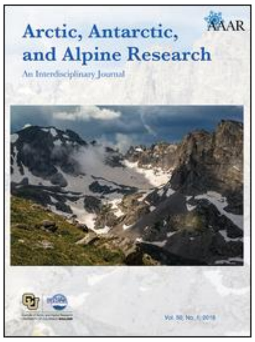

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CLASTIC SEDIMENTS IN CASTLEGUARD CAVE, COLUMBIA ICEFIELDS, ALBERTA, CANADA*

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ABSTRACT

Castleguard Cave contains a variety of clastic sediments of both allochthonous and autochthonous origin. The head of the cave, lying beneath the Columbia Icefield, displays breakdown and glaciofluvial injecta that are ancient. Principal deposits in the central cave are the eroded remains of at least three phases of silt filling. These are interpreted as varved sequences deposited under full glacial conditions. They are older than 140,000 BP. A channel abandonment facies occupies the inner part of the downstream entrance complex. The outer part is prone to flooding today and contains a remarkable shingle beach formed in situ where floodwaters must rise vertically.

CLASTIC DEPOSITS IN CAVES

Caves may function as giant sediment traps, preserving evidences of past erosional, floral, etc., phases of a region long after these have been destroyed at the surface. Cave sedimentary deposits include organic materials, chemical precipitates, and clastic sediments; often, there are complex sequences containing all three kinds. It is convenient to differentiate between entrance deposits and those of cave interiors; the former tend to be more complex because of dripline and colluvial effects, colonization by external flora and fauna, etc. They have been the subject of much detailed investigation and classification because of their archaeological importance (e.g., Laville, 1975). Distinctive entrance facies are absent at Castleguard Cave because the annual floods sweep the entry clean.

Interior clastic deposits are the subject of this paper. Renault (1968), Jennings (1971), and Gèze (1973) have provided general classifications and discussion. Three principal categories are recognized: (1) breakdown deposits, which are autochthonous; (2) weathering earths, autochthonous with an allochthonous eolian component in many instances, and (3) fluviatile, which may be of entirely autochthonous or allochthonous origin but are commonly admixtures of both. To these may be added the categories of morainic and fluvioglacial deposits in caves of glaciated regions.

In Castleguard Cave the deposits have been studied between the Ice Blockage and the cave entrance. Sites where sedimentary sections have been measured and photographed are indicated in Figure 1. Samples were taken at a selection of these sites for analysis in the laboratory. Unfortunately, the Boulevard de Quebec-Ontario Crawls sections of the Headward Complex (believed to be the oldest parts) have not been investigated. Explorers' and surveyors' observations (summarized by Ford et al.,

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*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.

1983, this symposium) suggest that the deposits there are complex and interesting, but we do not attempt to treat them here.

The most significant deposits are waterlaid, by flows originating in the Headward Complex. Accordingly, description and interpretation follows them from the head of the cave.

THE HEADWARD COMPLEX

In the passage between the Ice Blockage and the Crutch, the oldest surviving deposit appears to be an injection of subrounded limestone cobbles (*a* axis ≤ 30 cm). It is site A of Figure 1, and illustrated in Figure 2. The deposit is preserved as a veneer on passage walls close to the ice. It is 1 m or more above the present floor. The clasts are blackened by weathering or a manganese precipitate (a common feature in caves) and firmly cemented in place by secondary calcite. Some clasts preserve chattermarking, suggesting a subglacial origin. The deposit is interpreted as a first infilling that was later entrenched and largely cleared by vadose drainage towards the Crutch. Reworked clasts are found scattered among later debris, reducing in abundance as the Crutch is approached. P. L. Smart (pers. comm., 1980) noted a second blackened and cemented deposit emplaced in the entrenchment below the veneer at one place.

The principal deposit in this section is of breakdown blocks from local walls and portions of the roof. They occupy the entrenchment in the older deposits, and are not notably weathered or cemented by calcite. Sizes range up to 1 m in length. They conceal much of the bedrock floor and are often stacked in layers or piles. It was noted near the ice that basal blocks, which may be wetted by

