KARST ON VANCOUVER ISLAND – AN ICY HISTORY

by

Emil Silvestru

Abstract: Vancouver Island has the highest density of caves anywhere in Canada although karstic rocks do not represent a significant part of its geology. While all karst areas in Canada have been covered by ice during the last glaciation, Vancouver Island karst has had a number of peculiar glacial conditions during the Fraser Glaciation (Late Pleistocene equivalent to Late Wisconsinian in North America) which have allowed a better understanding of karsting processes beneath the Cordilleran Ice Sheet. Many caves, even the ones at high elevation, have preserved very coarse rounded allochthonous sediments, including blocks in excess of 1 m in size, which are clear indication of paroxystic subglacial aquatic transportation. It is thus inferred that subglacial karst was repeatedly submitted to high pressure, chemically aggressive water flooding followed by flushing which significantly enlarged the caves and established the karst drainages that are still in place today. Sediments in known caves on the island provide no indication of glacial episodes prior to the Fraser Glaciation which, corroborated with the scarcity of speleothems and the general juvenile aspect of the caves strongly advocates for a recent (Wisconsinian) age of the Vancouver Island karst.

1. The Island

Vancouver Island is the largest island along the western coast of North America. It extends north-west between 48°20' and 50°40' N respectively 123°10' and 128°30' W, a total length of 450 km and an average breadth of 70 km. The total land area is 32,000 km^2. The highest elevation is 2,197 m on the summit of The Golden Hinde in the central part of the island. Physiographically, the island consists of lowlands, highlands and plateaus and mountains. There is an abundance of lakes, most of them elongated N-S respectively E-W. Most of the many fjords on the western coast of the island have a similar orientation.

2. Geology of Vancouver Island

2.1 *General remarks*

The somewhat exotic geology of Vancouver Island is interpreted as evidence of it having its origins somewhere else, in a different terrane called Wrangellia. When it comes to the original location of this terrane, geologists are still trying to decide: paleomagnetic data puts it north of the present location, fossil contents south, close to the equator. (Matthews & Monger, 2005, pp.29-31).

2.2 *Igneous geology*

Vancouver Island is built predominantly of igneous rocks, with a fairly large petrographic and structural range. The bulk is part of a Large Igneous Province (LIP) characterized mainly by Late Triassic basalt flows. The Karmutsen basalt of pre-Carnian age represents the dominating geological feature of the island.

2.3 *Sedimentary geology*

The available information regarding the sedimentary geology of the island is rather puzzling to the karstologist scouring the bush for karst clues. First, there is not enough systematic geological work done. Some of the older research was done with a different (from the present) geological framework in mind and much of the more recently published data is essentially re-interpretation of the old. Second, there are virtually no significant, laterally continuous marker units making correlations between faulted blocks virtually impossible. Third, the geological nomenclature in use is often interpreted differently by different sources so that the same formations are placed in different groups. Thus the Sutton Limestone is presented by some authors as the final member of the Parson Bay Formation, others consider it an individual formation whilst others yet describe it as a member *within* the Parson Bay Formation (Caruthers & Stanley, 2008).

There are three main limestone sequences on Vancouver Island. The oldest one is the Late Carboniferous to possibly Early Permian Mt. Mark Limestone (a.k.a. Formation) of the Buttle Lake Group. The same formation is frequently presented as the Buttle Lake Limestone. This bioclastic calcarenite and calcirudite with frequent chert clasts and interbeds, appears as grey cliffs, especially around Buttle Lake, Horne Lake and Cowichan Lake. Its thickness never exceeds 300 m with an average of about 80 -100 m.

