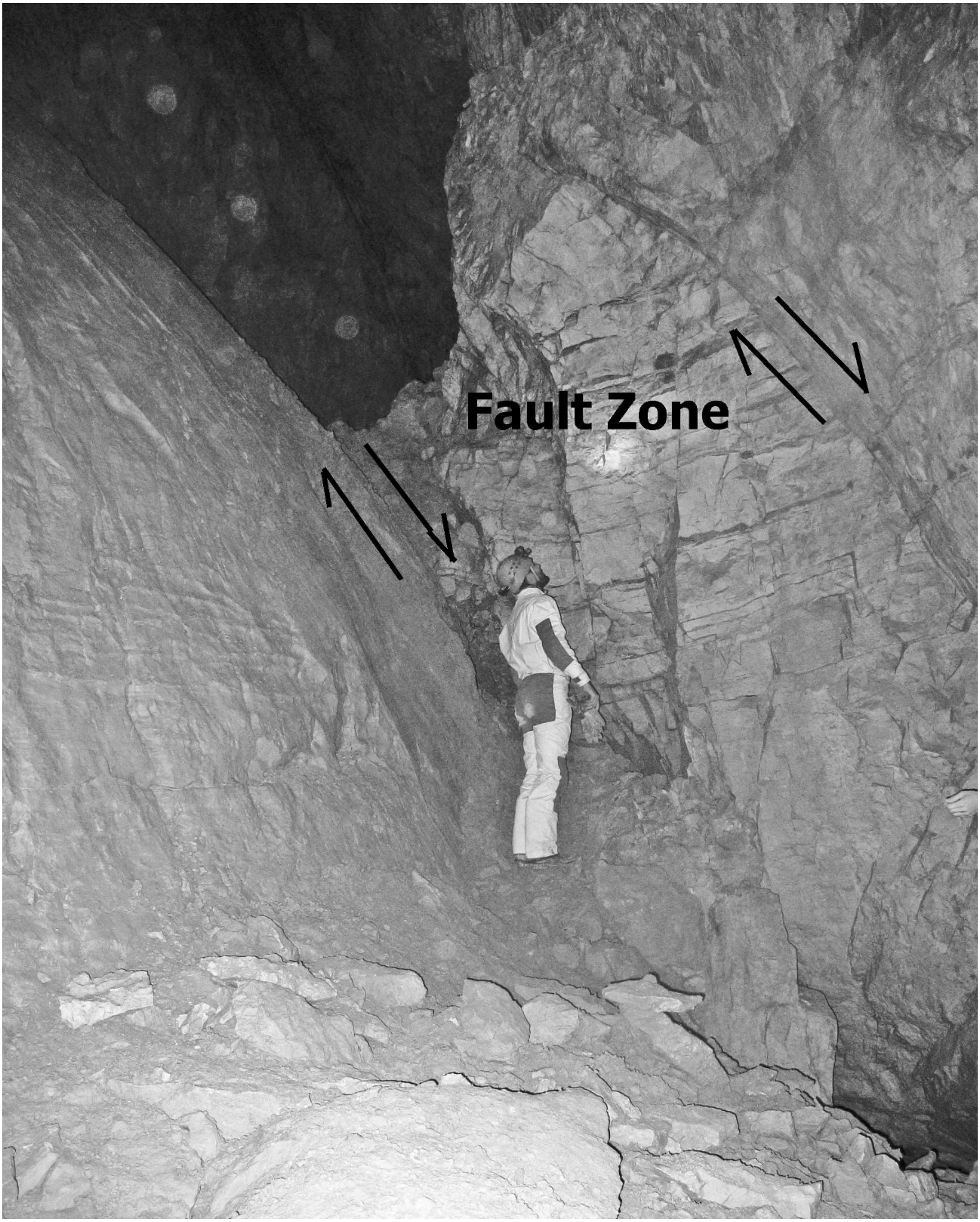

Figure 10. Normal fault zone in the Big Room of Poia Lake Cave. West side of fault zone runs diagonally from upper left corner of photo to near caver's feet. East side runs parallel to west side about 2 m to the right of caver's head.

Table 1. Description of lithologic units in Poia Lake Cave that are believed to be conformable as shown.

Abbreviation	Description
wls	Chalky-textured, tan-white, stylolitic limestone (or dolomite). Stylolites are about 0.5 m apart with 3 mm cubic hematite crystals concentrated where stylolitic sutures intersect cave walls.
glm	Light-gray massive limestone with discontinuous chert lenses.
glc	Light-gray silty dolomite with numerous dark chert lenses and a few gypsum beds about 3 cm thick. In places the dolomite is tinted dirty orange. Stromatolites are recognized in a few places.
gls	Light-gray silty dolomite with interbedded medium grained sand layers and a few dark chert lenses. Sand layers are less than 4 cm thick with 2 to 20 cm of interbedded sand-free dolomite. Ripple marks are observable at some places where sand layers are exposed on the floor.

development was probably along a few dolomitic units adjacent to or near gypsum beds.

Deep-Looping Phreatic Model

According to this scenario, early conduits develop along a deeply circulating flow path that initiated on a gently sloping phreatic surface. The flow paths follow partings (or other fractures) to considerable depth, then loop upward in phreatic lifts that follow intersecting fractures (Ford, 2000). Deep flow paths in looping systems are favored over shallower ones, even though they are longer, because increasing temperature at depth decreases viscosity and allows deep-flowing water to travel through the aquifer more quickly than it would along a shorter shallow path. Looping caves can consist of one or many loops, and the depth and frequency of loops is a function of flow-path length, stratal dip, and fracture anisotropy (Worthington, 2005). Poia Lake Cave and the other nearby caves may have originated as parts of a deep-looping system.

