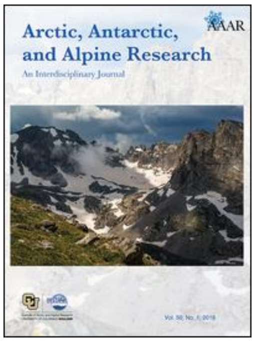

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THE PHYSIOGRAPHY AND SPELEOGENESIS OF CASTLEGUARD CAVE, COLUMBIA ICEFIELDS, ALBERTA, CANADA*

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ABSTRACT

Castleguard Cave is developed in massive limestones of the upper Cathedral Formation (Middle Cambrian), overlain by shaly or dolomitic carbonates that function today as a leaky caprock. The cave contains ca. 18 km of explored passages, with a relief of 350 m. It displays three sections: (1) a headward complex beneath the Columbia Icefield, (2) a central, linear cave that passes through Castleguard Mountain, and (3) a downstream or entrance complex underlying the Meadows; part of this discharges floodwaters in summer. The remainder of the cave is hydrologically relict, except for local invasion waters.

Development of the central and downstream cave in vertical section was as a State 2 phreatic looping system, incorporating dip tube passages in four principal bedding planes that were connected together at three groundwater lifting sites. With enlargement, upstream portions of tubes underwent vadose entrenchment. A model for the plan development of the cave envisages an initial southwest system underneath the icefield. This was disrupted, probably by glacial injecta, and two new protocaves extended through the mountain towards "target" caves beneath the Meadows. Linkup of the protocaves via a sedimentary dike created the central cave.

Most of the cave was abruptly abandoned by the genetic waters. Later invasion waters from the Columbia Icefield and caprock have carved local shafts and trenches that direct flow to an inaccessible lower cave.

SPELEOGENESIS

General principles of limestone solution cave genesis are briefly reviewed here as an introduction to a description of Castleguard Cave and an interpretation of its erosional origin and development.

The majority of limestone caves are created by solvent action of meteoric waters circulating through the rock without artesian confinement. Castleguard Cave belongs to this general class. Galleries and shafts composing such caves develop initially along secondarily permeable fis-

*A version of this paper was presented orally at a symposium, "Karst and Caves of Castleguard Mountain," at the 8th International Congress of Speleology, Bowling Green, Kentucky, U.S.A., 20 July 1981.

sures—bedding planes, joints, and faults. If these possess continuous openings 10 μm or greater in width, they may be penetrated and routes along them enlarged into caves by groundwater of normal solvent capability. When enlarged throughout their length (input to output) to minimum diameters of 5 to 15 mm, the caves may be considered "developed." Passage morphology may not change significantly after that, although diameters or depths may increase to many meters. The majority of cave passages in most karst aquifers remain inexplorably small.

In cross section, cave passages of explorable size display one of three general shapes, or may be composites of two or all three of them. Phreatic passages develop in conditions of complete waterfill; ceilings and walls may be eroded as readily as floors. The form is generally that of an ellipse along the host fissure; more circular forms (approaching the minimum friction cross section of a standard pipe) indicate faster solvent flow or lower lateral permeability in the fissure. Deep, blind, solution pockets are indicative of slower flow and the admixture of tributary water from lesser fissures (Bögli, 1971).

Vadose passages develop where the water has a free surface (i.e., in the vadose zone), and are varieties of entrenched, canyon-like channels as found with surface rivers. It is common to see a younger canyon entrenched in the floor of a phreatic passage, signifying a lowering of the watertable. Such composite features are well developed in Castleguard Cave. The third form is of breakdown, where part or all of the ceiling and walls have fallen. This is normally a consequence of the draining of a phreatic cavity (with loss of buoyant support by water) or of lateral undercutting by a vadose stream.

The classical literature in the field concerned itself with gross system development in the long section between sinkpoints and springs. Three opposed schools contended that the locus of major cave development would be below the watertable (Davis, 1930), above it (Martel, 1921) or along it (Swinnerton, 1932; Rhoades and Sinacori, 1941). Ford (1971a) and Ford and Ewers (1978) have offered the resolution depicted in Figure 1. Where the frequency of penetrable fissures is low (Figure 1A, States 1 and 2) cave channels tend to comprise a single deep loop or series of loops beneath the final, stabilized watertable. With higher frequency, the channel develops more nearly along the watertable. At Castleguard, the host carbonates are very massive, yielding a low fissure frequency, so that a State 1 or 2 system would be expected. This is found to be the case.

Vadose caves are of two basic types (Figure 1B):

(1) Drawdown caves, formed in an upper zone through

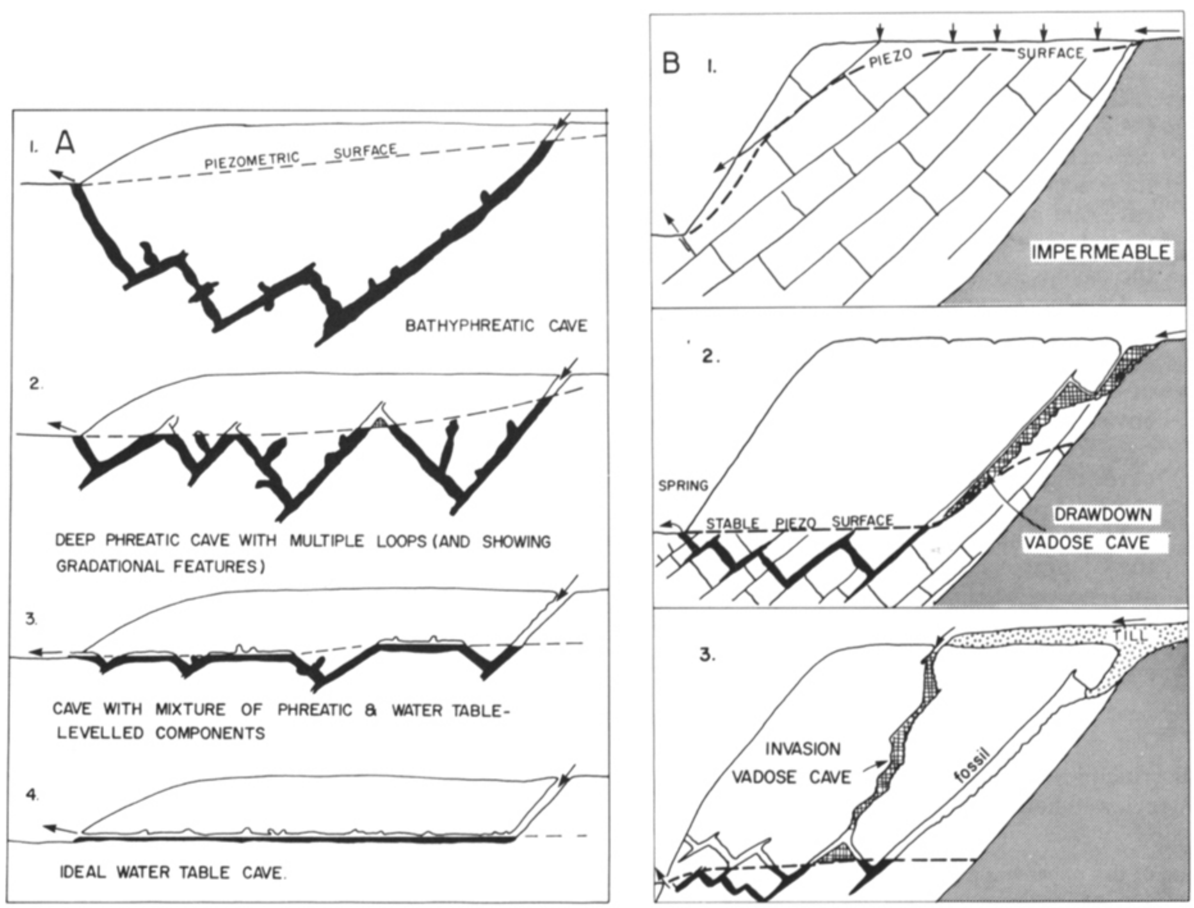

FIGURE 1. A. The four differing types of phreatic and watertable cave systems (from Ford and Ewers, 1978). B. The distinction between the "drawdown" and "invasion" types of vadose cave systems.

which the water table fell as the volume of solutional cavities (the underground reservoir) was enlarged, before stabilizing at or above the elevation of the spring: such caves usually preserve initial, but small, phreatic elements with greater gravitational channels cut below them.