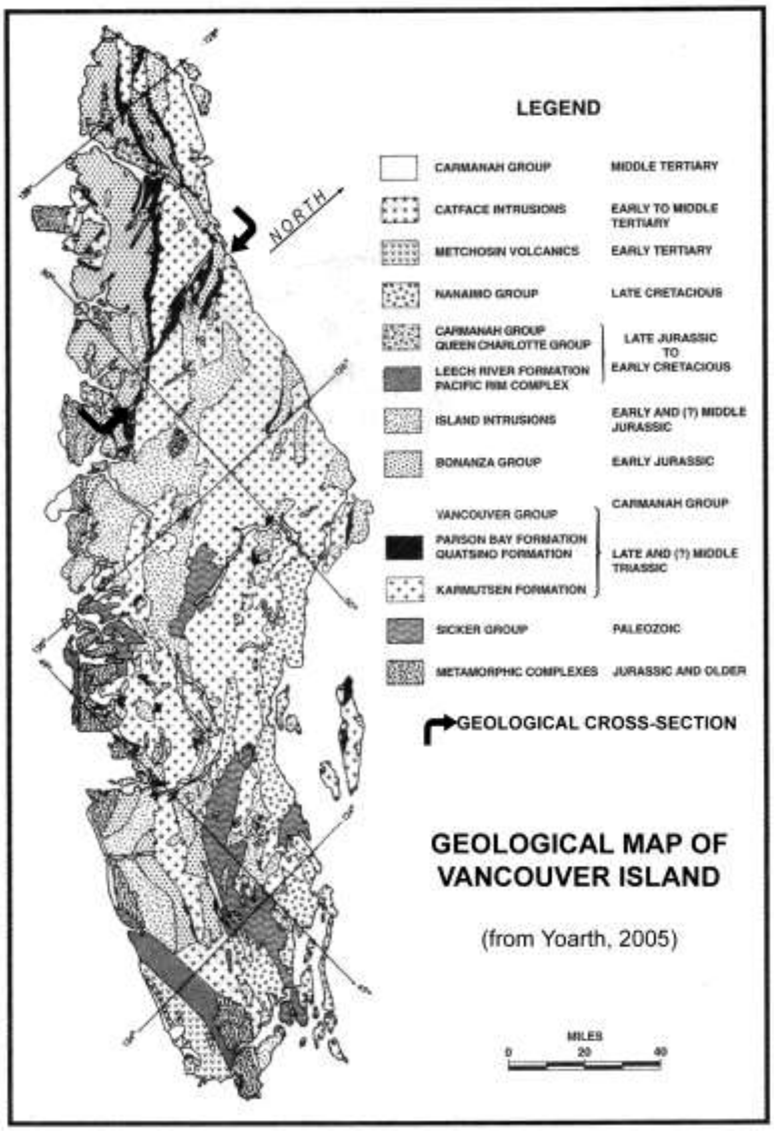

Fig. 1

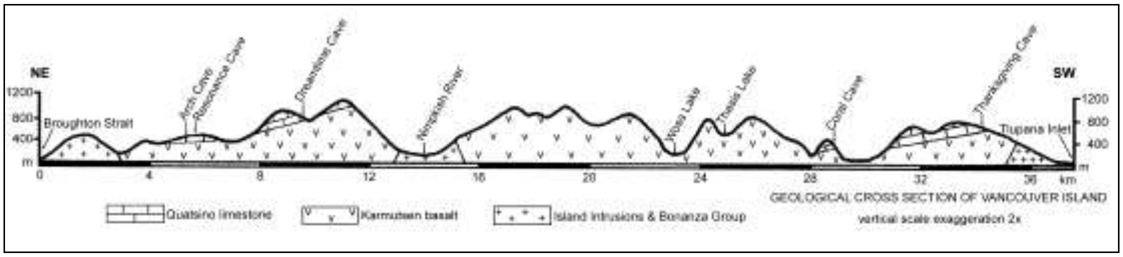

Fig. 2

Geological cross-section in the upper half of the island. Vertical exaggeration 2x (see map for approximate direction.)

The fossil inventory includes crinoids, brachiopods and bryozoans which suggests transported rather than in situ material, since the crinoid component is typical for deep sea whilst bryozoans and brachiopods for shallow sea. Attributing such a depth range to subsidence is not supported by any other geological data.

Two Late Triassic carbonate sequences follow, in two distinct facieses: the Quatsino Limestone (Carnian) with an average thickness of 30 meters, never exceeding 75 m. This thickly bedded or blocky micrite with coloration varying from black to gray overlays a transition sequence of flaggy limestone interbedded with tuffs, argillites and limestone clasts, underlain by basaltic flows. Some authors present the uppermost shaley sequence of the Quatzino Limestone (QL) as the Parson Bay Formation (Marshall *et al.*, 2009). Locally, resting on the Karmutsen basaltic flows there are thin sequences of biohermal carbonate known as Sutton Limestone (Norian?). When located on summits or close to the highest points of the landscape, the limestone is usually subhorizontal or gently dipping. When on slopes, even steep ones, the bedding is frequently parallel or near-parallel to the slopes. The best example is the Thanksgiving Ridge where the slope is at an average of 45° and on several locations where the Quatsino limestone reveals bedding, the average dip is 45° (see Fig. 9). Tectonic tilting comes to mind as the obvious explanation, especially since the limestone lies unconformably i.e. with no marine transgression sedimentary sequence preceding it, on the Karmutsen Basalt (KB).

There is another, quite rare characteristic regarding the geology of karstic rocks: their proximity to and intimate association with igneous rocks, mostly basalt. There are cases when the limestone is in fact sandwiched between lava flows (Fig. 3).

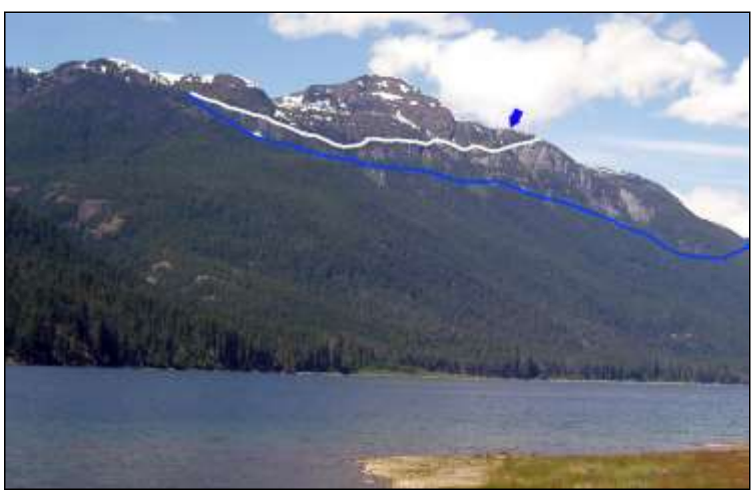

Fig.3

The Buttle Lake Limestone (the grayish rock at the center-right of the picture) above Buttle Lake, lying on top of the Sicker Group volcanics and covered by the Karmutsen Basalt. Notice the irregular upper contact (white line). The arrow points at an isolated limestone block in the basalt (xenolith).

Magmatic heat metamorphism is very rarely visible in the limestone and almost exclusively in the proximity of granites. Most common results are saccharoid texture and marble with reduced spatial extent. Basalt dykes are sometimes present in the QL and it is not unusual to find cave passages cutting straight through them with little to no change in the passage direction. Excellent examples are found in Thanksgiving Cave and Big Upper Elk Cave.