In the case of Poia Lake Cave, the deep-looping system could have initiated beneath a piezometric surface that was about 100 m higher than the present entrance. Inflowing water to the north of the cave could have descended along faults or other fractures that cut through the overlying

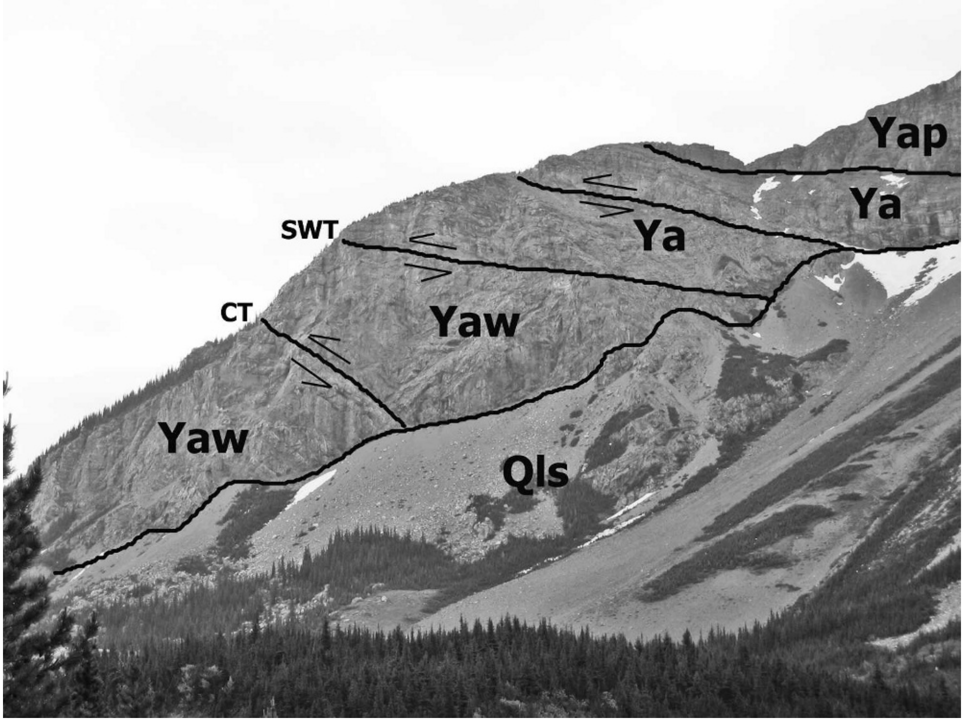

Figure 11. Southeast view of Swift Current Duplex. Zoo Cave is out of photo to the left about 200 meters. Core thrusts splay off the Lewis Thrust, which is the floor thrust of the duplex, and connect with the Swift Current Thrust, which is the roof thrust. Talus field in lower middle of photo is a landslide resulting from undermining of core thrusts in duplex. CT = core thrust. SWT = Swift Current Thrust. Ya = Middle Proterozoic Altyn Formation. Yaw = Middle Proterozoic Altyn and Waterton Formation undifferentiated. Yap = Middle Proterozoic Appekunny Formation. Qls = Landslide.