(2) Invasion caves develop when new stream inputs appear on a rock mass already drained and vadose as a consequence of one or more previous phases of speleogenesis. Creation of new inputs and, perhaps, the elimination of older ones will result from perturbing action at the surface. Most often, this is the stripping back of an impermeable caprock. As indicated in Figure 1B, glaciers are also powerful perturbing agents. At Castleguard, both caprock stripping and glacial derangement potentially play roles.

In Castleguard Cave a majority of passages have developed from penetrable bedding planes rather than joints and faults, and are oriented down the stratal dip. Ewers (1982) has analyzed the general problem of plan pattern construction in caves guided by bedding planes. Figure 2 depicts relevant findings. Figure 2A analyzes initial development from a single water input. A branchwork pattern of distributary micropassages propagates in the direction of the hydraulic gradient. Individual passages are in competition for renewal of solvent supply. Chance variations in the permeability of the plane eventually favor one; it attains the output boundary and enlarges to developed dimensions, as defined above. Its failed competitors may be utilized in later amalgamations of other inputs.

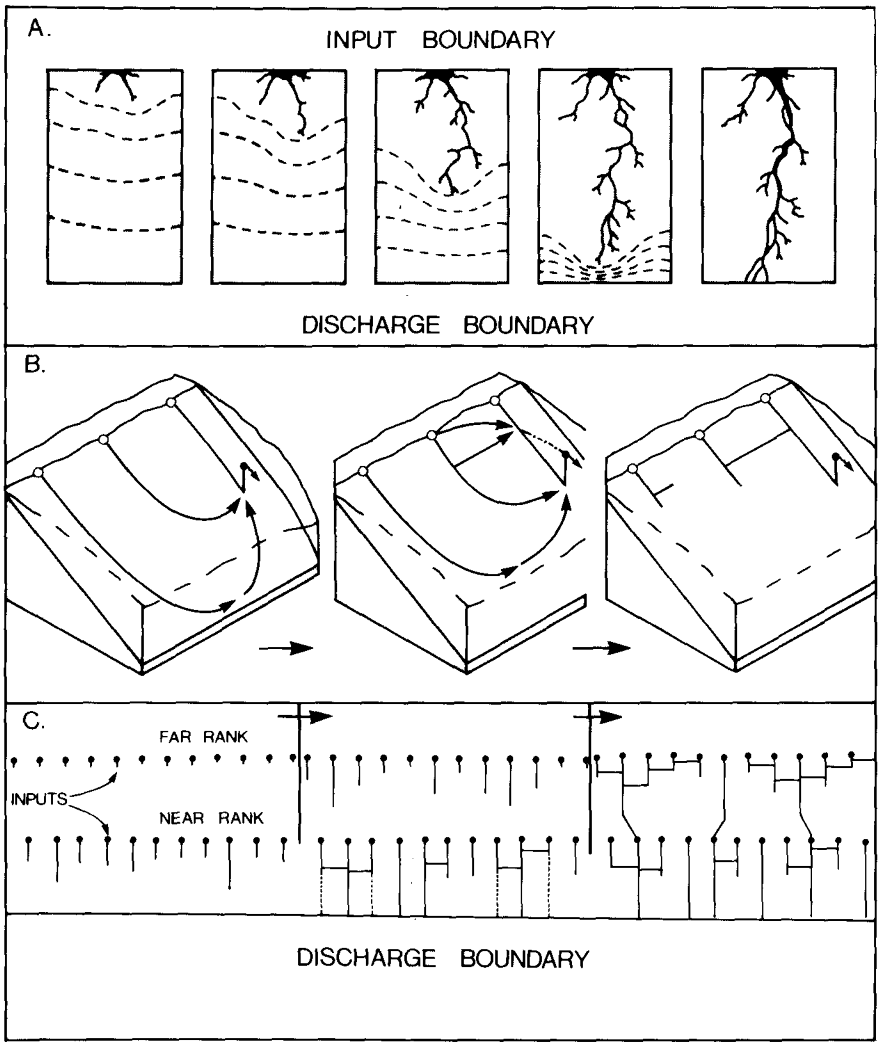

FIGURE 2. A. The development of a solutional protocave between a single input point and a discharge boundary in a bedding plane. A principal tube makes the connection along a random path, leaving abandoned secondary tubes. B. Illustrating the progressive linkage of three separate protocaves (principal tubes) propagating from an input boundary. That on the right establishes a connection with a discharge boundary. The others then connect to it. C. Illustrating patterns of growth and connection of principal tubes propagating from two ranks of inputs. The two ranks may be in different bedding planes. (From hardware simulations by R. O. Ewers, 1982.)

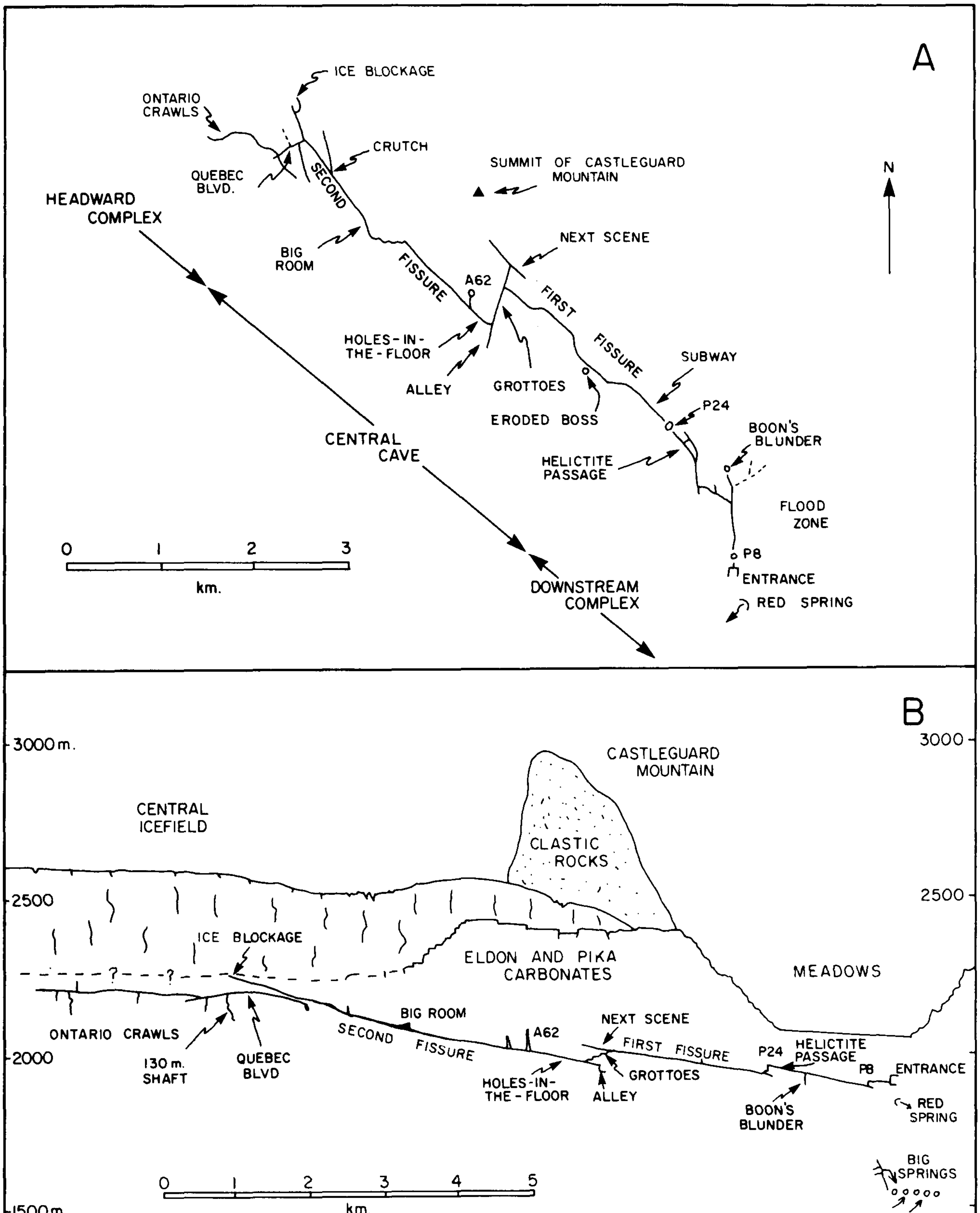

FIGURE 3. A. Plan of Castleguard Cave, with place names. B. Schematic long section of the cave and environs.