	Period		Environment/Event
CENOZOIC	Quaternary	Holocene	Erosion
		Pleistocene	Glaciation
	Tertiary		Erosion
			Carmanah Group sedimentary rocks
			Laramide orogeny
MESOZOIC	Cretaceous		Nanaimo Group sedimentary rocks
			Uplift and erosion
	Jurassic		Bonanza Group and Island Intrusions (volcanics and granites)
	Triassic		Vancouver Group volcanics (Karmutsen Basalt); Quatsino and Sutton Limestones
			Uplift and erosion
PALEOZOIC	Permian		
	Carboniferous		Buttle Lake Group sedimentary rocks, including Mt. Mark Formation (a.k.a. Buttle Lake Limestone)
	Upper Devonian		Sicker Group volcanic & sedimentary rocks Saltsprings Intrusions granitic rocks

Fig.3
Simplified geologic column of Vancouver Island (after Yorath, 2005)

3. Ice, isostasy, eustasy and karst

When it comes to Quaternary glaciation, the available surficial sedimentological and geomorphic data points to one certain episode on Vancouver Island: The Fraser Glaciation, (Yorath, 2005), the local expression of the Late Glacial Maximum. No sedimentary sequences in caves of VIK have been identified that can be correlated in any reliable way with other stadials and interstadials; nor does in any way karst geomorphology advocate for such episodes. Nevertheless, some geologists (Yorath, 2005 p.43, Al-Suwaidi, 2005 p. 15) extrapolate a pre-Fraser Glaciation interstadial – the Olympic Interstadial (nonglacial) – and an early Wisconsinian stadial – the Semiahmoo Glaciation described further south (in Washington State and Oregon) to southern Vancouver Island.

At the peak of the Fraser Glaciation (FG), the mainland glaciers (Cordillera Ice Sheet henceforth referred to as CIS) completely covered and plugged the Straits of Georgia (glacial grooves have been identified on its bottom, Clague *et al.*, 2005), the whole of Vancouver Island and probably tapered into shelf ice over the Pacific Ocean.

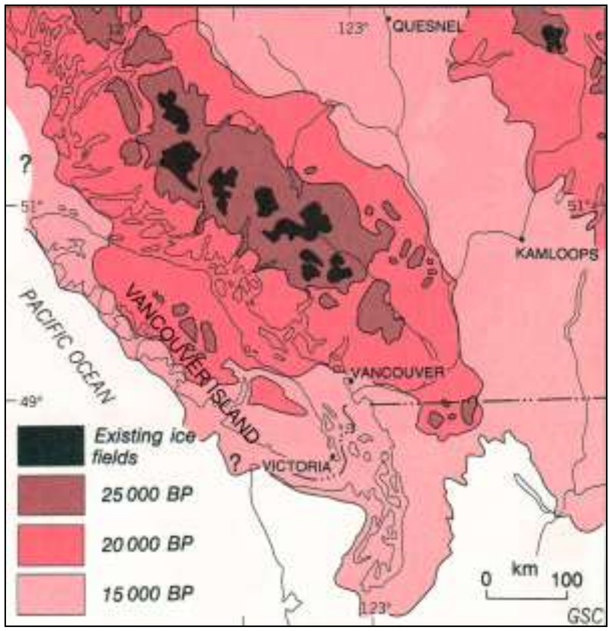

Fig. 4
Extent of Cordilleran Ice Sheet during the Fraser Glaciation (from Clague, 1989, p.57)

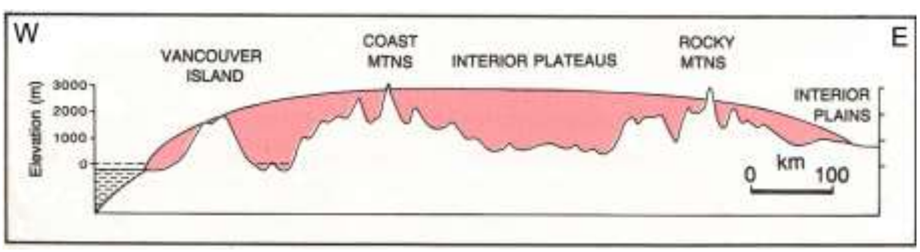

Fig. 5
Schematic cross-section with the maximum extent of Cordilleran Ice Sheet during the Fraser Glaciation (from Clague, 1989 p.41).

Interpretation of the complex set of ancient shorelines as well as sediments led to the conclusion that following deglaciation, Vancouver Island's isostatically rebounded about 150 m. On the other hand, at the peak of the FG – the equivalent of Late Wisconsinian in the USA – the ice depressed the island with at least 150 m, possibly 300 m (Clague *et al.*, 1982, 2005). Furthermore, it is generally accepted that eustatic sea level dropped 150 m at about the same time. So at the maximum of this last stadial, Vancouver Island may have been 150 m lower than today (closer to the "virtual" sea level). When deglaciation started, the Strait of Georgia shorelines were 60 to

120 m higher than today (Yorath, 2005). Yet, ancient shorelines revealed that glacial rebound (isostasy) was faster than eustatic sea level rise (due to deglaciation) so that the shoreline kept "lowering" at elevations below the present one. Once rebound came to an end, at about the time of the Neolithic, the sea level continued its rise to the present position.

There may have been some interesting consequences of geology and glaciation on the island. There is a marked difference in the geological make-up of the southern and northern tips of the island. This translates in terms of crustal density into a slightly lighter northern half of the island. That would have caused a slightly faster rebound after de-glaciation. On the other hand, deglaciation advanced from the south so rebound started from the south as well. Three possible outcomes come to mind: the northern half rebounded faster, at the same pace or slower than the south.

Based on the scenario above, the VIK karst rocks may have travelled some 450 vertical meters (above and below an oscillating sea level). If karst existed before glaciation, one would expect that at least the caves close to sea level today (Horne Lake area, Tahshis-Benson area – see Fig. 7) would have preserved evidence of marine invasion(s). However, there are few caves known to have such evidence. There is Boneyard Cave in the Tahsis area for example, with marine fossils like barnacles and tubeworms in it. The cave is located very close to the present sea level. There is then an unnamed cave on Texada Island (Fig. 6) located in the tidal zone and in the process of being invaded by the sea. The massive stalagmitic flows indicate this cave had formed at higher elevation, possibly in pre-glacial conditions. There are some other cases of tidal zone caves at the northern end of Vancouver Island (Paul Griffith, personal communication). This is of course the only area on the island where limestones consistently reach the sea level today.