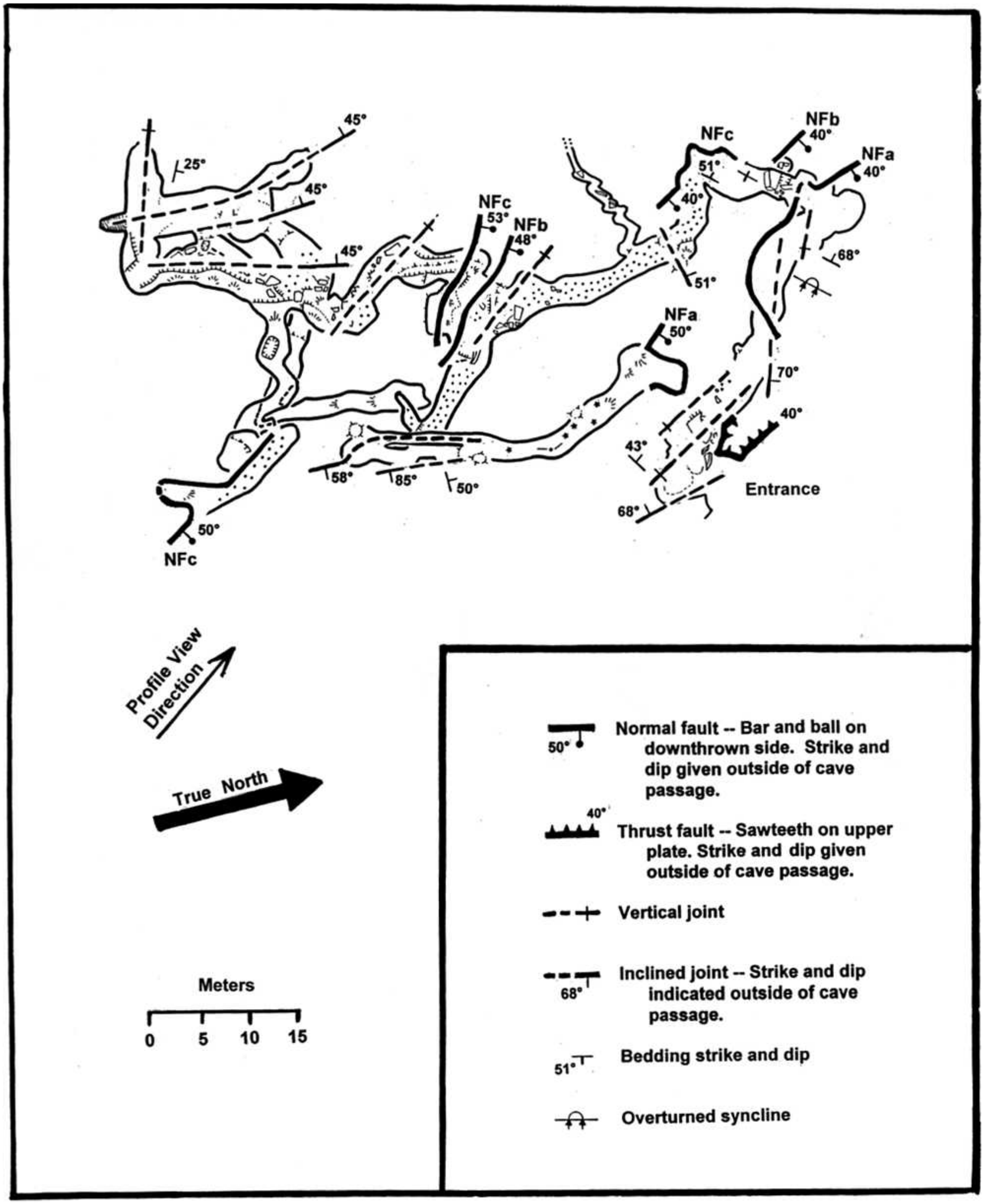

Figure 12. Structural map of Zoo Cave. Normal faults (NF) are labeled to correlate with geologic profile in Figure 14.

shaly Appekunny and into the calcareous Altyn Formation. The top of the piezometric surface was probably near or above the contact between the two. Below the piezometric surface, water flowed slowly southward following stratal dip, vertical joints, and thrust faults. A geologic profile diagramming a deep-looping system that could have been responsible for a phreatic origin of the caves is given in Figure 14. Early conduits near gypsum beds might have been favored, resulting in rapid enlargement in adjacent dolomite layers. Over time, a few large looping conduits might have developed, the largest of which is represented by the upper-tier passages, which were connected during this phase of development. The downstream end of the higher upper-tier passage and the upstream end of the lower upper-tier seem to be clay choked, indicating that they might have been connected