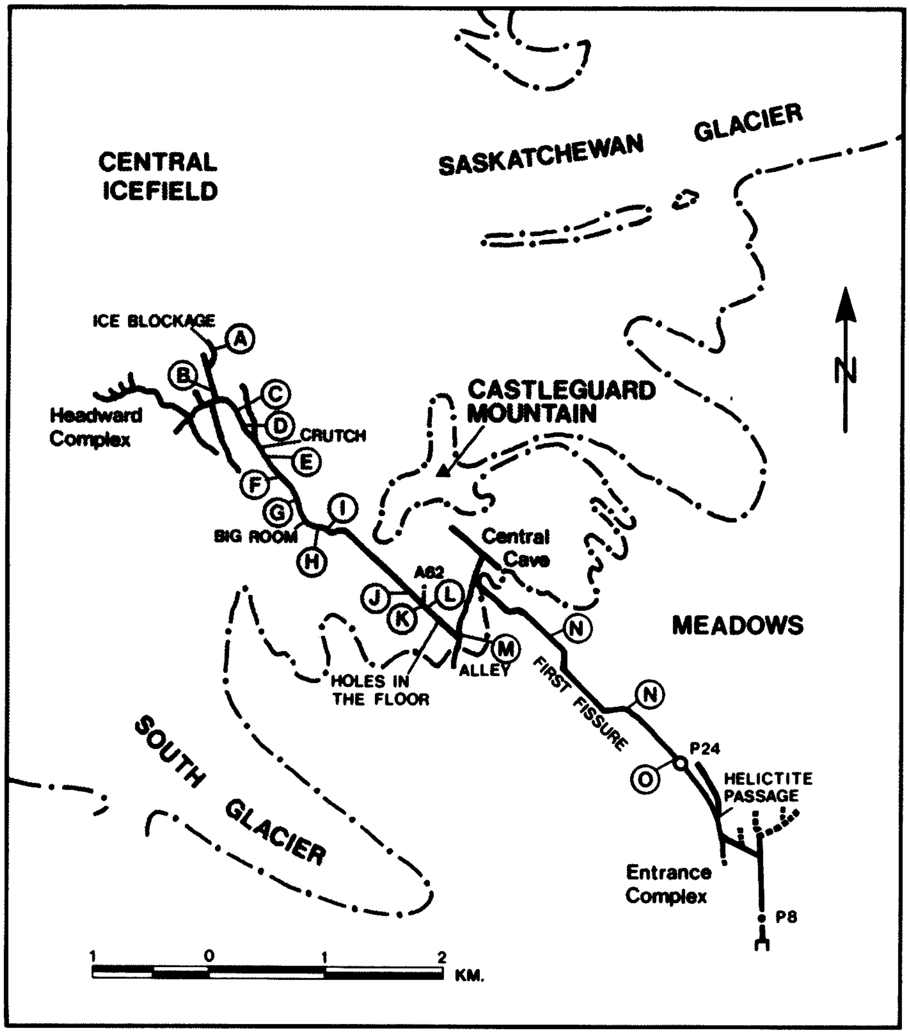

FIGURE 1. Plan of Castleguard Cave, showing the locations of sediment sampling sites dicussed in the text. Geographical coordinates of the summit of Castleguard Mountain are 52°06′30″N, 117°15′10″W.

TABLE 1
Sedimentary sequence of the Headwater Complex

Phase	Sedimentary sequence
7	Erosion by invasion waters; local calcite deposition; local breakdown continues today
6	Deposition of varve-like silt deposits
5	Principal breakdown phase
4	Weathering and calcite cementation
3	Erosion, and some redeposition, of fill by stream action
2	Cobble infilling; suspected subglacial origin
	Unknown interval
1	Origin of the cave, by aqueous solution

drainage from the ice blockage or overspill from invasion shafts, were frequently shattered into decimeter-sized pieces. This suggests possible frost action.

Five hundred meters from the ice blockages, but above the knickpoint that marks the head of Second Fissure (Ford et al., 1983, this symposium) the breakdown ceases. It is replaced by eroded deposits of varvelike silts, alternating grey and beige or pale beige in color. These are the principal deposits of the central cave, described in detail below. At sites B and C it was noted that the silts overlay the re-deposited clasts of the early veneer. They completely infilled lateral galleries. P. L. Smart (pers. comm., 1980) informs us that similar layered silts, now partly cleared, are the principal deposits in Boulevard de Quebec.

Above the Crutch, the head of Second Fissure is a narrow canyon whose walls have partly collapsed, producing a fill of wedged blocks. These appear fresh and unstable (many have shifted beneath the explorers' weight) but from place to place, remains of the varved silts can be seen in situ on top of them (e.g., Site D, Figure 3). Erosion of the silts has been effected by local invasion waters.

In this part of the cave, invasion waters are introducing modern debris via the larger shafts. Piles of subrounded Eldon and Pika carbonate, Arctomys shale, and Upper Cambrian sandstone clasts occur at the shaft bases, in transit to the nearby pits which descend to the lower cave.

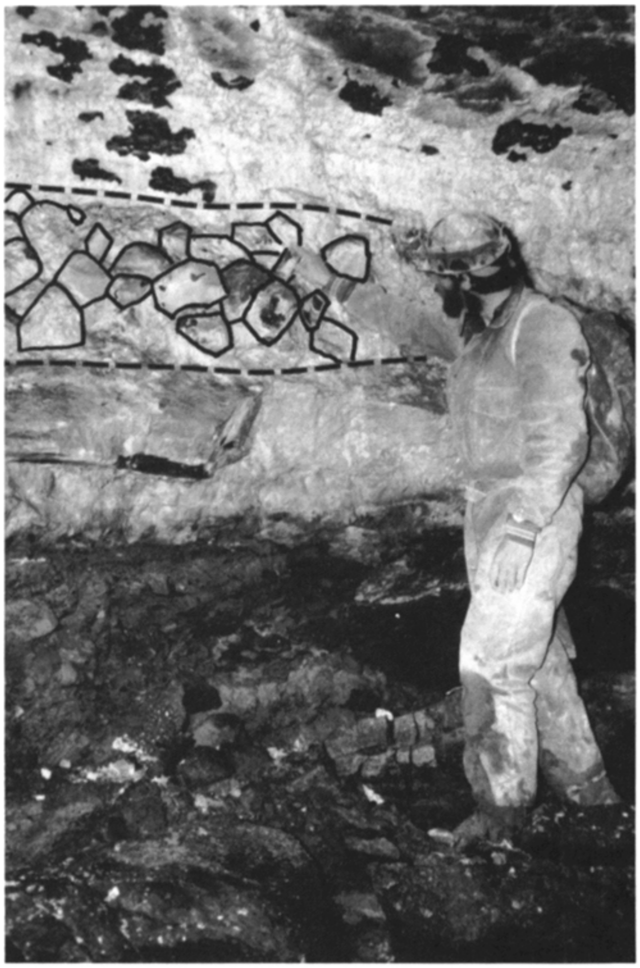

FIGURE 2. Site A, close to the glacier ice blockage at the head of the cave. A veneer of blackened clasts is cemented to the wall by secondary calcite. Some clasts are chattermarked. Breakdown debris on the floor are a later deposit.

The clastic sedimentary sequence of the Headward Complex, so far as it is understood, is summarized in Table 1. It must not be supposed that the identified phases directly succeeded one another in every case, because intervening evidences may be missing.