Figure 2B shows three separate input microsystems of this kind in a dipping bedding plane. One has established a developed (efficient) connection to a spring or earlier cave. Groundwater flow in the others is now directed towards it; it has become a "target." Connecting passages are eventually driven through to it, approximately on strike. Often, they twist and turn up and down segments of failed competitor passage to do so. This can create highly irregular plan patterns (e.g., Figure 1 of Ford and Ewers, 1978).

Figure 2C analyzes development where there are two successive ranks of inputs, probably in different penetrable bedding planes. The rank nearer the output is the first to establish connected through caves. Inputs of the second rank are then progressively linked up.

These models are considerable simplifications. Plan pattern development may be complicated by the occurrence of major fractures intersecting the planes, by the creation or elimination of inputs by caprock stripping, glacial action, etc., by blockage of developed passages, and by the relocation of spring points as consequences of external erosion or aggradation. All of these complicating factors are present in the Castleguard karst.

PHYSIOGRAPHIC DESCRIPTION OF THE CAVE

The topographic and geologic setting of Castleguard Cave is summarized by Ford (1983, this symposium). Figure 3 depicts the principal passages in the cave. At the present time, there are 18 km of mapped galleries. Explorers can enter only at the downstream terminus, at 1970 m a.s.l. From there the cave is followed northwest and upstream, ascending 335 m at a generally easy gradient. Almost all of it is now in a hydrologically relict condition (i.e., it is a fossil system), but the downstream end floods to the roof sporadically during the melt season, and invasion waters are seen from place to place farther in. The downstream flooding necessarily limits exploration and study to the winter season.

The cave has three genetic sections:

(1) The downstream complex is a warren of low tunnels largely underlying the southwestern Castleguard Meadows.

(2) The central cave is a remarkably linear underground river passage passing beneath Castleguard Mountain. Only one significant paleotributary enters the main gallery in a distance of 6 km. This is very unusual.

(3) The headward complex underlies part of the central Columbia Icefield. It is a network of branching, connecting and parallel passages, attenuated by detrital blockages and intersected by invasion shafts. It is incompletely explored. Portions of it are almost certainly older than the rest of the cave.

The downstream complex. The cave entrance is a broad, square passage truncated by surface erosion in the side of the Castleguard Valley, 270 m above Castleguard River (Figure 4). An obvious floodwater channel extends from it down cataracts until, 40 m below, it is joined by Red Spring, a perennial spring. This issues from an impassable bedding plane slot. The channel continues as a gorge, to join Meadow Creek canyon.

The first kilometers of passages are a low, wide bedding cave, squared off by block breakdown. There is little other debris,

FIGURE 4. The entrance passage, displaying a typical rock breakdown form. The floor is swept by flood waters each summer, keeping it clear of fine-grained detritus. This part of the cave is frozen except at times of flooding.

the passages being swept clean by floods. In winter there is a strong draft blowing in from the entrance; temperatures are below 0°C and residual pools of floodwater are frozen.

One hundred meters from the entrance, the passage descends 8 m on a small, vertical fault (shaft P8) to ramify in lower bedding planes. A fine shingle beach is an unexpected feature at its base; this is analyzed by Schroeder and Ford (1983, this symposium). At 500 m a major tributary, Boon's Blunder, enters from the north. This is a bedding plane elliptical passage with low tributaries. It extends 600 m updip where it ends in a descending vertical shaft. This is permanently waterfilled and appears deep. It is believed to be the principal source of the summer floods, which may spill from it to inundate the cave below in 2 to 4 h and perhaps persist for more than 19 d.

Beyond the junction, the principal passage is a phreatic ellipse of 5 × 1 to 1.5 m in cross section, turning through dip and strike in one or two bedding planes. Pools of standing water at 900 m indicate the end of the winter cold zone. Silt and clay banks suggest backwater flood deposits, and there are small calcite stalactites. Distributary passages extend down dip to water fills.

From 1.0 to 1.8 km the passage progressively changes from fully phreatic to drawdown vadose in form (Helictite Passage, Figure 3). The entrenchment is broad and attains 5 to 6 m in depth. There is local breakdown. The channel is entirely relict, having no modern streams at any season. There are local sand and silt deposits. Stalactites and stalagmites are quite abundant, and a few examples are 0.5 to 1.0 m in length. Pack rats nest here, presumably entering via tiny tributaries from the Meadows above. The passage terminates at the lip of a vertical shaft descending 24 m. This is P24.

The central cave, between P24 and the Crutch, displays a regular alternation of a few morphologic elements. P24 is elliptical in cross section, 8 × 5 m in dimension, and follows a minor fault (Figure 5). It is a phreatic lifting chimney, created by water flowing up it. A small vadose cave drains downdip from the base, now clogged with silt and clay.

Upstream is the Subway, an ideal example of a circular, bedding plane solution tube (Figure 6). It is straight and invariant in dimension for 450 m, oriented in the true dip direction.

Beyond the Subway the tube merges into the second major form element, a narrow vadose canyon, represented here by First Fissure (Figure 3, Figure 7). This climbs updip and deepens steadily from 5 to 15 m or more. It is a proper fit to the phreatic element downstream and evidently developed during the same phase. Initial phreatic form is preserved in the ceiling. Younger, invasion water shafts descend into it in a few places and supply streams in summer which follow the canyon floor for a few tens of meters before sinking below it in impassable slots. One example is perennial.

Layered silt-clay deposits are seen along much of the Fissure. They are highly eroded by invasion waters and discontinuous, but sections as deep as 5 m survive. The Fissure is well decorated with small stalagmite deposits. Beneath one large invasion shaft (Waterfall Room) are the remains of a great stalagmite, the Eroded Boss. Progressively, the roof of the Fissure becomes encrusted with efflorescent secondary minerals, including needles of gypsum seen growing from rock and clay.

First Fissure ends at a central phreatic section, the Grottoes. These descend gently to the south. Evidently, groundwater flowed up through them to spill over into the vadose fissure. The Grottoes are following the strike of a vertical sedimentary

FIGURE 5. A view up P24, a vertical shaft formed by solvent waters flowing up it. The shaft is 24 m in height; for scale, ladder rungs are spaced 25 cm apart. The shaft is guided by a small fault. The lefthand wall shows fault breccia. The righthand wall is a smooth phreatic solution surface.

dike of sandstone that is 20 to 40 cm thick. The passage switches from one side of it to the other and diverges temporarily into bedding planes. This has permitted abrupt changes of form and dimension, but the basic phreatic form is retained, with some deep solution pocketing indicative of slow flow in places (Figure 8).

The one significant paleotributary of the central cave enters at the north end of the dike. This is Next Scene, a smaller vadose canyon below an early phreatic tube. It becomes blocked by clay and silt fill.

The floor of the Grottoes is masked by clay and silt banks, locally reworked by modern trickling streams. One large tube is fully infilled. The Grottoes are highly decorated by deposits of calcite stalactites, stalagmites, and flowstones that appear to be actively growing. One example, a column, is 3.5 m in height, 1.0 m in girth, which is a considerable dimension for an alpine cave. There are many nests of the spherical pisolites termed "cave pearls" (Hill, 1976). There are abundant gypsum growths and efflorescences of rarer minerals, discussed by Harmon et al. (1983, this symposium). Seepage water is still flowing at many places here when we observe in April, the end of the winter season. It is the warmest place in the cave, + 3.6°C.