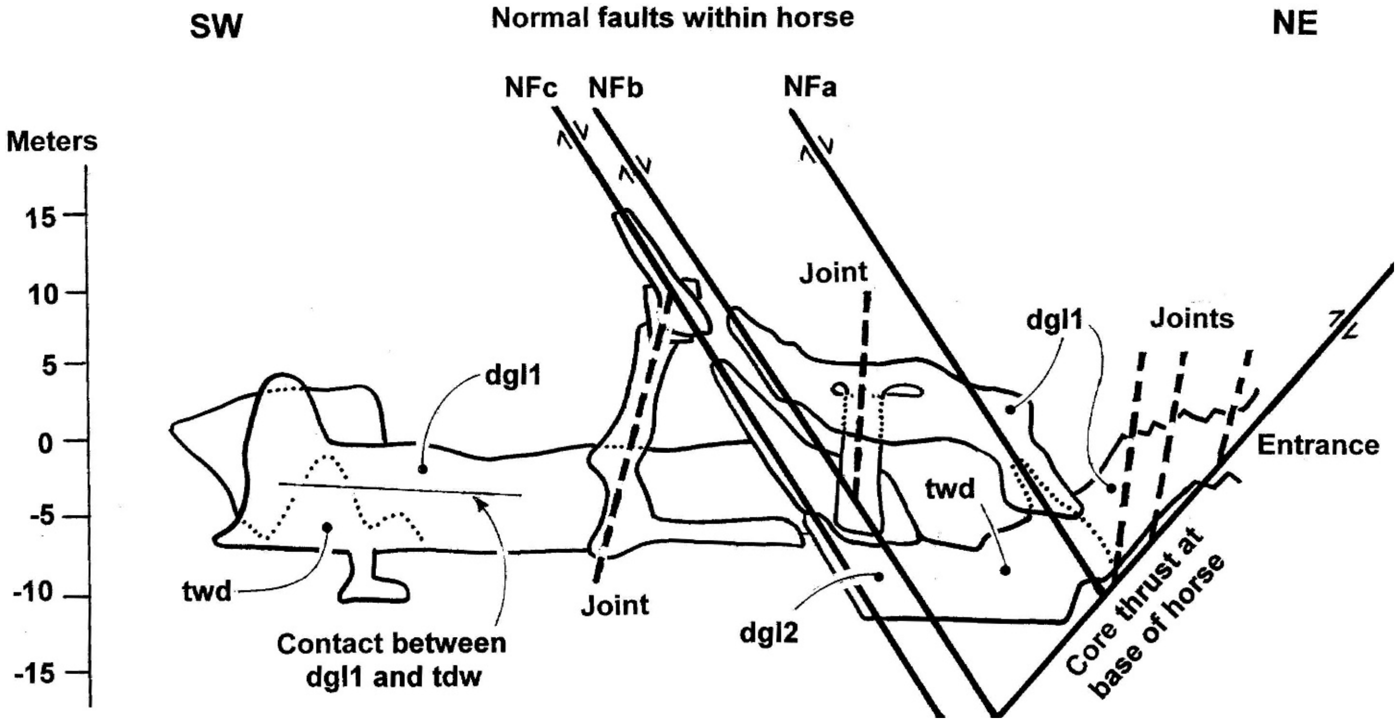

Figure 13. Geologic profile looking along the strike of normal faults in Zoo Cave. The cave lies between the Lewis Thrust and Swift Current Thrust in a structural horse that connects between the two major structures. Stratigraphic unit abbreviations: dgl1 = dark gray thin bedded limestone, dgl2 = dark gray limestone with numerous gypsum veins, tdw = tan to white chalky, massively bedded dolomite.

during development but have since been filled in by clay. If the two sections of upper-tier passage were once connected, they could have delivered water to some point south of, and probably lower than, the present entrance. Here water might have looped upward in a phreatic lift that has since been removed by erosion. Placing a connection between these two upper-tier passages makes a deep-looping model seem viable. However, there are other difficulties to consider.

Connections Between Lower-Tier Phreatic Passages

Lower-tier phreatic passages could have developed as downcutting dropped the piezometric surface, which caused lower tiers to develop as a new loop at a lower level (Worthington, 1991). However, establishing a flow path between lower phreatic tiers is more difficult than one between the two sections of clay-choked upper-tier passages. There are no clay choked middle-tier passages that would likely connect, and the lower-tier passages are almost entirely modified by vadose entrenchment.

Development of Multilevel Mazes in Poia Lake Cave

Multilevel mazes in Poia Lake Cave are challenging to explain as part of a deep-looping origin. Cave maze patterns are categorized into four general forms, each of which is associated with particular types of recharge and porosity. The four patterns are spongework, anastomotic, network, and ramiform (Palmer, 2000). Based on morphology, the multilevel mazes in Poia Lake Cave are either network or ramiform. Network mazes in plan view look like interconnecting, rather linear passages, and ramiform mazes look more irregular and curvilinear. Network mazes can be formed by diffuse downward percolating water or by upwelling water, whereas rami-

Table 2. Description of lithologic units in Zoo Cave with less certain stratigraphic relations. Unit dgl1 overlies unit twd, but the relationship of dgl2 to the other units is difficult to determine because of displacement along normal faults.

Abbreviation	Description
dgl2	Dark gray thin bedded limestone. Limestone is folded and tilted near entrance.
dgl1	Dark gray brecciated limestone. Gypsum infills breccia to give unit a mottled appearance.
twd	Tan-white massive dolomite. In some places the dolomite is chalky.