THE CENTRAL CAVE

The principal sediments are two or more sequences of the varve-like silts with local basal gravels. There are also locally reworked deposits of little significance. It appears that the silts once extended continuously between site B and P24. They are now much eroded by invasion water action and removed entirely in some localities. Seven sites (stratigraphic sections) exposed by erosion were studied in detail and are illustrated in Figure 3. Photographs of two examples appear in Figure 4. Fourteen representative grab samples were taken for laboratory analysis. An attempt to take columnar cores for sedimentologic and magnetic analysis failed because the cores collapsed during transport out of the cave; the material is thixotropic.

COMPOSITION OF THE SILTS

Grain-size and other analyses show that the silts are alike at all sampled sites. There is a regular succession of gray and beige, or beige and pale beige, layers. Thick-

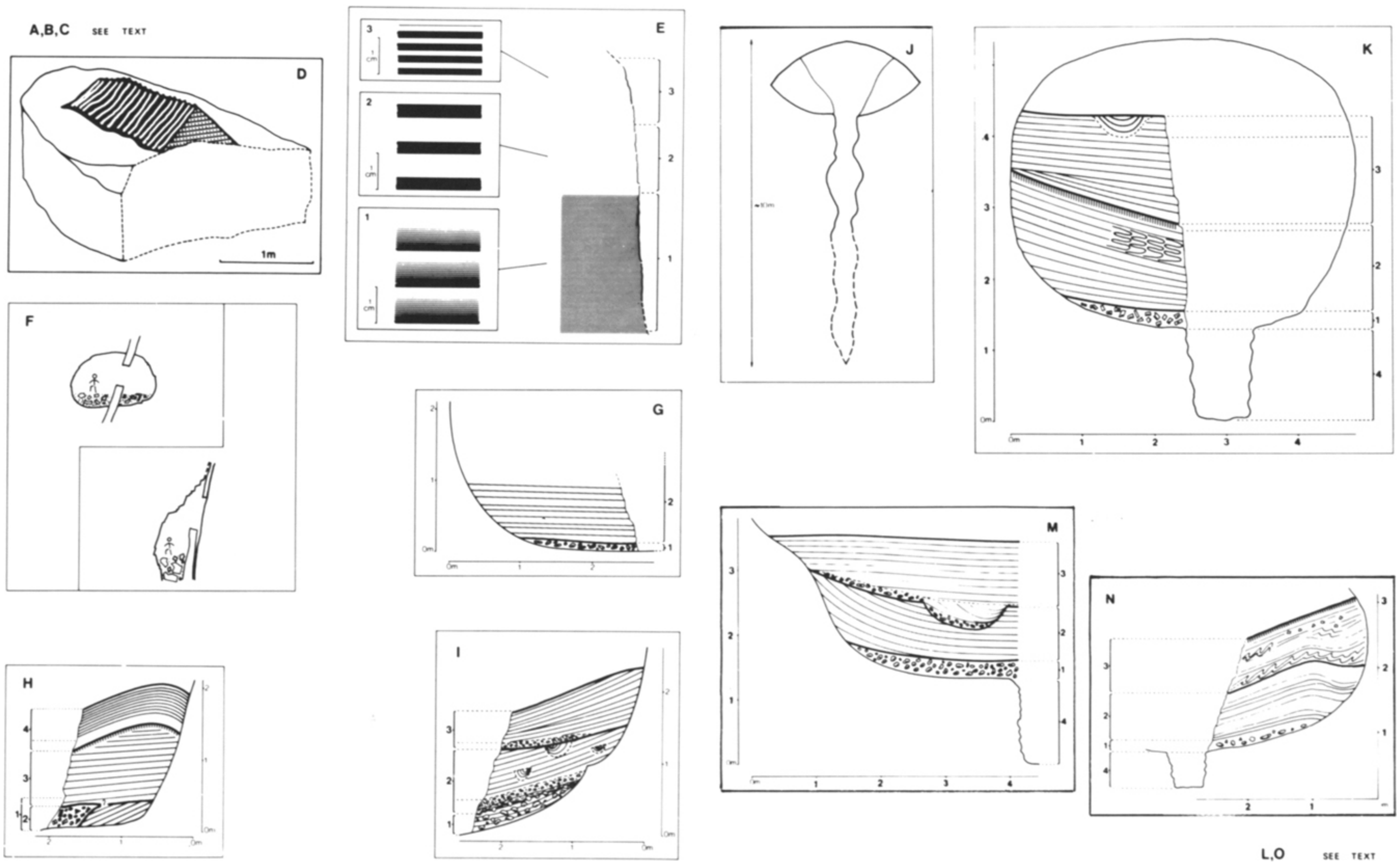

FIGURE 3. Sketch diagrams of selected sedimentary sections in the central cave. Code letters are keyed to the text and Figure 1.

ness of individual layers ranges from ≤1 mm to ~15 cm in most instances. Of the constituent particles, 92 to 99% are <37 μm in size; while only 4 to 21% are <4 μm (i.e., clay). The envelope of the 14 grain size curves obtained in the size range, 4 to 8 ϕ, is given in Figure 5. The gray beds are the more purely silty in composition, the clay fraction ranging only 4 to 12%. The beige or pale beige layers, especially the thicker ones, are silt-clay mixtures containing up to 21% clay fraction.

Total carbonate was determined for the 10 to 37 μm fraction by calcimetry. The average carbonate content was 62%, with a range from 45 to 90%. X-ray diffractometry of the <10-μm fraction revealed 60 to 85% calcite, and no more than 5% dolomite. Illite was present in all samples, ranging 5 to 25%. Other minerals identified were chlorite (3 to 15%), and traces of quartz and expandable clays.