Fig. 6

Cave on Texada Island in the tidal zone. Note the height of maximum tide marked by the white salts deposit. Photo by and used with the permission of Paul Griffith.

A peculiar position is occupied by Port Eliza Cave which is at about 85 m above present sea level but is a non-karstic cave. Some authors consider it a marine abrasion cave excavated in the Bonanza Group volcanics (Al-Suwaidi, 2005) but the evidence for marine invasion is questionable. The cave may well be the result of weathering and chemical alteration along a fault line (pseudokarst).

4. Karst on Vancouver Island

4.1 *Karst areas*

The Vancouver Island Cave Exploration Group (VICEG) has been active on the island since the 1960s and has explored and surveyed caves often times following forestry works and as a consequence their cave inventory is less geomorphically focused. The map in Fig.7 presents the approximate location of the karst areas as surveyed and inventoried by VICEG. Individual karst areas are small in extent and distributed as discontinuous patches across the island with some more consistency on its western half. The largest limestone exposure is on the northern end of the island, north and west of Port McNeill. This is also an area in which the limestone is located at the lowest elevation, reaching the sea level at the extreme northeastern point of the island.

Seen from a karstological and geomorphic point of view, karst areas on the island can be divided into East Coast Karst (ECK) – areas 7, 8, 9, 16 in Fig. 7; Interior Karst (IK) – areas 2, 3, 5, 10, 11, 13, 15, in Fig. 7; West Coast Karst (WCK) – areas 1, 4, 6, 12, 17 in Fig. 7. The coastal karst has the sea as base level whilst IK has rivers or lakes as base level.

Tempting as it may be, it is practically impossible to group karst areas by elevation since in almost every case cave entrances in a given area range over several hundred meters of elevation, geology and glacial geomorphology being the main controlling element. Also, there are no multiple stage cave systems that one can correlate with well-defined karsting episodes.

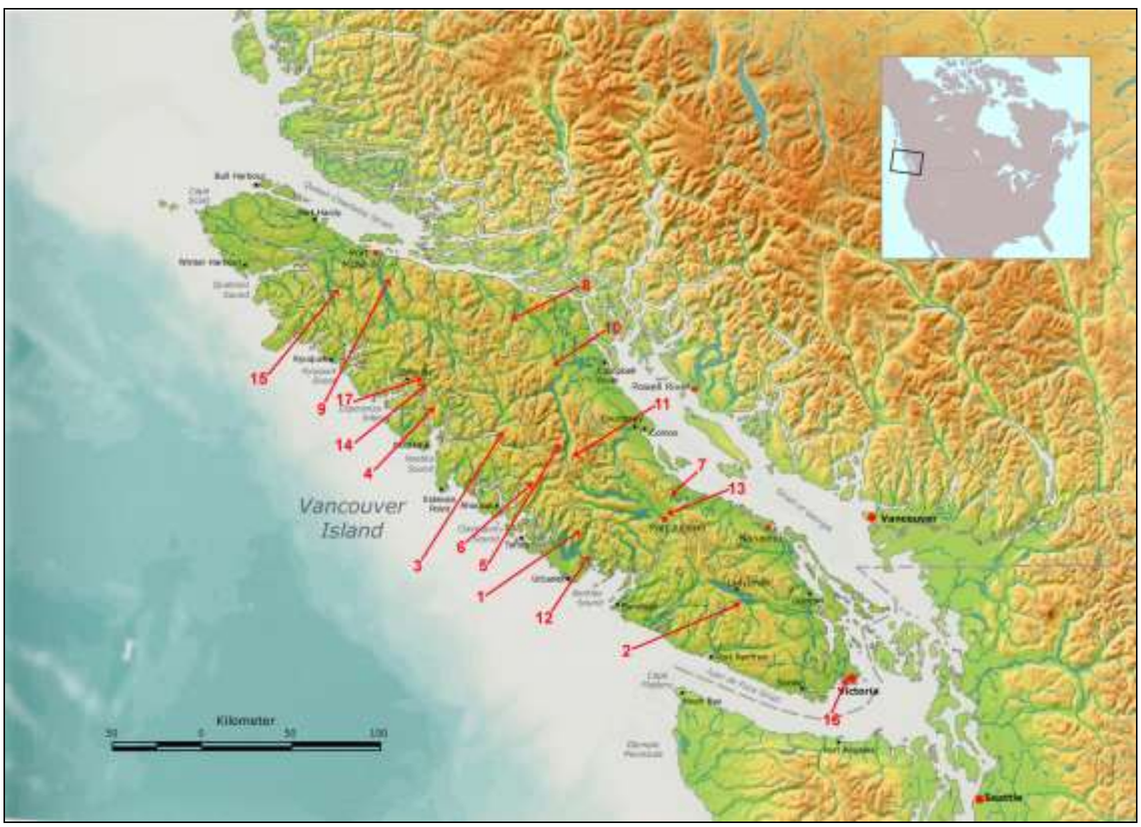

Fig. 7

Vancouver Island and karst areas as surveyed by VICEG: 1. Clayoquot Plateau; 2. Cowichan Lake; 3. Gold River; 4. Head Bay; 5. heaven's Ridge (Strathcona); 6. Holely Mountain; 7. Horne Lake; 8. Memekay – Kelsey Bay; 9. Nimpkish Lake; 10. Oyster – Iron Rivers; 11. Patterson Lake; 12. Pipestem Inslet; 13. Port Alberni; 14. Tahsis; 15. Tahsish – Benson; 16. Victoria; 17. Zeballos – Holberg.