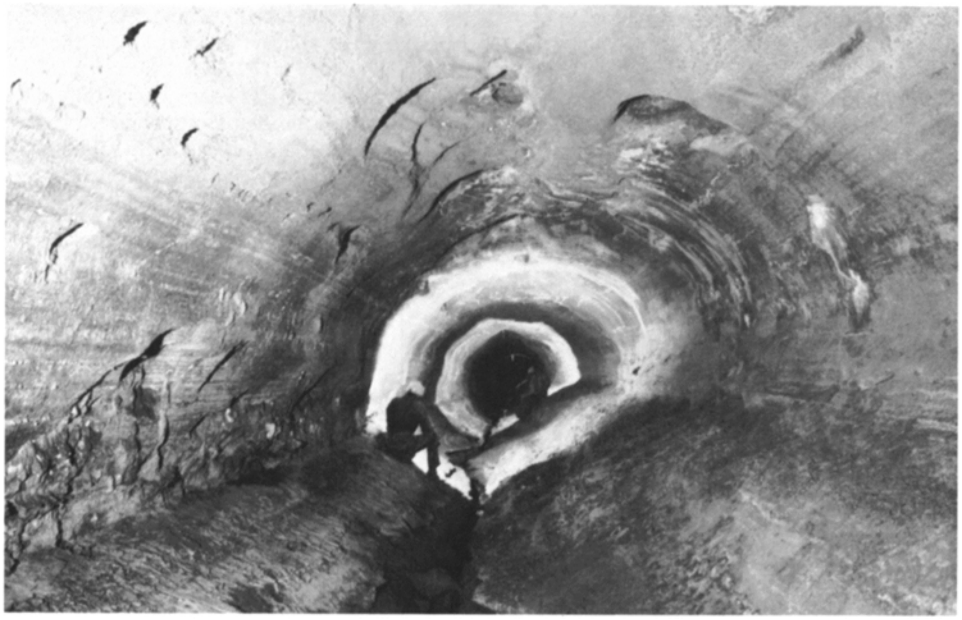

FIGURE 6. The Subway, an ideal example of a nearly circular, phreatic tube developed in a penetrable bedding plane. This passage is nearly straight and of constant dimensions for 500 m. Following its dewatering, a small invasion water stream carved the slot seen in the floor. Eroded banks of layered silts and clays are preserved to either side of it.

It is also the deepest, in the sense that thickness of bedrock cover is greatest, being 500 m.

From the south end of the Grottoes, the Subway–First Fissure sequence is repeated. Here, the large, phreatic tube component is Holes-in-the-Floor (see the frontispiece). Its form, dimension, and orientation are nearly identical to those of the Subway, but it has been modified by a larger invasion water entrenchment that is 8 m deep. The water comes from a series of invasion shafts, including A62 (Figure 9): it is known that these are active in summer. The invasion canyon descends south for 250 m (the Alley) where it drains to a waterfilled passage. Holes-in-the-Floor contains large deposits of layered silt and clay fill. These are sapped into the canyon.

Second Fissure is a vadose canyon comparable to First Fissure. At two places it criss-crosses sedimentary dikes, becoming more sinuous. The Big Room (Figure 3) is a large breakdown chamber at its junction with a fault. Eroded clay-silt deposits are common along the canyon. Deposits of calcite become progressively smaller and fewer, but the remarkable cubical cave pearls were found just above the Big Room (Roberge and Caron, 1983, this symposium). Gypsum and the other efflorescent minerals disappear.

The frequency of invasion shafts intersecting the cave increases as the Second Fissure is ascended (i.e., as it passes out from beneath the deep rock cover of Castleguard Mountain). A summer exploration was made here by J. M. Boon and P. Thompson in 1967. They reported considerable waterfalls in all shafts. These are dry or merely dripping during our winter explorations.

At the Crutch, ca. 8.0 km from the cave entrance, the Fissure divides into two narrower, tributary canyons. The northern one, Thompson's Terror, is rendered very dangerous by wedged breakdown. Its exploration was abandoned after 800 m. The winter draft blowing up the cave follows the southern canyon, which is again decayed by breakdown of the walls. After 700 m

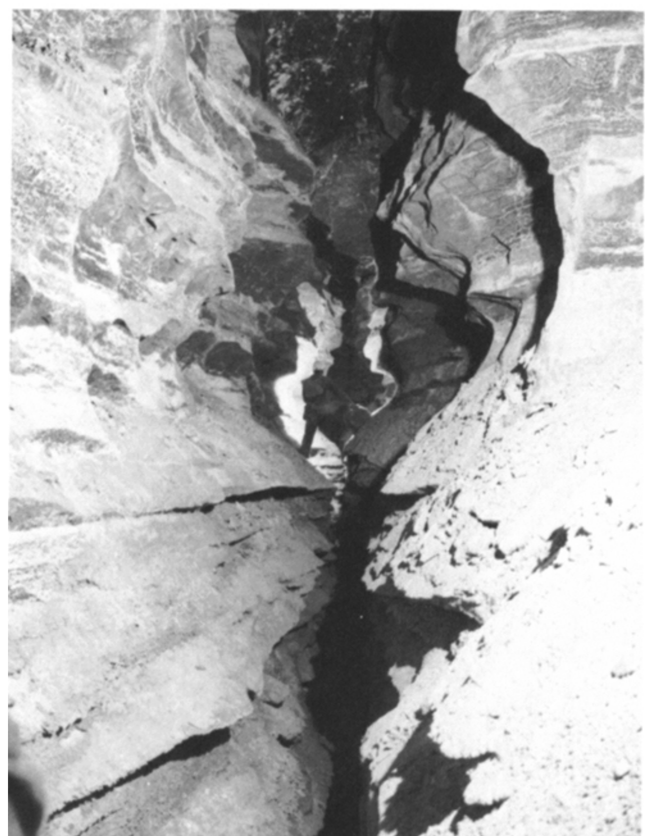

FIGURE 7. A typical scene in the First Fissure. This is a drawdown vadose canyon entrenched below an initial phreatic passage. Phreatic form is seen in the ceiling. The canyon is 10 to 15 m in depth and 2 km in length.

it ends abruptly at an 8-m cliff; this is a classical knickpoint at the canyon head.

The Headward Complex has been visited by few persons; there is comparatively little observation although all explored passages are accurately mapped, and sediment, speleothem, and ice samples have been taken.

Above the knickpoint the passage is a well-formed but low phreatic ellipse. There are angular blocks on the floor, but the roof is unbroken. Tributary passages enter that are blocked with clastic fills. Invasion shafts intersect the old cave and are drained by young pits in the floor. At 800 m the passage terminates at a blank wall of ice (Figure 10).