The grainsize distribution strongly suggests that these are deposits of glacial flour, while the predominance of carbonates implies that they were not introduced into the cave until the clastic Upper Cambrian caprocks had been stripped back far from the Headward Complex.

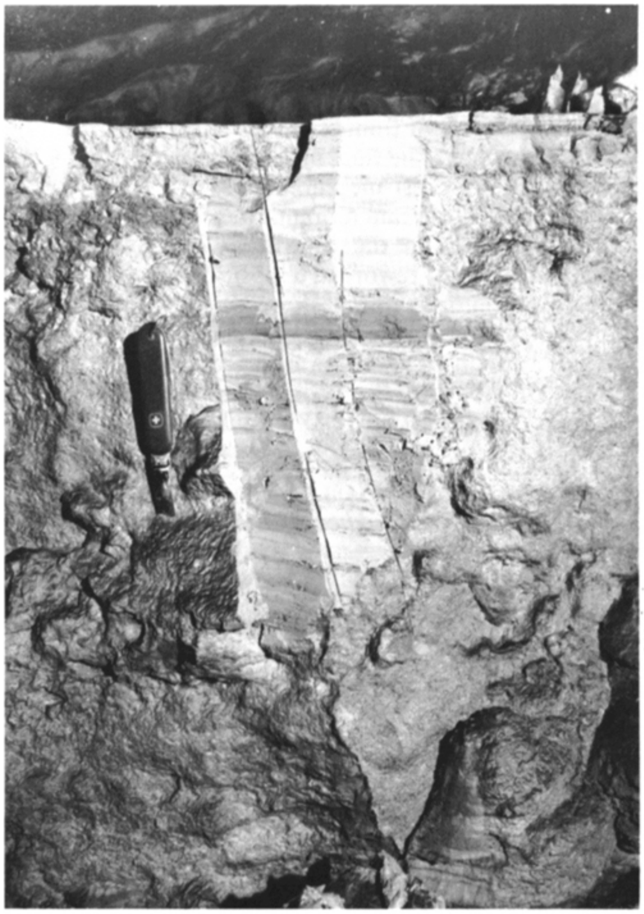

FIGURE 4. An example of the varved silt fillings that predominate in the central cave, at site N′, First Fissure.

The sample sections. Section E (Figure 1) rests in the main vadose entrenchment close to the head of Second Fissure. The deposit was approximately 1 m in depth, the lower 50 cm being well exposed. This lower part is shown in Figure 3. The basal 25 cm comprises silt layers ca. 1 cm thick. Each layer is gray at the base, becoming beige (clay-rich) towards the top, i.e., the sequence is a succession of fining upwards units. The central 20 cm shows more distinctly differentiated gray beds (±3 mm), each over-

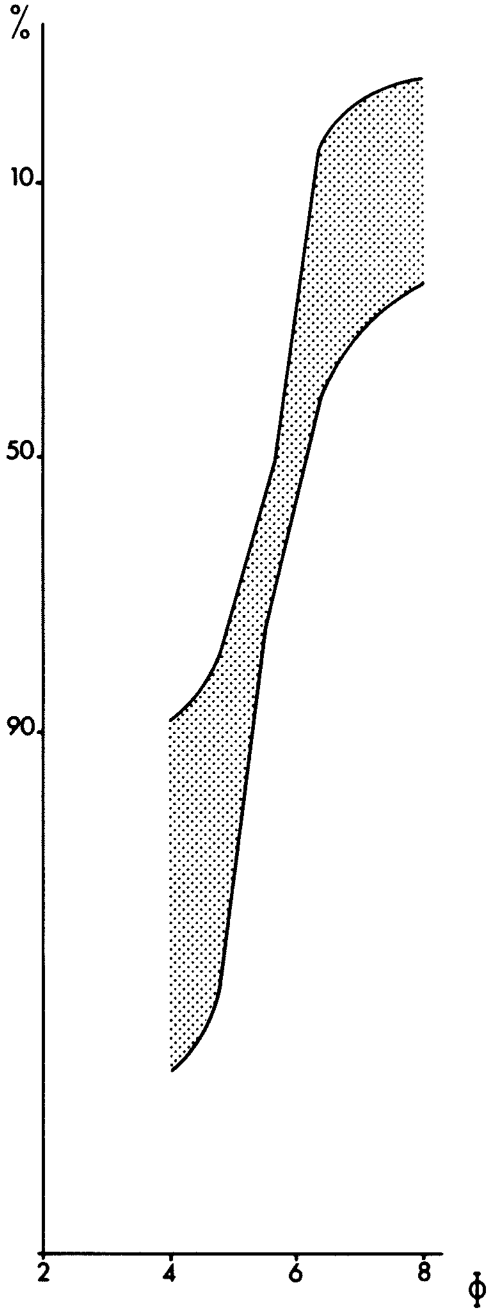

FIGURE 5. Envelope containing the 14 grain-size distribution curves obtained for varved silt samples in the central cave.

lain by a beige bed of ±7 mm. The top of the section displayed the same gray and beige alternation but the individual beds were no more than 1 mm thick.

These characteristics, particularly the fining upwards that is well seen in the thicker basal beds, suggests that the deposits are true varves in the sedimentological sense. However, it is not certain that each gray-beige couplet represents one year's accumulation. Possibly, pulses of turbid water were injected into the cave more frequently than once per climatic year.

Site F is a place where the Second Fissure is breaching a sandstone sedimentary dike. Invasion waters have removed the silts. It can be seen that the sandstone is friable and readily breaks down to yield pebble-sized debris (Figure 3). Site G is located approximately 100 m downstream. At the base, on bedrock, it displayed a 15-cm bed of gray silt containing blackened pebbles of limestone and the sandstone, 1 to 5 cm in length. This was overlain by ca. 1 m of finely laminated beige silts. The top of the section was masked. Proceeding downstream, it was noted that there was a progressive thickening of the basal gray silt but with a decrease in its pebble content, especially of siliceous pebbles. This suggests that the latter derived from erosion of the dikes at Site F.