Table 1 The longest caves on Vancouver Island

	Cave/Cave system	Region	Total surveyed length (m)	Total dislevelment (m)
01	Weymer Cave System	Weymer Creek	13,171	370
02	Arch Cave	Nimpkish Lake	10,616	353
03	Thanksgiving Cave	Head Bay	8,311	416
04	Ursa Major Cave	Weymer Creek	8,049	190
05	Windy Link Pot	Gold River	4,449	209
06	Minigill Cave System	Tahsish/Benson	3,162	35
07	Wormhole	Weymer Creek	2,819	93
08	13th Avenue Cave	Holely Mountain	2,557	222
09	Glory 'Ole Cave	Nimpkish Lake	2,340	312
10	Pellucidar Cave	Nimpkish Lake	1,943	127

Data from http://www.cancaver.ca/

Table 2 The deepest caves on Vancouver Island

	Cave/Cave system	Region	Total dislevelment (m)	Total surveyed length (m)
01	Thanksgiving Cave	Head Bay	416	8,311
02	Weymer Cave System	Weymer Creek	370	13,171
03	Arch Cave	Nimpkish Lake	353	10,616
04	Glory'Ole Cave	Nimpkish Lake	312	2,340
05	Q 5 Cave	Gold River	301	1,837
06	Big Money Cave	Holely Mountain	230	1,303
07	13th Avenue Cave	Weymer Creek	222	2,557
08	Windy Link Pot	Gold River	209	4,449
09	Titanic	Holely Mountain	202	397
10	Ursa Major Cave	Nimpkish Lake	190	8,049

Data from http://www.cancaver.ca/

4.2 Karst characteristics

To this European-bred karstologist, the most striking characteristic of VIK is its youth. Youth in the sense of absence or/and scarcity of features specific to what is normally perceived as "mature karst". Large rooms, well-decorated multiple levels of fossil cave passages, complex sedimentary sequences both in caves and surface karst, troglobiontic fauna (extinct and extant), well-established surface and sub-surface karst connections, from karren and doline fields to base level lowering controlled, multiple stage karst systems are all conspicuously missing in VIK and in the Canadian karst as a whole.

Canada's longest cave, Castleguard (in the Rockies) is identical to many of the caves of the VIK and in fact of all Canadian karst. There are no caves in Canada like the ones say in the Western Mountain Ranges, Colorado Plateau, Appalachian Mountains, Interior Low Plateaus and Ozark Plateau in the USA (Palmer, 2007 p.41). The immediate reason that comes to mind is, of course, glaciation: the whole of Canada was practically covered by ice, while most of the karst in the USA was not. Geology is secondary in this case since about half of the karst in the USA is in very similar settings with the Canadian one. Since ice covered practically all Canadian surface karst, it is appropriate to label it (as a whole) *glaciokarst* (Sweeting 1973, Ford & Williams, 1992) and expect most of the caves and cave systems to have been influenced by glaciation. When under continental ice, glaciokarst is described as *Canadian type* i.e. karst inputs and outputs are glaciated. When in alpine setting, glaciokarst is termed *Pyrenean type* with karst inputs glaciated and the outputs not (Ford & Williams, 1992). The same authors (p.483) list 9 types of glacier effect on karsting. (Table 3) The majority of these effects are found in VIK.

Table 3

	Effects of glacier action upon karst systems
Destructive, deranging	
1	Erasure – of karren, and residuals
2	Dissection – of integrated systems of conduits
3	Infilling – of karren, dolines (sinkholes) and larger input features; aggradation of springs
4	Injection – of karstic detritus into cave systems
Inhibitive	
5	Shielding – carbonate or sulphates-rich drift protects bedrock surfaces from postglacial solution
Preservative	
6	Sealing – clay-rich deposits seal and confine epikarst aquifers
Stimulative	
7	Focusing inputs, raising hydraulic head – with superimposed glacial streams or aquifers
8	Lowering spring elevations – by glacial entrenchment
9	Possible deep injection – of glacial meltwaters/groundwater when bedrocks are being flexed during crustal rebound or depression?

Caves on Vancouver Island are located both in gently dipping limestone on summits and medium- to steeply dipping limestone on slopes. And in both settings there are long caves (Windy Link Pot, Q5 for the former, Weymer Creek System, Arch Cave and Thanksgiving Ridge System for the latter). Fig. 8 presents the most typical geological settings of VIK:

A. The Horne Lake area: limestone is capped and exposed only on the slope. Inputs infiltrate diffusely through igneous rocks (allochthonous recharge) and outlets are located both in limestone and at the boundary with the subjacent non-karstic rocks.
B. Thanksgiving Ridge, Dreamtime Cave, Arch Cave. Limestone exposed mostly on slope of valley which is also the local base level. Inputs go directly into limestone (allochthonous or autochthonous recharge), outputs in limestone and boundary with subjacent non-karstic rocks.
C. Memekay area. Limestone exposed in the slope, reaches the base level, inputs and outputs in the limestone (allochthonous or autochthonous recharge).
D. Resonance Cave. Limestone exposed and only on summit inputs in limestone (autochthonous recharge), outputs on the boundary with subjacent non-karstic rocks.

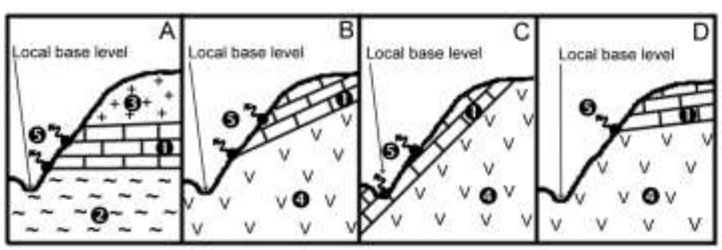

Fig. 8

❶Karstic rocks. ❷Volcanic and sedimentary rocks. ❸Igneous rocks of Bonanza Group. ❹Karmutsen basalt. ❺Outputs (resurgences). More information in the text.