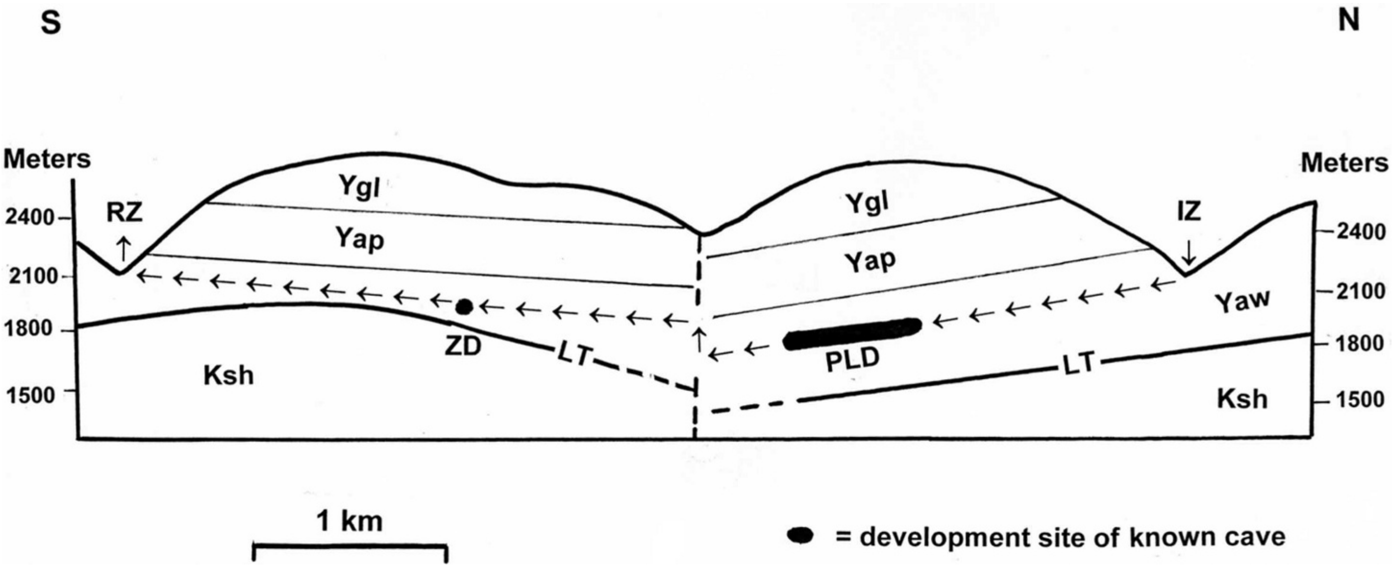

Figure 14. Deep-looping model that could have developed after the contact between the Altyn Formation and Appekunny Formation was breached by downcutting (late Pliocene?). Lines of arrows represent possible deep-looping groundwater flow path. LT=Lewis Thrust, Yaw=Altyn and Waterton Formations undifferentiated, Yap=Appekunny Formation, Ygl=Grinnell Formation, Ksh=Cretaceous shale and sandstone. ZD=Site of development for Zoo Cave, PLD=Site of development of Poia Lake Cave, IZ=Insurgent zone, RZ=Resurgent Zone. Roof thrusts, core thrusts and piezometric surface are omitted for clarity. The location of roof and core thrusts relative to the Lewis Thrust can be seen in Figure 2. The piezometric surface would have trended from the insurgent zone to the resurgent zone.

form mazes are thought only to be formed by upwelling water. Diffuse recharge resulting in the development of network mazes has been attributed to recharge through a porous caprock or by mixing at depth in a porous soluble rock. None of the strata overlying or containing the caves is notably porous. This indicates that the multilevel mazes, whether classified as network or ramiform, developed as a result of upwelling water. Because each multilevel maze is higher than adjacent upper-tier passages, the mazes possibly developed by water that ascended from the developing upper-tier passage in the same way it would in a phreatic lift. Instead of reaching another descending passage, the water returned to the upper-tier passage along a circulating path that eventually developed into a multilevel maze. The notion of multilevel mazes developing in circulating paths above developing upper-tier passages is feasible, but seems contrary to the development of the deep-looping system that initiated because the deep-looping path was more efficient than a shallower one.

Development of Middle-tier Rooms

The middle-tier rooms and connecting passage are much larger in cross section than nearby upper- and middle-tier passages. The larger size may be attributable to upwelling water following short circulating paths similar to those discussed in the preceding section. During development of the middle tiers water could have ascended along fault zones that intersect these tiers. Further enlargement of the Big Room could be attributable to stoping at fault zones caused by undermining of vadose waters that invaded the cave much later (see section on postphreatic modifications). However, the notion of initial enlargement of the middle-tier rooms by water circulating above developing middle-tier passages suffers from the same problem of inefficiency as discussed in the preceding section.

Length of Flow Path in Poia Lake Cave

In order for a deep-looping system to develop, a distance of at least 3300 m is needed between inflow and outflow points because the lower viscosity at depth does not compensate for the longer flow path (Worthington, 2005). The suspected inflow for Poia Lake Cave is about 3200 m north of the entrance. An outflow zone may have existed at least 100 m or more to the south of the current entrance, which might be far enough away to have established the critical length. However, downcutting of 30 m is required to drop the piezometric surface below the upper tier. Considering the 12° dip of the Altyn and overlying Appekunny Formations, maintaining critical length for development of lower phreatic tiers is difficult to explain.

Length of Flow Path in Relation to Zoo Cave

Zoo Cave is higher than Poia Lake Cave and directly in line with the major trend of Poia Lake Cave. Both caves were possibly connected before the valley between them was cut (Figs. 4 and 14). This would have required a phreatic lift just to the south of the present entrance to Poia Lake Cave that would have delivered water upward at least 100 m to the level of Zoo Cave. From there, the water could have flowed southward through Zoo Cave to a resurgence about 3500 m south of the present entrance to Poia Lake Cave. This scenario would have created a nice long flow path for a deep-looping system (Fig. 14). However, flow in the vicinity of Zoo Cave would be up dip, which is inconsistent with a conventional deep looping model. Furthermore, Zoo Cave is a maze cave, and explaining its development as part of a deep-looping system presents the same difficulty as discussed above in the section on the multilevel mazes in Poia Lake Cave.

Long-Flow Artesian Model

Poia Lake Cave might have originated as part of a long-flowed artesian system. Initially this model was not considered because it is difficult to imagine a flow path for an artesian system because strata in the vicinity of the cave dip toward the crest of the mountains. Classic artesian systems in the western United States, such as those in the Bighorn Mountains of Wyoming and the Little Belt Mountains of Montana, are established in strata that dip away from the mountains (Downey, 1984). However, unsolved difficulties with a deep-looping model, led to development of a long-flow artesian model, that accounts for the incongruent dip of strata in the vicinity of the caves.

The development of caves in artesian systems is attributed to the concept of transverse speleogenesis (Klimchouk, 2000). According to this theory, water traveling along a long-flow artesian path will encounter fractures and rise upward as a result of hydrostatic head. As the water rises up through the fractures, it moves through strata of differing permeability, and mixes with other long-traveled artesian waters, making the ensuing mix more corrosive. The name transverse speleogenesis implies the upward flow is typically transverse, or normal, to bedding. This type of spelogenesis has a few important characteristics as follows:

- Caves can develop at depths well below the water table so long as the site of development is lower than the hydrostatic head.
- Cave development is typically slower than development in unconfined settings, but because the site is deeply buried during artesian development, cave formation can span tens of millions of years.
- Cave patterns are typically guided by tectonic structures and are quite uniform in size and morphology within individual lithologic units.
- Cave patterns formed in artesian systems of differing lithology and structure are highly variable, including large rooms, mazes, and dead-end branches.
- Some linear sections of artesian caves give a false impression that they were formed by unconfined downward-moving water, but these sections are only following lateral discordances between lithologies.
- Clastic sediment in artesian caves is mostly fine silt or clay, and deposition is generally uniform and distributed evenly throughout most of the cave.