Between the Big Room and the Grottoes the sedimentary sections that were examined in detail at sites H, I, J, and M all display the same basic sequence, which is of three distinct phases of deposition separated by quiescent periods when sedimentary surfaces became indurated. Facies vary a little between the different sites. At H the basal deposit is 40 cm of the gray silts, with a conglomerate of broken gray and beige silt plates that contains local limestone and siliceous clasts and broken stalactites in lateral contact. The top is indurated and overlain by more than 1 m of beige silts with a second indurated crust. A 15-cm bed of pale beige silt rests conformably upon this and is succeeded by a section of beige-pale beige couplets.

At site I the basal silt with pebbles is well varved and overlain by a thin stalagmitic floor that has suffered resolution. Pebbles, probably a reworking, rest on it and are succeeded by varved silts with small channel cut-and-fill features in them. A second silt with basal pebbles rests on top.

The deposits thicken progressively down Second Fissure and >5 m are preserved at places in Holes-in-the-Floor. Much of the thickening is to be attributed to an increasing number of individual pale beige beds, 10 to 15 cm thick, that are intercalated between typical sequences of thinner varves, such as are seen higher up the cave. The "holes" in the passage occur where the silts which once nearly filled it with a flat-floored deposit have been sapped into the underlying, deep entrenchment carved by invasion waters (site J, Figure 3). We have not established by site inspection whether the entrenchment predates the silt, but it appears necessary to suppose that at least part of it does because, otherwise, the invasion waters would have entrenched the silts throughout the length of the passage, instead of sapping them from place to place.

Sections K and M are very similar to section I, but deeper. Deposits of the second phase at K displayed some gravity plications and the indurated surface at their top was the thickest buried surface observed, 0.5 cm. It contained desiccation cracks. At site L, at the junction with the vadose drain from A62, a 2- to 3-m section showed only massive, pale beige silts. It was very wet due to its proximity to the great invasion water shaft: excessive wetting may explain the apparent lack of structure. At site M it was noted that the basal pebbles were all of limestone. It appears that siliceous pebbles from the sedimentary dikes in Second Fissure were not transported this far from their source, or that they were comminuted.

There has been little subsequent erosion by invasion waters in the Grottoes so that the silts are poorly exposed in section. Also, there is much masking by flowstone sheets. The final depositional surface is well preserved at one place, where it can be seen that the last waters to lay down silts withdrew via the Alley, the modern drain of invasion waters at the south end of the Grottoes.

Throughout First Fissure there are the same deep sequences of silts as found in Holes-in-the-Floor. They are much eroded but at two places the final depositional surface is preserved; it was plane and horizontal. A section at the head of the Subway (site N) displayed a lower unit comprising basal pebbles succeeded by 70 cm of thick gray-beige couplets with an indurated surface. This was overlain by 70 cm of thinner varves locally disturbed by gravity plications. The final induration surface was 3 cm in depth, the thickest measured.

P24 is the downstream terminus of coarse clastic debris transported through the central cave. Roundness of pebbles in banks of reworked deposits there was studied. Pebbles were entirely of limestone, derived from original cubical or parallelipedical angular clasts. The Pettijohn index of roundness values ranged from 0.5 to 1.0 with a mean of 0.7, i.e., the pebbles are rounded or well rounded. Absence of any exotic rocks, e.g., sandstone,

TABLE 2

Sedimentary sequence of the Central Cave

Phase	Sedimentary sequence
9	Induration of Third Silt surface; considerable erosion by invasion waters; local speleothem deposition; continues today
8	Deposition of Third Varved Silt
7	Induration of Second Silt surface; local speleothem deposition
6	Deposition of Second Varved Silt
5	Induration of Silt surface; local speleothem deposition
4	Deposition of First Varved Silt
3	A phase or phases of speleothem deposition; early invasion water entrenchments
2	Drainage of phreatic portions
1	Origin of the cave by aqueous solution

in this size range suggests that the limestones are autochthonous and have attained this degree of rounding during transport within the cave.

The sedimentary sequence of the central cave is summarized in Table 2. Three phases of varved silt deposition are recognized; the Second and Third were larger than the First and accumulated at least 2 m of sediment each in low-lying trap sites such as Holes-in-the-Floor. Because all deposits are substantially eroded, it is probable that erosion by invasion waters succeeded the First and Second phases, as it succeeds the Third today. It is quite possible that other silt phases preceded the First, but have been fully destroyed or reworked. Silt deposition in the Headward Complex (Phase 6, Table 1) correlates with one of the central cave phases; on volumetric grounds, this will be either the Second or Third silt.

THE ENTRANCE COMPLEX

Clastic deposits here place in two distinct groups: (1) paleodeposits of Helictite Passage, which lies above the modern flooding limit, and (2) modern deposits in the flood zone.

The paleodeposits have not been studied in the detail that they warrant. They are of particular interest because their source was the phreatic lift up P24, and because Helictite Passage receives no invasion waters to erode and redistribute older sediments except at its downstream end. The Passage is a vadose entrenchment of the same phase as First and Second Fissures in the central cave. Portions are much broken down, concealing the sediments.

The deposits are quite different from those described above. They are sparse and of a kind seen in relict passages in extraglacial caves throughout the world, that may be characterized as an "abandonment facies." When waters are rerouted to a new, lower level there is a period during which the older passage is activated only in floods, and with decreasing frequency. There is net erosion and reworking during the peak of a given flood, and deposition of new sediment as it abates. As the abandonment proceeds to completion, the new sediment becomes progressively finer. A complex cut-and-fill sequence results.