Thanksgiving Cave (as well as its satellites in the Thanksgiving Ridge) is important for the understanding of speleogenesis on the island. The cave follows (virtually paralleling) the surface slope over 1.5 km of distance and 300 m dislevelment (Fig. 10). There are a number of entrances into the cave along the slope, but none has indication of having functioned at some point as a resurgence; they all are in fact temporary input points. Since the cave closely follows dip, the obvious conclusion is that there was no rapid entrenchment of the local base level to which the cave could have adjusted. If the cave formed before the FG, it could have still adjusted to a slow base level entrenchment which one would expect during an interstadial.

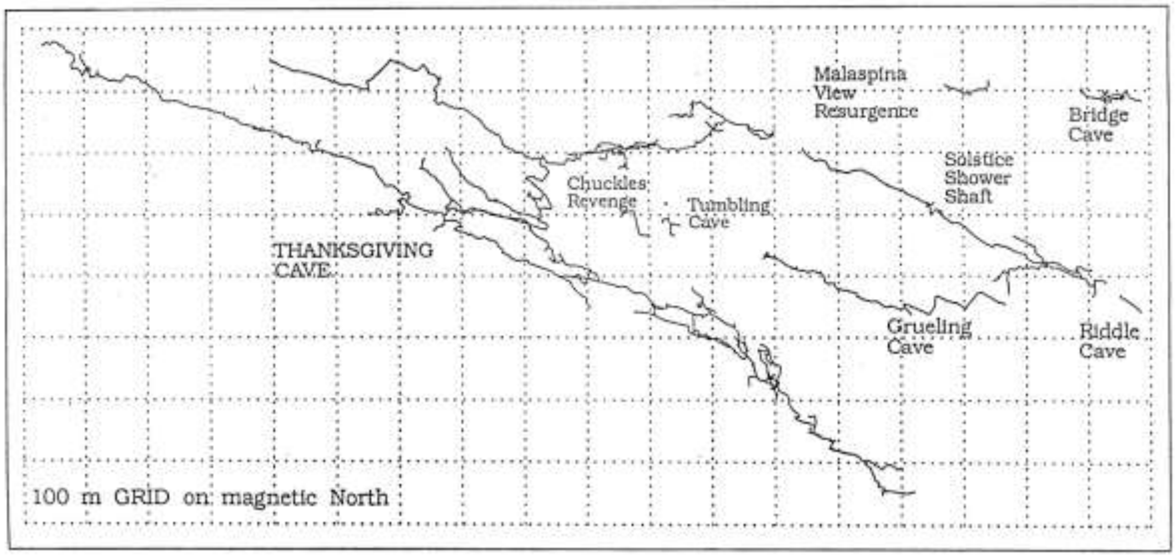

Fig. 9
Map of caves in the Thanksgiving Ridge, Head Bay area. Map provided by VICEG.

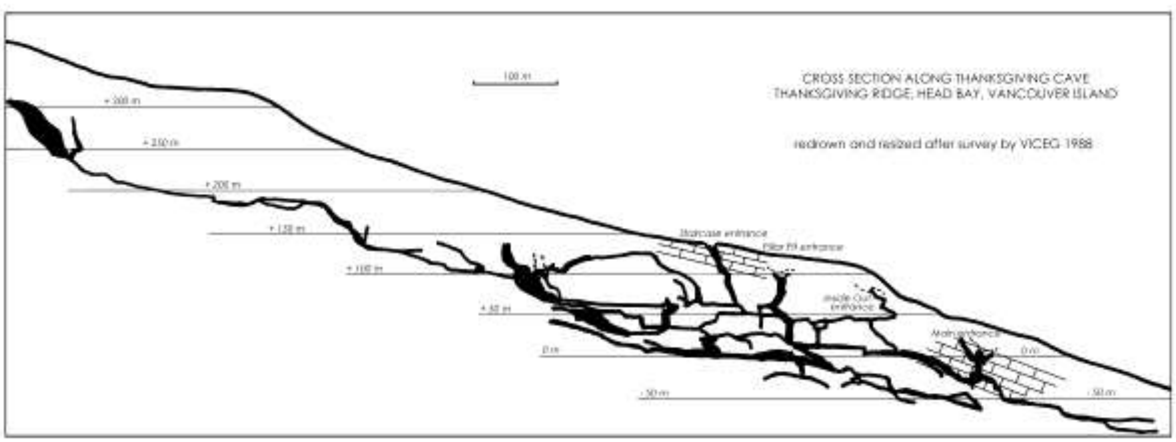

Fig. 10

The Devil's Bath (Fig. 11) on the northern end of the island is a quite unexpected and exotic feature. It is, by all accounts a cenote fed by bottom karst springs originating from Benson River. Since the river's elevation is only 100 m a.s.l. it must have been below sea level during FG. It is therefore possible that the entire system: the Benson River Gorge, the caves and the cenote formed after glacial rebound elevated the area above sea level. As mentioned before, at some point before the Neolithic the sea level was lower than today so that the hydraulic head in this area was higher than the present and consequently karsting and fluvial erosion unfolded faster. During this time the cenote probably did not exist, being some sort of annex to the surface drain. As the sea level rose to the present elevation, the annex became flooded and the inputs and outputs adjusted to the present setting.