In the case of an artesian model for Poia Lake Cave, and the other caves in the area, an artesian system could have developed after the movement of the Lewis Thrust during the Laramide Orogeny (Late Cretaceous to early Tertiary). While the hinterland was elevated, strata dipped away from the mountain. Movement of the large slab of Middle Proterozoic rocks above the Lewis Thrust is believed to be driven by uplift at the hinterland of the thrust followed by gravity sliding away from the uplift. Water descending along fractures in the hinterland region eventually encountered strata near the Lewis Thrust and followed the dip of the strata. Variability in the lithology of strata near the Lewis Thrust set the stage for transverse speleogenesis as waters flowing through these rocks developed differing chemistries. As water flowed into the vicinity of the present-day caves, it ascended along fractures such as core thrusts in duplexes. When the ascending water flowed through gypsum layers and into dolomite, it became corrosive and gradually hollowed out the phreatic parts of the caves. A geologic profile diagramming a long-flow artesian model for Poia Lake Cave is presented in Figure 15.

Long-Flow Artesian Model Versus Deep-Looping Model

In a deep-looping model, water flows laterally between inflow and outflow points. If upper-tier phreatic passages constituted the first loop to form, they would need to be connected. However, in an artesian system, the two sections could develop independently at the same time, because the flow can transverse across strata. Furthermore, in an artesian system, lower tiers could have developed at the same time as upper tiers, and none of the tiers need to be connected.

In a deep-looping model, development of multilevel mazes and middle-tier rooms require flow that circulates from the developing loop, and this circulatory flow seems incongruent with the efficiency of a deep-looping system. Mazes and large rooms are typical in artesian systems. Their flow typically follows structures through various lithologies. Mazes can develop as water moves up through many closely spaced fissures that cross several layers, and large rooms can develop as water circulates in fracture zones within one layer.

In a deep-looping system, a critical flow length between an inflow and outflow must be maintained. This critical length may have been difficult to maintain when the piezometric surface dropped during cave development in

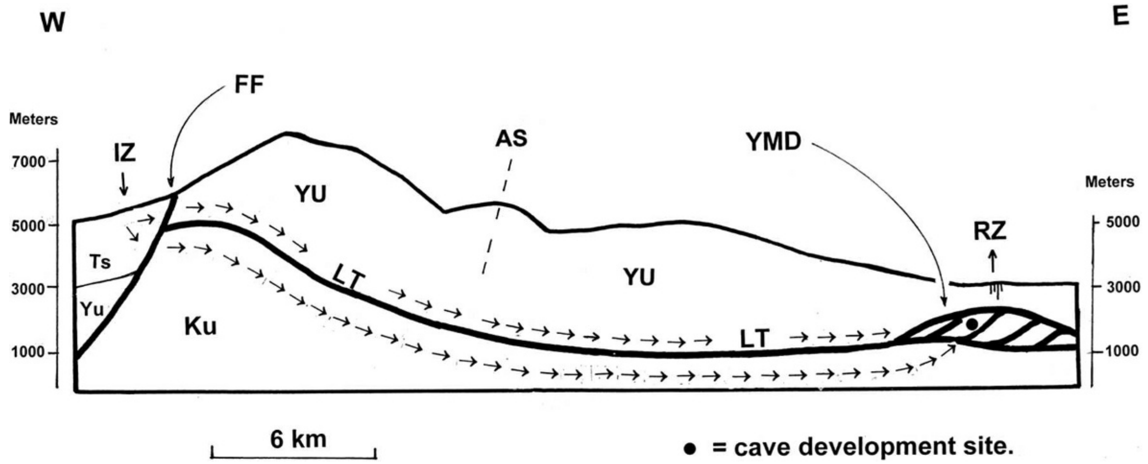

Figure 15. Long-flow artesian model that could have developed following uplift of the hinterland of the Lewis Thrust and development of insurgent and resurgent zones (Oligocene to Pliocene?). Line of arrows represents flow path of artesian water. LT=Lewis Thrust, FF=Flathead Fault, YMD=Yellow Mountain Duplex, AS=Axis of Akimina Syncline, YU=Undifferentiated Middle Proterozoic strata, Ku = Undifferentiated Cretaceous sedimentary rocks. Ts= Tertiary valley fill, IZ =Insurgent Zone, RZ =Resurgent zone.

Poia Lake Cave. In an artesian model, distance between insurgence and resurgence is tens of kilometers long, and caves develop in a deeply buried setting, far below the piezometric surface where they are not affected by downcutting for tens of millions of years.

Long-Flow Artesian Model Fits Cave Features

Caves developed by artesian systems typically have dead-end lateral passages, because flow can be perpendicular to the bedding along vertical fissures. These deliver water upward across the bedding and not exclusively along it. This process explains dead-end passages in the multilevel mazes and upper tiers in Poia Lake and Zoo Cave.

When water ascends a vertical fissure during the development of an artesian cave, it may be more corrosive than when it first enters a bed. This causes the passage to narrow from bottom to top across a rock unit. This process might explain the cross sectional shape of the upper-tier passages nearest the entrance of Poia Lake Cave.

During the development of an artesian cave, if corrosive water ascending a vertical fissure enters a lithology that causes it to become less corrosive, the passage may terminate or narrow abruptly. This process could explain the open narrow fissures that extend upward out of dome-shaped rooms in the multilevel maze nearest the entrance of Poia Lake Cave.