Helictite Passage displays banks of fine gravels, coarse to fine sands, silts and clays. Much of the material is reddish, suggesting that it is allochthonous. This was confirmed by a cursory investigation of the gravels. They are granule-scale (*a* axis ≤ 2 cm), of blade form because this is the form most readily lifted up P24, and many are of sandstone from the Upper Cambrian section. The banks of varved silts that dominate the suite in the central cave are absent. It appears that the Passage was not inundated during the three known phases of silt deposition. Its deposits are older, representing the original abandonment. Inundation waters of the silt phases may well have overspilled P24 as a vadose flow, contributing to the erosion of the earlier sediments.

The modern flood-zone, ca. 100 m in length, is inundated by waters spilling from a tributary passage, Boon's Blunder, that enters midway along it (Ford et al., 1983, this symposium). This creates a backwater flooding zone towards Helictite Passage, and an effluent zone to the cave entrance. The backwater zone contains many sand, silt, and clay banks that are reworked with each flood. There is much large block breakdown in the effluent zone. This serves to trap some sand and small limestone clasts of local provenance; otherwise, the zone is swept clean, except at the base and top of the final lifting shaft, P8. Here, a beach shingle is being created by a combination of local frost shatter and violent flood processes. It is a unique feature in our experience of cave sediments, is not related to sedimentation in the main cave, and is discussed separately at the end of this paper.

DISCUSSION

Distribution of Breakdown

By site and supposed origin, breakdown in the cave may be divided into two categories: (1) collapse caused by acidic invasion waters. Roofs of older passages are often broken where invasion shafts penetrate them, and there is fall from the shaft walls. Invasion water entrenchment has also induced local wall collapse by undercutting, but this appears to be on a lesser scale. (2) Other breakdown at the two ends of the cave. Both are in the uppermost parts of the Cathedral Formation, where packages of thinner beds appear between the massive ones that predominate lower in the sequence. Thinner bedding favors more breakdown. The Entrance Complex suffers vigorous flooding in the summer, when hydraulic wedging may detach roof and wall slabs. As it freezes in the winter, frost shatter is also known to be effective in the first 100 m.

Such frost shatter may also have played a role in the Headward Complex if it was ice free at times in the past. Comminution of wetted blocks was noted at the extremity there. The present thermal regime, insulated by 300 m of glacier ice, is probably too stable for effective shatter, although the temperature is very close to 0°C. McGreevy and Whalley (1982) have recently contradicted much earlier work by suggesting that frost shatter may be effective with depressions to as little as -3°C, but it seems most unlikely that even this small measure of change can be obtained at Headward Complex in the present circumstances.

A final feature that the two ends of the cave have in common is that the upper carbonate caprock has been largely or entirely stripped from overhead. Cave roofs are weakest where the cover is thinnest. We suspect that much of the extensive breakdown may be due to repeated loading and unloading plus uneven application of shearing stresses, as flowing glaciers have waxed and waned overhead. However, there is no evidence of substantial lateral displacement of passage roofs by glacier ice action, such as Schroeder (unpublished) has recorded at a shallow cave in Montreal.

Deposition of the Varved Silts

The silts are rhythmites that appear to be true varves in the sedimentological sense. However, it is not certain that each couplet necessarily represents one climatic year of accumulation, because subglacial bedrock caves are a different depositional environment from the proglacial lakes in which varved sequences are normally studied. Varves or varve-like deposits have been reported from a number of caves in glaciated regions, including Nakimu Caves 100 km southwest of Castleguard (Ford, 1979), but the Castleguard deposits appear to be more extensive and continuous than at other sites.

It is established that at least three phases of varved silt deposition are preserved in the central cave. They were separated by periods when the surfaces of deposits became indurated. During each of the Second and Third Silt phases >2 m of material was deposited between the lower ends of the First and Second Fissures. In at least one of those phases, varved silt deposition extended into the Headward Complex; the cave was then completely inundated between it and P24, including original drawdown and invasion vadose passages as well as phreatic ones. The First Silt phase was less substantial in volume and more limited in geographical extent. It probably represents a shorter period of time when the cave was inundated between A62 and the head of First Fissure. Alternatively, it was comparable in scale to the two later events but was succeeded by considerable erosion, removing the evidence; its lack of depth where observed suggests that this was not the case. At site H this basal deposit includes a conglomerate of indurated silt platelets, suggesting at least one earlier phase of deposition for which all other evidence is destroyed.

Small cut-and-fill trenches occur within both the Second and Third Silts in Holes-in-the-Floor, one of the lowest places in the central cave. They are vadose features, indicating that at times during the deposition the cave must have drained almost completely; however, the draining was very slow because there is not catastrophic damage to the weak sediment, and conditions of full inundation were soon resumed. Conversely, the very thick (>15 cm) pale beige silt-clay layers interposed between more normal varved sequences suggest times when water circulation was particularly slow for protracted periods of full inundation. It appears that the hydrologic state of the system varied quite substantially within the Second and Third Silt phases.

The three silts were deposited at some time after the first dewatering of the cave. There was an intervening period (or periods) of stalagmite deposition in drained phreatic areas. It is also inferred that invasion water entrenchments draining to lower levels were well established before the First Silt. At the close of the Third Silt phase, the waters were withdrawing slowly southwards via these entrenchments. It is deduced, therefore, that the impounding of the waters was caused by obstructions to free discharge into the Castleguard Valley. Either the modern springs were obstructed, or the precursor springs noted in the Neoglacial zone of the South Glacier (Ford, 1983, this symposium), or both.