The ice blockage is coarsely crystalline and apparently supporting limestone blocks transported in its base. It is slightly ablated at the edges but evidently functions as a watertight, airtight seal. It did not change in appearance or position during the period 1972 to 1980. Oxygen isotopic composition is identical to that of glacier ice taken at 2500 m a.s.l. on the southwest Castleguard Glacier. We interpret the feature as an injec-

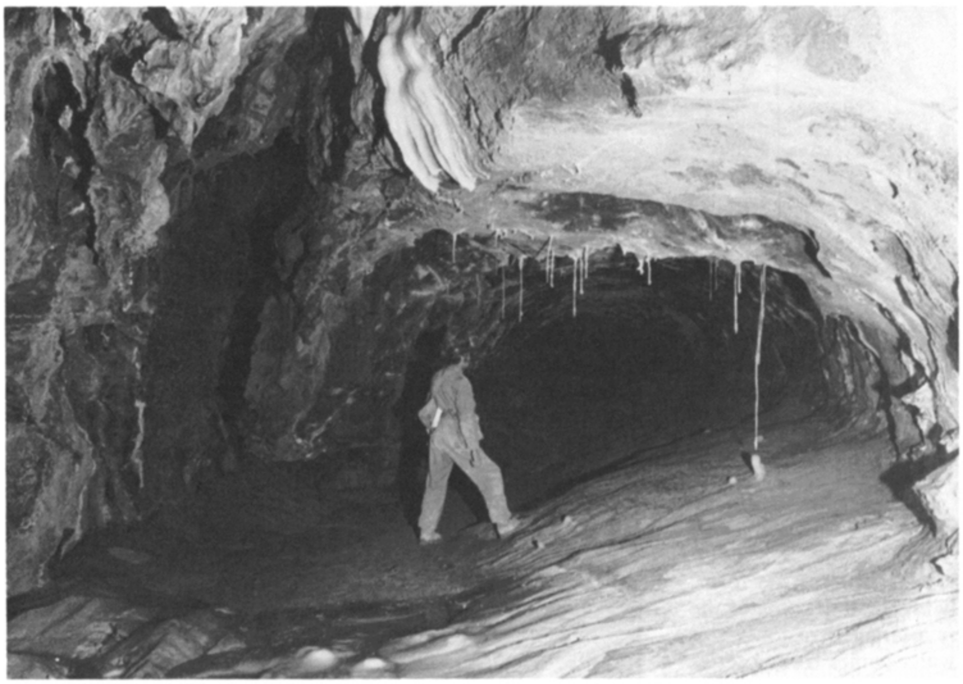

FIGURE 8. A scene in the Grottoes, the central phreatic part of Castleguard Cave. An asymmetric cross section where the passage follows a sedimentary dike. The dike rock and deep solutional pocketing is seen to the left.

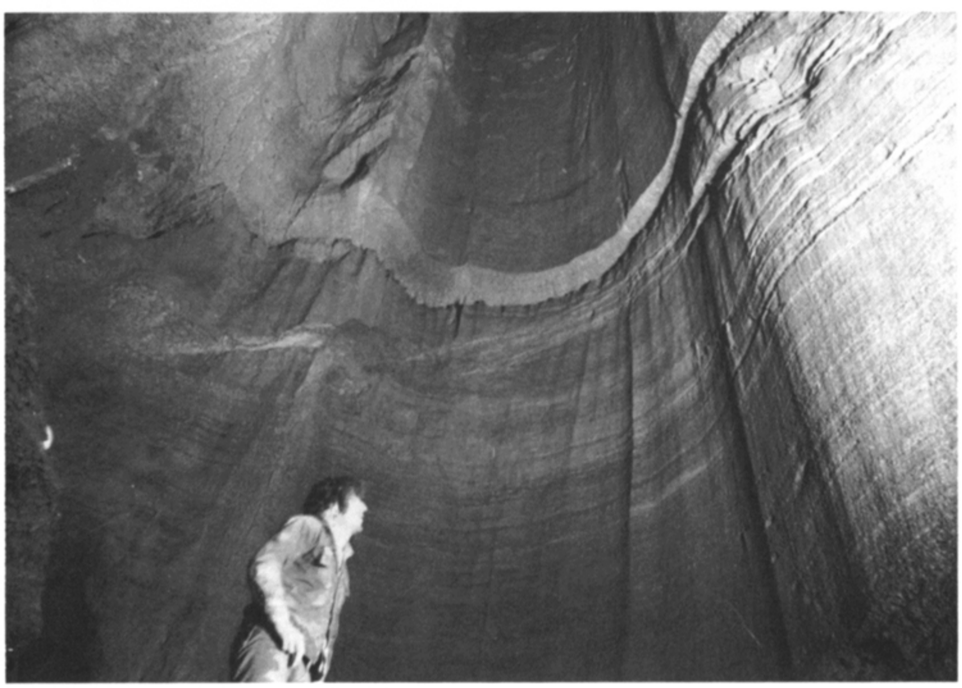

FIGURE 9. Looking up the A62 invasion water shaft in the center of the cave. This shaft was formed by vadose waters falling down it. It is seen here during the winter dry season. Its height was plumbed to 62 m with a captive hydrogen balloon.

FIGURE 10. Dr. Peter Thompson at the glacier ice plug in the headward complex of Castleguard Cave. The ice is coarsely crystalline and appears to be supporting blocks of limestone at its base. It was stable in position during the observing period, 1970 to 1980.

tion of basal glacier ice. It is at 2305 ± 10 m a.s.l.; the surface of the central icefield directly overhead is at 2590 m. The length of this remarkable plastic injection into a cave is unknown. The first small stalactites are seen growing in the roof within 150 m of the ice blockage, indicating summer seepage flow in rock warmed a little above the freezing point. Larger stalagmites and flowstones occur on and in clastic deposits farther down the passage.

A traverse across the top of a 25-m invasion pit near the knickpoint leads to the remainder of the Headward Complex. The winter draft from the cave entrance flows into it. The principal element is a large sinuous gallery, Boulevard de Quebec, oriented close to the strike but descending gently in a southerly direction. It is a fine example of a composite passage (Figure 11). Both ends are infilled, and it is probable that the entire passage was choked at one stage but has been partially reexcavated by invasion waters from new sources. Two sinuous phreatic tubes may be followed for several hundred meters southeast of the Boulevard (i.e., down the stratal dip). They are also progressively infilled. To the west is a complex of smaller inlet passages of phreatic form with vadose entrenchments, the Ontario Crawls. One large breakdown chamber is intersected here; it is reported to be roofed in orange dolomite, so it is possible that at its extremity the cave is developed in basal Stephen strata. Because the Stephen Formation is more susceptible to glacial erosion than the massive Cathedral rocks, it is surprising to find it surviving here, well downstream in the flowpath of the central icefield and, as the injected ice implies, very close to the glacier base. It is entirely possible that at this point the explorers are standing inside a roche moutonnée that is "live," so to speak! The winter draft finally disperses into the inlets in the area, which become impassably small.

There is abundant evidence of invasion water action. In a first phase, water from overhead shafts locally cleared earlier sediments and entrenched bedrock floors before draining into early pits located to the east (downdip). Now, a later generation of pits has developed closer to the inlet shafts. Many of

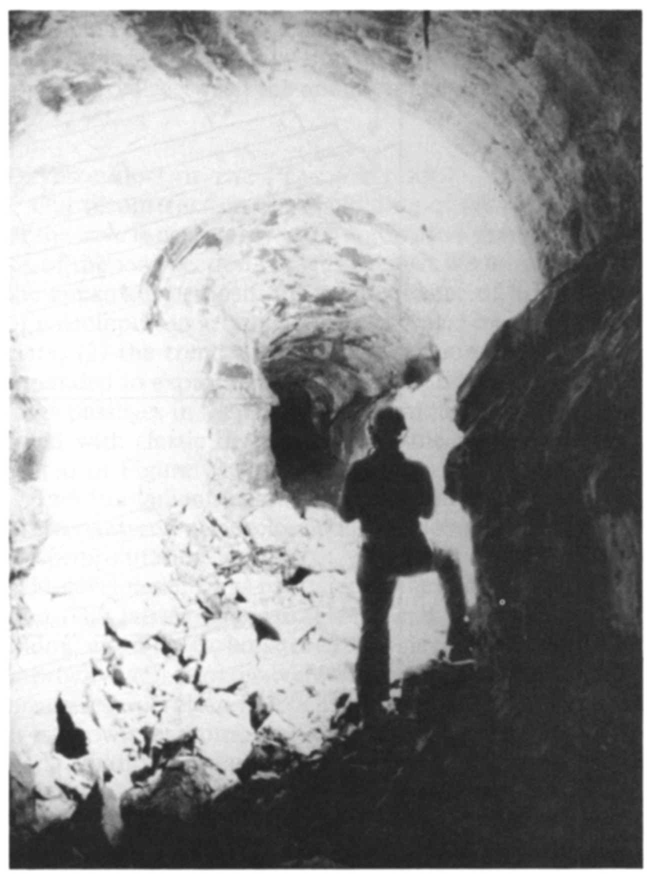

FIGURE 11. Boulevard de Quebec, the principal passage in the headward complex. It is a fine example of composite development, with upper phreatic and lower vadose elements. Note the platy spalling of portions of the trench walls.

these are believed to carry considerable volumes of water in summer, and small flows survive at the end of winter. Eight principal pits have been descended; all become impassably small or obstructed by debris at depths ranging 15 to 130 m. There is little flow now in the relict cave, and effective reexcavation of paleofillings has ceased. Small, fresh stalactites and flowstone sheets occur everywhere in the relict passages, although they are by no means as abundant as in the central cave. Their presence indicates that seepage infiltration and calcite deposition is occurring beneath the deep ice. There is no deposition in the modern invasion channels; these are supplied by acidic water.