Water moving out of a tight fracture into a solutionally enlarged fissure may create small eddies that can direct flow outward and down the walls. Eddies such as these might explain the mounding of clay deposits in the middle of the floors of the upper-tier passage nearest the entrance of Poia Lake Cave.

Springs that drain large regional karst aquifers are typically high in dissolved sulfate (Worthington, 1991). The long-flow artesian system proposed for Poia Lake Cave and the caves nearby was at least 35 km long from inflow to outflow. At this length, the water flowing through the aquifer likely would have gained sulfate, making the upwelling water more corrosive. This could account for the development of the caves in lithologies that are highly siliceous. It also might explain the presence of cubic hematite crystals concentrated at the intersection of cave passages and along sutures of stylolites. The hematite crystals may be residual from oxidation of pyrite induced by sulfate rich waters.

Postphreatic Modifications

Whether the caves described in this article originated in a deep-looping, long-flow artesian system, or some other as yet to be explained system, after phreatic development, the caves were modified by events associated with downcutting of surface streams and glaciers. Although all the caves were modified by these events, Poia Lake was the most affected. Poia Lake Cave is the only cave in the area that presently has an active stream flowing through it, and it may be the only cave in the area that was ever invaded by a surface stream. For this reason, most of this section focuses on features in Poia Lake Cave.

As downcutting incised valleys above the developing phreatic caves, the piezometric surface lowered, causing reduced velocity of water flowing through the cave, which in turn caused clay in suspension to be deposited. If the caves developed according to the deep-looping model, incision of valleys would have resulted in decreased flow velocities. Because flow velocities through the deep-looping system would not have been fast enough to transport clay in the late stages of development, clay was deposited as passages were progressively abandoned during valley incision. If the caves originated as part of a long-flow artesian system, flow velocities through the caves would have increased as piezometric lows directed and concentrated flows toward incised valleys, but, because the velocities were still relatively slow, clay deposition remained uniform throughout the cave (Klimchouk, 2000).

As phreatic passages were abandoned and drained, ceilings may have collapsed in some places as a result of loss of buoyant support (White and White, 2000). Collapse was more severe in passages and rooms developed in fracture zones. In the Big Room and nearby middle-tier rooms of Poia Lake Cave, clay was deposited on top of breakdown. In some places the clay is over 10 cm thick. These deposits may indicate that dewatering of phreatic passages occurred in distinct stages, or that other events flooded the cave after valley incision had lowered the piezometric surface.

As valley incision progressed, it eventually exhumed the middle-tier passage of Poia Lake Cave and allowed a surface stream to enter the cave. The stream left scallops on the lower parts of the walls and deposited silt, sand and rounded cobbles on the floor (Fig. 7).

The Big Room in Poia Lake Cave may have been partly undermined by vadose stream erosion. Collapse in the back part of this room is extensive and breakdown is deposited on top of previous clay-covered breakdown.

Sediment in the upper-tier passages above the Big Room could have been washed in by vadose water. These deposits are coarser than the clay that covers the floor of most phreatic passages elsewhere in the cave. Collapse of the Big Room temporarily blocked vadose water flow beneath the Big Room and diverted water through the upper-tier passage (Bodenhamer, 2006).

Clay laminations deposited on the floor of the middle-tier passages in Poia Lake Cave are probably varves derived from glacial outwash. However, the suspected varves are difficult to distinguish from other clay deposits in the cave making it difficult to determine if glacial melt waters flooded the cave.

Since the initial invasion of the middle-tier phreatic passages in Poia Lake Cave, the middle tier near the entrance has been abandoned by the cave stream. Coupled with this abandonment is the entrenchment of the lower-tier passage to a depth of over 7 m, development of Campbell Falls, and creation of another lower tier downstream from the falls that feed the spring below the entrance. From the time a surface stream first invaded Poia Lake Cave to the present, the level of the resurgence has dropped about 20 m.

Timing of Speleogenetic Phases

Poia Lake Cave and the caves nearby developed in two distinct speleogenetic phases. The first phase was phreatic and the second was vadose. Estimates of the timing of each phase are possible by relating the development to timed surface events and by considering the development of features within the cave relative to similar features on the surface and within other caves in the region.

Phreatic Phase (Oligocene to Pleistocene?)

The thick slab of Middle Proterozoic rock above the Lewis Thrust was emplaced during the Laramide Orogeny (74 to 59 Ma). Following emplacement, the slab and the Lewis Thrust were deformed due to isostatic rebound (Sears, 2001). An artesian system may have initiated at this time, if fracturing in the inflow and outflow zones penetrated through the Lewis Fault and into the underlying Cretaceous strata. However, it is more likely that an artesian system developed after movement of the Flathead Fault. The Flathead Fault is related to the slow subsidence of the hinterland of the Lewis Fault, which began in the Oligocene and ended in the Miocene (McMillan et al., 2006). At the beginning of subsidence, some strata in the hinterland dipped eastward and would have provided an ideal setting for establishment of a multistory artesian aquifer. As subsidence continued, strata were gradually rotated until it was dipping east as it does today. However, regardless of dip after its establishment, the artesian aquifer probably remained active as long as the recharge area was higher than the resurgence area, and the confining strata of the aquifer were not disrupted by downcutting of the surface. The earliest downcutting is believed to be in the Pliocene as discussed below.