Taking the above points into account, there seems little question that the preliminary interpretation of the silts offered by Ford et al. (1976: 228) is essentially correct, although the detailed analyses reported here reveal that the story is more complicated than was then supposed: the inundations occurred during full glacial conditions (or some parts of them) when the Castleguard Valley was occupied by a deep valley glacier. The varved silts are deposits of glacial flour, as lacustrine varves are also. They were injected into the cave from the sole of the central icefield, or are lateral backflood deposits from Castleguard Valley. We suggest that the obstruction may have been an elevated water table in the valley glacier, which drowned the springs. Solid obstructions such as injected glacial ice or clay-rich till (a) would be unlikely to seal all outlets simultaneously, and (b) would "blow" catastrophically as the pressure head built up behind them in the cave. As noted, the sediments indicate events of both slow dewatering and very sluggish flow with full inundation within each of the Second and Third phases, and of slow dewatering as they terminated. These are characteristic responses within a system to slow variations of an external water table that is controlling it. They are not catastrophic.

Another feature of the silts supporting the contention that they must be associated with some part of full glacial conditions is the predominance of carbonate minerals, especially calcite, in their composition. It can be seen today that the carbonate rocks are the poorest producers of rock flour in the region. This is because they are soluble, particularly when reduced to the tiny dimension of a silt or clay particle. The Upper Cambrian clastics are the source of much flour. Glaciers contacting them have very turbid meltwaters; those resting wholly on limestone produce water of low turbidity, though some flour is still present.

Invasion waters entering the head of Castleguard Cave today are seen to carry large quantities of clasts from the dolomite-rich upper carbonate plinth and from the Upper Cambrian clastic rocks. This is because ice is able to flow westward from the (clastic rock) horn peak of Castleguard Mountain to join the central icefield upstream of the cave (see Ford, 1983, this symposium, Figures 1 and 3). The calcite-rich flour of the three silt phases suggests that their source rock was largely or entirely restricted to the Castleguard Formation underlying the central icefield itself. Such restriction can only occur when ice from a very thick icefield is flowing east across the upper carbonate plinth, reversing the modern direction of ice flow there. A thick icefield implies full glacial conditions. We note also that the predominance of calcite indicates that the preserved varved silts were not introduced into the cave before the upper carbonate and clastic caprocks were stripped from the central icefield area (see Ford et al., 1983, this symposium, Figure 14). This is independent evidence that they arrived comparatively late in its history.

The approximate age of the silts can be determined from the speleothem dating program described by Gascoyne et al. (1983, this symposium). To summarize the relevant results: the base of a large stalagmite in the Grottoes, that has been severely eroded by later inundations, is greater than 720,000 yr in age. The Third Silt partly buries this deposit and is younger than it. The First and Second Silts are not preserved at the site, but are also believed to be younger than the stalagmite. Sample 79016 (Gascoyne et al., 1983, this symposium, Table 1) was a flowstone deposited on top of the Third Silt nearby. It has not suffered erosion by inundation. It is 144,000 ± 6,000 yr in age. Two other undamaged flowstones on top of the silts halfway down the First and Second Fissures have basal ages of 109,000 and 121,000 yr, respectively. It appears well established that the Third and final silt was deposited at some time before the Last Interglacial. The cave was not inundated by varve-depositing waters during the Wisconsinan Glaciation.

THE SHINGLE BEACH AT P8

The base of P8 is a steep ramp of rounded limestone pebbles, generally ranging 3 to 7 cm in length. It looks very much like a marine shingle beach, and is unique in our experience of cave sediments. It appears to be produced by interaction of local frost shatter and periodic violent flooding in a phreatic lifting situation, a combination that could be expected in an alpine cave environment.

The topography is shown in Figure 6. The shaft is vertical, of roughly quadrangular cross section measuring 9 × 2.7 m. Flood waters enter it from a low-roofed bedding plane passage that is rounded upwards at the junction. They are discharged at the top into a squared-off passage measuring 4.3 × 0.9-1.3 m. This contains a pebble bar 7 m in length. Scattered pebbles and smaller bars extend downstream to the cave mouth, 100 m distant. It is clear that the top bar is being replenished by pebbles lifted from the greater deposit at the base of the shaft. Pebble samples are shown in Figure 7.

The pebble clasts derive from the walls of the shaft itself. There is no supply of coarse debris from upstream because of screening by breakdown there. The shaft walls are fresh, multifaceted surfaces of cubical and platy riving in dark limestone. They are whitened everywhere by concussion marks from pebbles striking them during floods. The high rate of riving is a combination of flood and frost action. Walls are thawed by summer floods, when water under hydrostatic pressure is injected into all cracks. The rock freezes during the fall, when floods are gone and cold air flow in from the entrance commences. On winter nights, -5°C has been recorded in the shaft. In July 1969 -3°C was measured there, just before the first flood of that year. The walls were coated with hoarfrost at the time (Figure 6), which held any loosened blocks in place. Evidently, they are detached by hydraulic wedging and pebble impact during floods. There is one freeze-thaw cycle per year.

Rounding of fallen clasts is largely or entirely accomplished at the bottom of the shaft. It is an ideal sediment trapping site. Under flood conditions of constant velocity