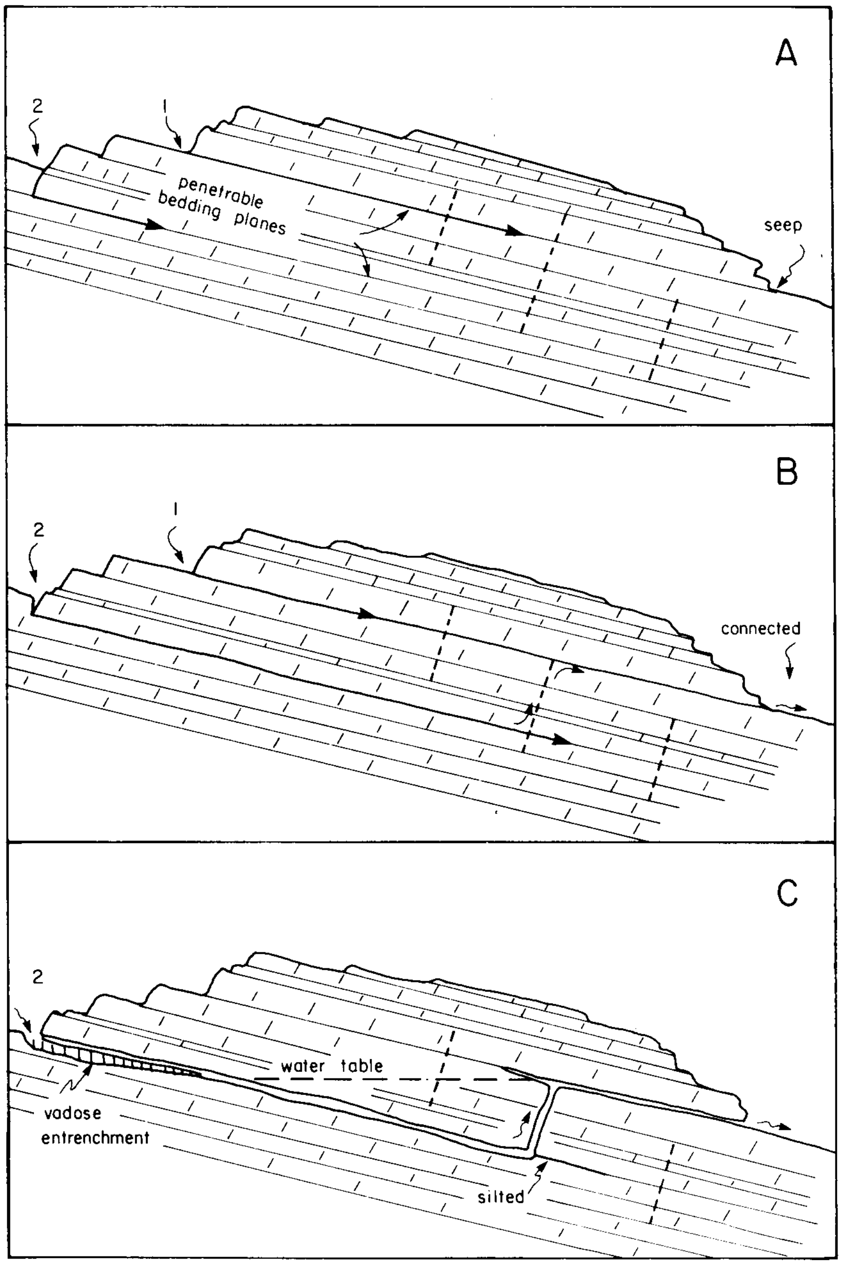

FIGURE 12. Development of ascending water connections ("phreatic lifts") between protopassages propagating in different situations. Dashed lines represent major joints or small faults. A: Protopassages 1 and 2 have extended to tips of large arrows. B: Protopassage 1 has extended to the outlet position. It is now continuous between sinkpoint and spring point. Protopassage 2 (with potentially larger discharge) is not yet continuous and begins to pass water to passage 1 via a common fracture. C: The situation fully developed and stable.

Development of the Cave in the Dimensions of Length and Depth

Explanation of the origin and development of most of Castleguard Cave in its long section is straightforward. The cave below the head of Second Fissure is a rather regular alternation of deep phreatic and drawdown vadose passage approximating the State 2 hypothetical system drawn in Figure 1. Phreatic tubes extending down the dip of penetrable bedding planes were drained and entrenched in their higher or upstream parts during the drawdown reservoir expansion phase (Figure 1B); the lower parts were expanded into the great tunnels such as the Subway. The individual tubes are linked by shorter, fracture-guided sections such as P24 or the Grottoes, up which water flowed under hydrostatic pressure.

Development of this pattern of ascending water connections ("phreatic lifts") between dip tubes constrained in different bedding planes is illustrated for a hypothetical case in Figure 12. A small, first input (No. 1) propagates an initial tube through a penetrable bedding plane (as in Figure 2A). When it has established continuous connection to an outlet point (Figure 12B), a second, potentially larger, input tube (No. 2) propagating below it links up via a common fracture. Following solutional enlargement, a stable watertable is established (Figure 12C). Input No. 1 remains inexplorably small upstream of the link point.

The model is applied to Castleguard Cave in Figure 13. This is schematic, with considerable vertical exaggeration. The basic structure of bedding plane dip tubes appears in Figure 13A; only four to six planes are utilized in the >80 m of the stratigraphic section of the upper Cathedral rocks that the cave traverses. The remainder were impenetrable. Potential connection (lifting) fractures are identified at P8, P24, and the sedimentary dike at the Grottoes. Note that the explorable tubes pass through other fractures that were larger and more penetrable than these, e.g., at the Eroded Boss and Big Room; these were not exploited because they did not connect to efficient tubes in higher planes.

In Figure 13B the system is fully integrated between a principal input at the head of Second Fissure and an outlet at the Entrance, and an early passage has been expanded along this line to cross-sectional dimensions of, perhaps, 2 × 1 m. At this stage it remains fully phreatic, and precisely corresponds to the State 2 general model in Figure 1A. Integration has been effected via vertical phreatic lifts at P8 and P24, and a gentle ascent on the strike of the sedimentary dike.

Figure 13C shows the system fully developed. Watertable elevations are fixed by the tops of the phreatic lifts and a spring at the modern entrance, and there is drawdown vadose entrenchment in the tube segments that have been drained.

The input river from Second Fissure that created this great cave rather abruptly disappeared, instead of abandoning it piecemeal in a series of headward steps as is common. Figure 13D identifies major features of the modern relict cave. The river first vacated it via a sinkpoint in the canyon floor of Second Fissure. The sinkpoint is now clogged with debris. Probably, it offered connection to a lower dip tube linked to lower, evolving springs. Before the canyon upstream could be entrenched more than a very few meters to this new sinkpoint, the river was lost to the system altogether. One phreatic lift remained in operation, and continues to this day sporadically. This is the Boon's Blunder flooded shaft in the Entrance Complex. It is possibly a later addition, but appears to be an essential component of the original cave, as explained in the last part of this paper. It survives as a phreatic lift in that part of the system where the hydraulic gradient is steepest, i.e., where it should be most readily drained. This peculiarity is considered in C. C. Smart's (1983, this symposium) discussion of the modern hydrology.