Vadose Phase (Late Pleistocene)

Features within Poia Lake Cave suggest that phreatically developed parts of the cave were exhumed during the late Pleistocene as a result of rapid and alternating glacial and fluvial downcutting.

Vadose modification in middle tiers is minor compared to that in lower tiers. Furthermore, no vadose modifications occur in upper-tier and multilevel mazes. If valley incision had been a result of uninterrupted fluvial erosion, surface streams would have invaded the upper-tier and multilevel mazes as the valleys were cut. Also, the middle tier would be more entrenched. This suggests that the upper-tier passages were affected by a glacier that cut through the level of these passages and down to that of the middle-tier passages before fluvial erosion was resumed after the glacier retreated.

If the lamenated clay deposits in Poia Lake Cave are varves, they are relatively thin in comparison with similar deposits from other caves in the region. Varved clays in Castleguard Cave, which is at about the same altitude and approximately 350 km to the north, are over 2 m thick and represent several episodes of glaciation (Schroeder and Ford, 1983). Varved clays in Virgil Cave, which is also at about the same altitude, but 150 km to the south, are about 1 m thick (Rykwalder, 2007). The suspected varves in Poia

Lake Cave are only about 40 cm thick. If Poia Lake Cave had been exhumed early in the Pleistocene, and glacial flooding in the cave was similar to that in the other caves in the region, glacial meltwater would have flooded the cave several times, and varves would be thicker. The relatively thin depth of the suspected varves suggests that if glacial meltwaters entered Poia Lake Cave, it was not until late in the Pleistocene.

Paleoflow through Poia Lake Cave was similar to present day flow. Estimates of paleoflows can be derived from the dimensions of scallops and rounded cobbles in abandoned stream passages. A relationship for stream velocity as a function of scallop length is provided by Moore and Sullivan (1997). Scallop lengths in the modified phreatic passages near the entrance are up to 4 cm long, which yield a velocity of 0.5 to 1.5 m s^{-1}. Scallops cover only the lower part of cave walls in Poia Lake Cave; that cross sectional area of 0.75 m^2 multiplied by the estimated velocity gives an estimated flow volume of 1.5 to 2.3 m^3 s^{-1}.

A relationship for size of particles transported as a function of stream velocity was developed by Hjulstrom (1939). The largest cobbles in the abandoned stream passage measure 25 cm. Using the same cross sectional area, a flow of 0.375 to 1.1 m^3 s^{-1} can be estimated. Present-day flow through Poia Lake Cave ranges from 0.25 to 5 m^3 s^{-1}. The two estimates of paleoflow are close enough to present-day flows that it seems reasonable to assume that a surface stream invaded the cave during an interglacial of the late Pliestocene when flow rates where similar to those of today.

Conclusions

Speleogenic models for the evolution of alpine caves in previously glaciated areas should consider the possibility that the caves originated as deep phreatic systems that might have initiated after regional uplift. In lieu of absolute dating techniques, detailed mapping of guiding fractures, lithologic variations, and distributions of floor deposits all provide considerable insight toward developing a speleogenic model and timeline for events. In the case of Poia Lake and Zoo Caves, three models were considered, each with a different phreatic origin. The phreatic origin in the first model is attributed to development in a semi-confined, descending aquifer that was established during downcutting. This model does not adequately explain the steep dip of phreatic passages within Poia Lake Cave or the multilevel mazes in both Poia Lake and Zoo Cave. In the second model a deep looping system with phreatic lifts is considered. This model better explains the steeply dipping passages in Poia Lake Cave, but does not adequately explain mazes in both caves. Also, the flow path may be too short for the development of lower phreatic passages in Poia Lake Cave. The third model involves a long-flow artesian aquifer. This model accounts for steep passages,

Table 3. Comparisons of the phreatic origin of 3 speleogenic models of Poia Lake and Zoo Cave.

	Origin 1	Origin 2	Origin 3
Characteristic	Semi-confined down-flowing aquifer during downcutting	Deep looping with phreatic loops	Long-flow artesian aquifer
Length of flow	2.5 km	2.5 to 5.5 km	35 km
Timing of origin	Pliocene to Pleistocene	Pliocene to Pleistocene	Oligocene to Pliocene
Upper tier passages	Develops near surface of piezometric surface	Develops as loop below piezometric surface	Develops as upwelling water follows intersection of thrust faults, bedding planes and joints
Middle tier passages	Develops as piezometric surface drops	Develops as a second loop after piezometric surface drops	Develops simultaneously with upper tier passages along lower structures
Multilevel mazes	Develop at mixing zones where descending vadose water meets phreatic water	Develop in recirculating paths at quasi phreatic loops	Develop as upwelling waters rise through closely spaced joints and faults
Large rooms	Develop below fault zones by undermining of cave stream during vadose phase	Develop either in recirculating paths or by undermining of cave stream during vadose phase	Develop by circulating of upwelling waters in fault zones
Clay deposits	Deposited during dewatering and flooding	Deposited during dewatering and flooding	Deposited uniformly by upwelling waters

mazes, and is a better fit for other features in both caves, but requires an unconventional artesian flow path. Table 3 compares the phreatic origin of each model. After a phreatic origin each model recognizes that downcutting and other events modified both caves, but had the greatest effect on Poia Lake Cave, which was invaded by a surface stream. Postphreatic modifications include partial collapse, vadose entrenchment, and deposition of coarse clastic sediments

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