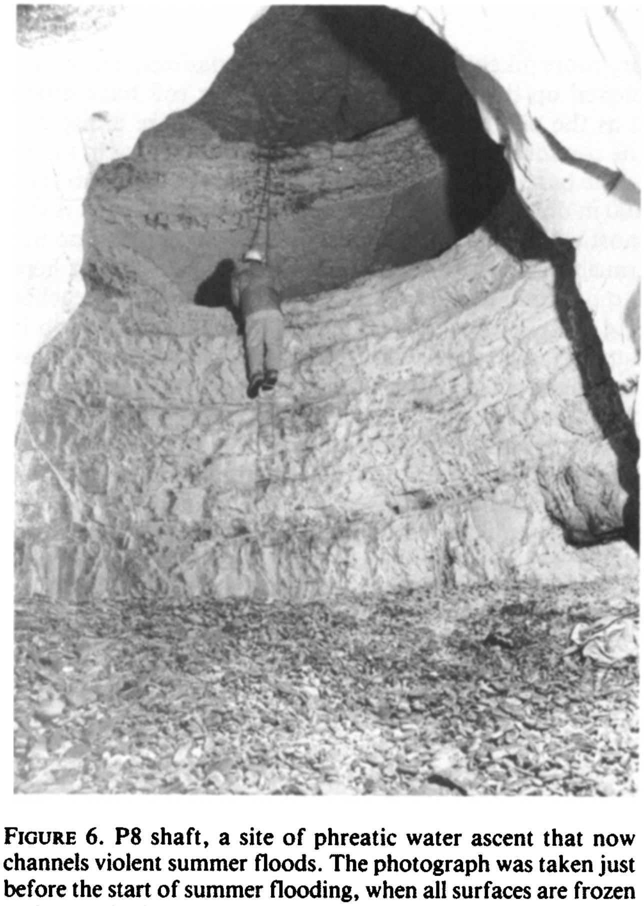

FIGURE 6. P8 shaft, a site of phreatic water ascent that now channels violent summer floods. The photograph was taken just before the start of summer flooding, when all surfaces are frozen and coated with hoarfrost. The frost conceals the many concussion marks on the walls. Shingle at the base is rived from these walls and rounded in situ. A substantial proportion of it is carried up the shaft and out of the cave.

FIGURE 7. Pebble samples; lower left, from the base of P8 shaft; center right, from the top of the shaft; rear, from the flood channel at the cave entrance. The scale is graduated in inches and centimeters.

or, more likely, pulsing velocity variations, clasts are moved up the basal pile to rebound or roll back down it as the pile becomes oversteepened. Figure 8 displays the rounding of three samples of 50 pebbles each, taken at the base and top of the shaft and at the cave entrance 100 m downstream. In the mean, the basal deposit is the most rounded although its clasts have undergone no net transport away from original fall sites. Rounding here is quite comparable to that measured on marine beaches (e.g., Guilcher and King, 1961). Rounding at the top is intermediate between that of beaches and of clasts transported short distances in river channels. At the entrance, clasts from the shaft sites are diluted by material riven from the passage downstream of them.

It was at first supposed that attrition at the base of the shaft reduced clasts to some critical dimension, whereupon they could be carried up the shaft by available flood power. We were surprised when clasts at the top proved to be somewhat larger in the mean than those below. They are also notably less rounded. Suitability of clast shapes has been much discussed by sedimentologists in the contexts of saltating, rolling, sliding, and settling in normal channels, but not in the context of this site, which is that of lifting vertically upwards through a distance equal to the channel width. A roundness greater than 700 (Cailleux's and Tricart's index, 1963) appears to prohibit lifting in this particular combination of clast size and fluid velocity.

Peak flood discharges of 6 to 7 m^3 s^{-1} have been measured at the cave entrance. These imply a mean velocity of 1.14 to 1.33 m s^{-1} through a measured cross section at the top of the shaft. Applying Rubey's (1937) formula for the force required to prohibit settling of a spherical particle, to parameters of the top pebble sample, minimum velocities of 0.78 to 1.06 m s^{-1} are obtained for the same cross section. It is apparent that the modern floods are fully capable of the lifting work ascribed to them here, especially as it has been shown that less rounded particles are lifted more readily than Rubey's spheres.

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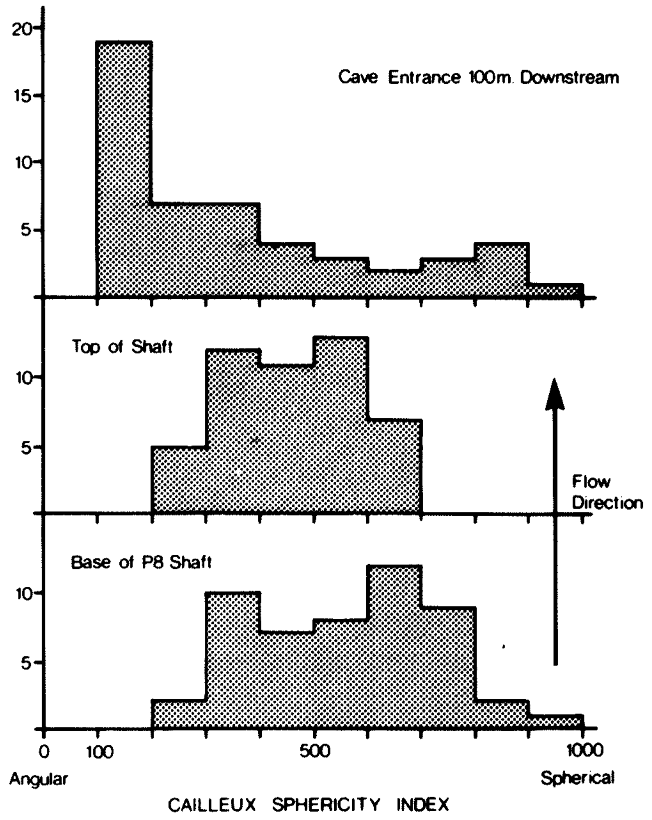

	x̄, a/b ratio	x̄, a/c ratio	x̄, length
CAVE ENTRANCE	1.73	3.22	8.0 cm.
TOP OF SHAFT	1.42	2.66	6.5 cm.
BASE OF SHAFT	1.38	2.23	5.0 cm.

FIGURE 8. Histograms of the pebble samples from the base and top of P8 shaft and from the cave entrance. Mean *a:b, a:c* ratios, and lengths for the three samples.

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