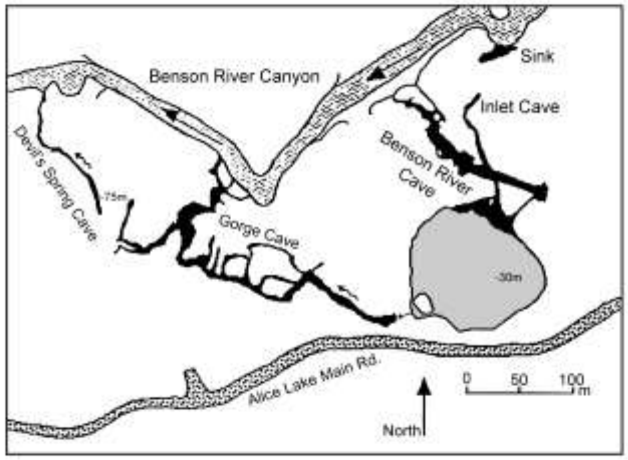

Fig. 11
The Devil's Bath and caves (Tahshis – Benson area). Map provided by VICEG.

5. Clastic sediments in Vancouver Island karst

Several of the caves that I have visited on the island have significant amounts of allochthonous clastic sediments. There seems to be a predominance of coarser sediments in caves of ECK and some of the IK caves, compared to the WCK. The lower caves, especially the ones on the western side of the island have predominantly finer sediments, mostly gravel and sand.

The coarsest sediments – boulders - are often rounded, regardless of their petrographic nature. Basalt predominates, followed by granites. Percussion marks even on the largest blocks are not uncommon.

5.1 Some VIK c*aves with significant sediments*

5.1.1 *Resonance Cave - Nimpkish Lake area (ECK)*

At 710 m a.s.l., this is one of the highest large caves in VIK and close to the top of the local topography. The access passage is nearly straight, gently descending and displays classical phreatic morphology – one of the most beautiful in VIK. A large rounded, elongated boulder nearly 1 m in length is stuck in the middle, some 60 m from the entrance. The boulder is basalt but covered, like most of the passage, with secondary calcite. (Fig 12) This may have been initially moonmilk as deeper into the cave there is moonmilk on both sides of the passage. There is another bigger block, about a third the size of the passage further down the same passage. There are however no similar (rounded) allochthonous blocks outside the cave and on the summit area.

Fig. 12

Resonance Cave: the author squeezing past a large rounded basalt block covered with a thin calcite layer which also cemented it to the ceiling. Notice allochthonous gravel and sand on the floor as well as the presence of scallops indicating inflow (towards the reader).

5.1.2 *Dreamtime Cave – Nimpkish Lake area (ECK)*

The 15 x 4 m entrance (Fig. 13) is at 836 m a.s.l. It is a classical (fossil) *ponor* (swallow hole) with a single passage leading downhill to a plug made of medium and large boulders of various petrographic natures: black and greenish basalt, granite and limestone (Fig. 14). A series of phreatic tubes in the ceiling bypass the plug, ending in a large room with some lower phreatic passages.

The cave entrance location is somewhat surprising: although high on a steep slope it lays at one end of a flat encased valley-like depression almost coalesced with a doline. (Fig.15) The ancient drain into the cave seems to have been following a pattern I have seen with many ponors in Europe: after a relatively straight flow, the sinking streams turn to the right, usually 180 degrees (on rare occasions even 270 degrees) before sinking to one or several swallow holes. There seems to be no connection to Coriolis forces since the straight section can go in any direction (not just north as expected with Coriolis forces). The enclosed character of the depression rules out a ravine or any other kind of slope drain and indeed there is no visible continuity of it further uphill.

Fig. 13

Dreamtime Cave entrance.

Fig. 14
Large, fairly rounded basalt and granite blocks and angular limestone blocks at the bottom (plugged) of the entrance room of Dreamtime Cave. The block at the top is slightly over 1 m in length.

What this seems to indicate is that there has been a concentrated flow arriving at the swallow hole even at this high elevation and on a steep slope. This most likely could have happened underneath the ice cap.

I have found no similar allochthonous blocks outside the cave and along the road leading to and past the cave. There are however massive angular granite blocks in the proximity.

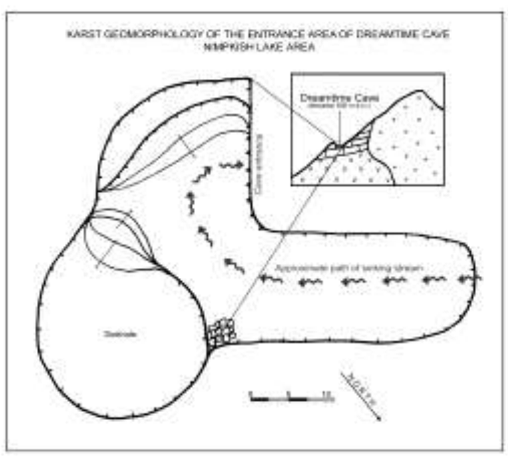

Fig. 15
Legend of geological symbols same with Fig. 2

5.1.3 *Chicken II Cave – Memekay – Kelsey area (ECK)*

With its entrance located at 465 m a.s.l. this cave contains one of the most important sedimentary archives on the island. Large, well-rounded allochthonous boulders up to 140 x 120 cm in size are present on the floor of the main passage from the entrance to the bottom (Fig. 16). The most important is an 80 cm diameter, well rounded quartzite boulder with many obvious percussion marks (Fig. 17). Whilst the source area of such a massive quartzite clast is anyone's guess, it is certainly not on Vancouver Island but somewhere on the mainland. Based on existing published data, the nearest possible source is the Belt-Purcell Supergroup (Matthews & Monger, 2005, p.17, 290), more than 500 km to the east! This boulder is undeniable evidence of long, high-energy hydraulic transport.

Fig. 16
Assortment of allochthonous rounded boulders in Chicken II Cave, mostly basalt. The grey rock in the foreground is the limestone bedrock (passage floor). The measuring tape spans 182 cm.

Fig. 17
Rounded quartzite boulder (80 cm diameter) with many obvious percussion (lunate) marks. See details in the text.