Following the abandonment, portions of the central cave were invaded by waters now able to leak down through the Stephen-Eldon-Pika caprock formations. Two prominent invasions, Eroded Boss and A62, are shown in Figure 13D. The paper by Gascoyne et al. (1983, this symposium) will show that there was probably a very long interval between the abandonment and these invasions.

Development of the Plan Pattern

Our reconstruction of the building of the plan pattern of the cave is necessarily more speculative than the analysis of the long section. This is because we must infer (1) the approximate positions and sequence of appearance of paleoinputs in ground that is concealed by modern glaciers, (2) the trend of genetically important tubes not expanded to explorable dimensions, and (3) the roles of large passages in the Headward Complex that were later filled with clastic detritus. A possible sequence is presented in Figure 14.

Two fundamental assumptions are made: (1) that the preferred trend of development was down the stratal dip to springs in the Castleguard Valley and (2) that significant development was restricted to the Cathedral Formation. This latter point is problematic: it casts the Stephen, Eldon, and Pike carbonates in the role of an impenetrable caprock that is progressively stripped by surficial erosion processes operating independently of the karst genesis. It is known that almost all of this caprock is drained via karst sinkholes today; groundwaters penetrate its entire stratigraphic sequence beneath the southwest Castleguard Glacier. However, these drains appear to be late-stage invasion features such as are found in the cave and are not judged to have been significant at the time of development of the paleosystem. It appears, therefore, that cave genesis began at a given site when the Stephen Formation was reduced to a basal 30 m or so, there.

Each figure in the sequence 14A-D is drawn to show the appearance of significant new elements in the evolving system. It must not be supposed that the time intervals separating each illustrated step are equal, or that they indicate approximately equal volumes of erosion, etc.

The sequence begins with removal of the caprock at the southern end of what is now the line of ice flow down the central icefield. This permitted a simple downdip cave to develop in the southwest. This is a hypothetical system that does not survive today. Figure 14A shows two developments: initiation of new caves from sinks extending headwards or to the north as the cap receded, and their lateral integration via a strike conduit, to the previous cave. This stresses that normal cave patterns are built up by headward steps and lateral connections from pre-existing systems; successive inputs tend *not* to generate completely new protocaves to new spring positions (Figure 2B, C). The integrating conduit in Figure 14A is Boulevard de Quebec. The headward extensions are the Ontario Crawls.

Figure 14B violates the general rule of integration that has just been stated. For some reason, conditions changed

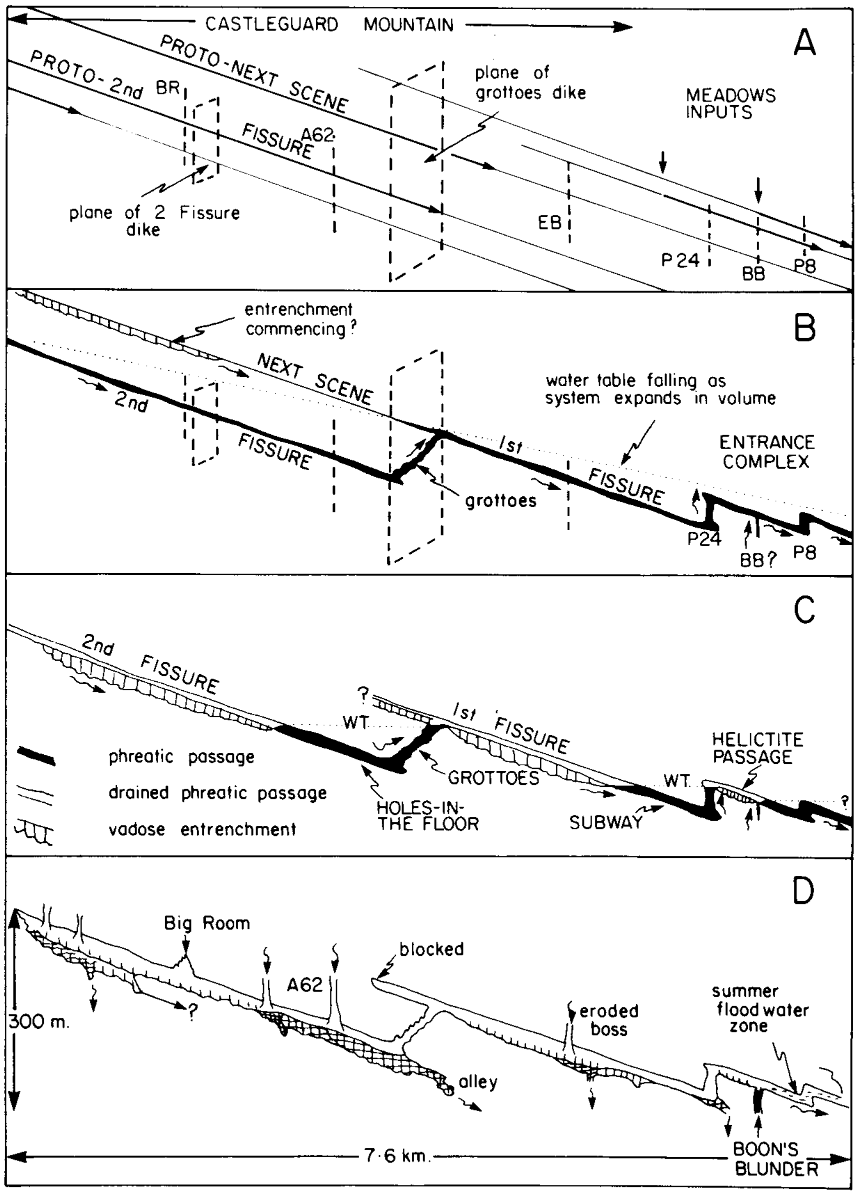

FIGURE 13. Schematic illustration of the sequence of development of the central cave and downstream complex in the dimensions of length and depth. Drawing is not to true scale and contains considerable vertical exaggeration. In 13A, solid inclined lines represent penetrable bedding planes in the upper Cathedral limestone. Dashed lines are prominent fracture planes. BR = Big Room fracture. EB = Eroded Boss. BB = Boon's Blunder.

drastically in the Headward area, such that the next two caprock recession inputs *did* generate new protocaves which passed through the Castleguard Mountain massif rather than connecting to the southwest as Boulevard de Quebec had done. Stripping in the southern Meadows had progressed sufficiently far at approximately the same time to permit early, short, sub-Meadows caves to develop. These functioned as "targets." Proto-First Fissure connected with them via the phreatic lift at P24.

We hypothesize that the effect that compelled these new conduits to pass through the massif was an infilling of the hypothetical old cave by glacial injecta that sealed off drainage to the original springs. The old cave was at shallow depth in the Cathedral Formation and the earliest

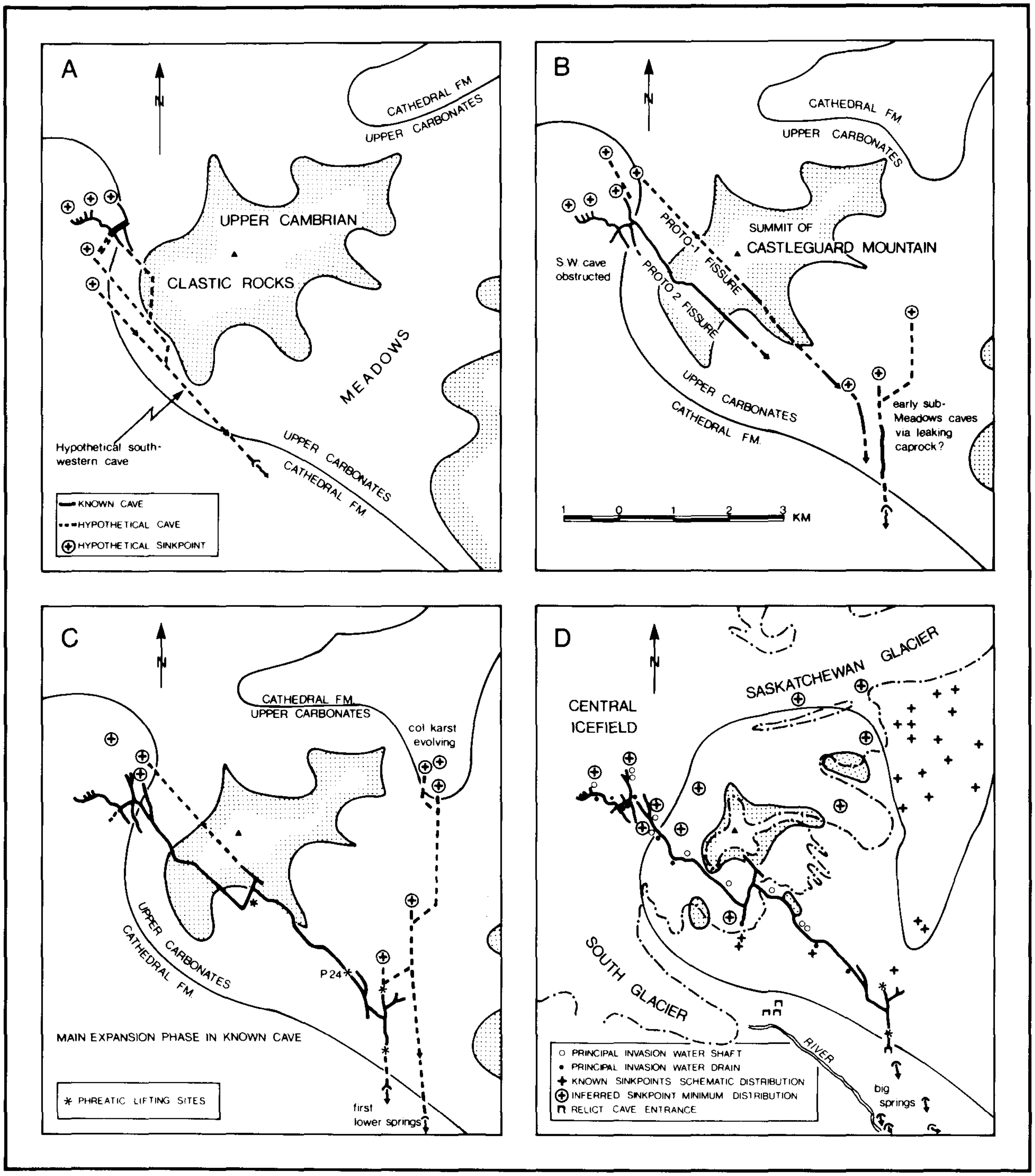

FIGURE 14. Schematic illustration of the sequence of development of Castleguard Cave in plan view.

parts of it may have been unroofed by glacial action. Capping strata were still close and would furnish the necessary sealing debris; they are now far removed from this locality and the ice base is probably particularly clean there. Although it is not of an explicit kind, we take this as the earliest good evidence of significant glacial action in the karst. Its antiquity will be suggested by Gascoyne et al. (1983, this symposium).

Figure 14C shows the cave during its principal period of enlargement. Obstructions of the old, southwest cave ensured that all sinking waters in the central icefield area were supplied to it. It is supposed (for reasons given below) that there was also a substantial extension northwards of the quasi-independent sub-Meadows system; nevertheless, it was extending more slowly than the cave because it did not possess the favorable downdip orientation. At the downstream extremities, the first springs lower in the Cathedral Formation perhaps appeared in primitive form at this stage, as a consequence of deepening of the Castleguard Valley.

The modern system is shown in Figure 14D. The principal morphological changes in the paleocave are clastic infillings, particularly in the Headward area, and the penetration of invasion waters through the carbonate caprock, karstifying it. Known sinks and other subglacial ones for which there is evidence are shown. It is inferred that the many invasion pits in the Headward area and others like them to the north and west of it drain to the Big Springs, so comprising the Castleguard II system. Small, relict outlet caves known in the Neoglacial area of South Glacier probably developed to drain the western cave during its abandonment and early invasion water stages.

It is surprising that the central cave received no important tributaries from the extensive massif to the north of it. We suppose that this was because the sub-Meadows system (Castleguard III of Ford, 1971b) was able to extend far into the north flank of Castleguard Mountain to intercept them, as shown in 14C. It is known that it now extends to the base of the upper Saskatchewan Glacier (C. C. Smart, 1983, this symposium).

SUMMARY AND CONCLUSIONS

Castleguard Cave has developed in the upper member of the Cathedral Formation. Overlying carbonates functioned as a caprock; the cave extended as this was progressively stripped. Most of the cave is a State 2 system in Ford and Ewers's model (1978), being a regular alternation of drawdown vadose entrenchments and phreatic loops, utilizing four principal bedding planes. Magnitude of the passages is substantial, implying a duration of at least tens of thousands of years for the main phase of expansion. The system is believed to have derived headwaters from an older cave that had been obstructed by glacial action; thus, it does not antedate glaciation in this region. It was abruptly abandoned, and channels only local invasion waters today. Morphological evidence in the cave clearly indicates that there is a younger, hydrologically active system in the main member of the Cathedral Formation beneath it. The overlying carbonate caprock is now fully karstified as well, although at a lesser scale. Glacial action in this alpine glacier source region has therefore proceeded in tandem with considerable karst development.

REFERENCES CITED

Bögli, A., 1971: Corrosion by mixing of karst waters. *Cave Research Group of Great Britain, Transactions,* 13(2): 109–114.

Davis, W. M., 1930: Origin of limestone caves. *Geological Society of America Bulletin,* 41: 475–628.

Ewers, R. O., 1982: Cavern development in the dimensions of length and breadth. Ph.D. dissertation, McMaster University. 398 pp.

Ford, D. C., 1971a: Geologic structures and a new explanation of limestone cavern genesis. *Cave Research Group of Great Britain, Transactions,* 13(2): 81–94.

———, 1971b: Alpine karst in the Mount Castleguard–Columbia Icefield area, Canadian Rocky Mountains. *Arctic and Alpine Research,* 13: 239–252.

———, 1983: The physiography of the Castleguard karst and Columbia Icefields area, Alberta, Canada. *Arctic and Alpine Research,* 15: 427–436.

Ford, D. C. and Ewers, R. O., 1978: The development of limestone cave systems in the dimensions of length and depth. *Canadian Journal of Earth Sciences,* 15: 1783–1798.

Gascoyne, M., Latham, A. G., Harmon, R. S., and Ford, D. C., 1983: The antiquity of Castleguard Cave, Columbia Icefields, Alberta, Canada. *Arctic and Alpine Research,* 15: 463–470.

Harmon, R. S., Atkinson, T. C., and Atkinson, J. L., 1983: The mineralogy of Castleguard Cave, Columbia Icefields, Alberta, Canada. *Arctic and Alpine Research,* 15: 503–516.

Hill, C. A., 1976: *Cave Minerals.* Huntsville, Ala.: National Speleological Society. 137 pp.

Martèl, E. A., 1921: *Nouveau traité des eaux souterraines.* Paris: Editions Doin. 840 pp.

Rhoades, R. and Sinacori, N. M., 1941: Patterns of groundwater flow and solution. *Journal of Geology,* 49: 785–794.

Roberge, J. and Caron, D., 1983: The occurrence of an unusual type of pisolites: the cubic cave pearls of Castleguard Cave, Columbia Icefields, Alberta, Canada. *Arctic and Alpine Research,* 15: 517–522.

Schroeder, J. and Ford, D. C., 1983: Clastic sediments in Castleguard Cave, Columbia Icefields, Alberta, Canada. *Arctic and Alpine Research,* 15: 451–461.

Smart, C. C., 1983: The hydrology of the Castleguard karst, Columbia Icefields, Alberta, Canada. *Arctic and Alpine Research,* 15: 471–486.

Swinnerton, A. C., 1932: Origin of limestone caverns. *Geological Society of America Bulletin,* 43: 662–693.