Along the main passage there are suspended mixed sediments consisting of rounded gravel, sand and secondary whitish films most probably the result of chemical alteration of minerals in the sand. The lower end of the main passage is completely plugged with sand and gravel, the present stream in the cave following a lower, impenetrable path. The cross section of the plugged passage and scallops on the walls indicate that before plugging, the passage was the main drain and therefore may continue (is not just a side pocket).

I have found no similar allochthonous boulders on the surface in the proximity of the cave.

5.1.4 *Coral Cave – Tahsis area (WCK)*

Another swallow hole with a sizable entrance at 536 m a.s.l. The main passage begins very steeply and is covered by massive breakdown limestone blocks but also a fair number of allochthonous blocks, mostly basalt. One of them is over 1 m in length and much less rounded than the boulders in other caves.

5.2 ***The significance of cave sediments***

Caves are about the best environments one can hope for, for the preservation of undisturbed sedimentary sequences. Not all caves are equal though, maze caves and branching caves being the best in terms of preserving sediments, floodwater caves the worst. That would make most caves of VIK unsuitable for sediments and the fact a few do have them is remarkable. But there is one major difference: the bulk of cave sediments in this case are very coarse ones, blocks and boulders.

Studies on Castleguard Cave, which extends under and active alpine glacier and has many similarities with VIK caves (Smart, 1986) revealed that while water drainage is very active underneath glaciers, sediment transport is very restricted. It is therefore inferred that massive sediment deposits in glaciokarst accumulated during interstadials.

As mentioned before, there are no sedimentary sequences preserved in caves of VIK that can in any reliable way be attributed to pre-FG times. In fact the scarcity of gravel and sand (the most frequent cave sediments) in VIK caves suggests that either there was no sediment transport into caves prior the FG (a rather unusual situation) or that the caves were not there at that time. One could of course invoke paroxystic flushing of sediments by repeated flooding during deglaciation but in caves like Chicken II, where plugged passages were preserved, the sediments contain large rounded allochthonous boulders as well, suggesting a glacial origin. So the absence of larger caves before the FG remains a reasonable deduction.

The very large, yet rounded allochthonous blocks and percussion marks on some of them is solid evidence for very energetic water transportation through caves and, as mentioned before, that could have been by subglacial flooding.

6. The subglacial environment and karst

6.1 ***Subglacial flooding***

Recent years and systematic work by John Shaw (2002) at the University of Alberta and other Canadian geologists have brought into light a geomorphic force long ignored or discarded: subglacial sheet floods. Repeated outbursts of meltwater accumulated at the base of the Laurentide Ice Sheet proved to have shaped the land much more than previously accepted. From depositional forms like drumlins to erosional forms like grooves, channels and potholes, subglacial drainage has left a deep signature in the Canadian topography. To my knowledge, the effects of such floods on caves have not been rigorously studied anywhere in Canada, even if it is common knowledge that all Canadian karst areas have been covered by ice. The traditional view seems to be that karsting processes are slowed down or even arrested by ice caps and only during the final, melting phase will occasional meltwater flooding either plug or un-plug cave passages. Sediments preserved in many of VIK caves tell a different story.

During the FG, the lower caves were below sea level and one would expect the only ones active were those at higher elevation today (Resonance, Arch, Glory 'ole, Thanksgiving etc.) Given the particulars of the ice cover over the island though, such a situation may have been valid only for WCK where the CIS terminated as sea ice. Since at the peak of glaciation the Strait of Georgia was completely plugged with ice and consequently there was no physical sea level, only a virtual one. The glacial grooves on the floor of the strait suggest a cold (dry) based glacier. Consequently if there was any drainage of meltwater it was not enough to lubricate the base of the glacier. Furthermore, one can reasonably assume that most of the karst outlets were plugged most of the time and the caves behind them flooded. On the west coast on the other hand, if the ice cap ended abruptly into an ice shelf and/or the continental ice continuously calved into the ocean, it is possible that the karst outlets were active most of the time and karsting may have proceeded at a steady pace. That would explain the length of cave systems in the WCK.

6.2 *A case for englacial pseudokarst*

One other aspect needs to be considered with subglacial meltwater floods and does not appear to have been a major concern for most of the authors I consulted: what happened to the superjacent ice? High-velocity subglacial water displacement must have seriously affected the ice, breaking it up into large blocks. Present-day fragmentation of continental ice sheets is generally attributed to ice flow (uneven bedrock), tectonics and earthquakes (Davis, 2007). The large amounts of subglacial meltwater suggest another major source of glacial fragmentation.

As mentioned before, Shaw has proposed that glacial sediments like drumlins accumulated between the bedrock and melt hollows on the bottom of the ice (Shaw, 2002). Shaw however has not dealt with the extent of such melt hollows inside the ice (englacial cavities).

The existence of karst-like features in ice deposits (thermokarst or more accurately thermopseudokarst, Silvestru, 1990) has been recorded for a long time. The Saint Gervais catastrophe in 1892 at the foot of Mont Blanc in France (175 people were killed by the catastrophic drain of an estimated 200,000 cubic meters of water released from an elevation of over 3,000 m underneath the Tête-Rousse Glacier (Vincent *et al.*, 2010), has given water circulation in glaciers (through karst-like conduits) a new and frightening dimension. It was however through the advent of extreme exploration inside glaciers that the true extent and similarities with orthokarst (Silvestru, 1990) were revealed. Ben & Gulley (2005) clearly state, after having surveyed nearly 3 km of englacial cave passages in the Himalayas:

> "Indeed, we found that current glacial hydrological theory is inadequate in almost all respects to explain the characteristics and distribution of the caves and that karst hydrology provides a much more powerful theoretical framework."(p.14)

What they essentially refer to, is the existence of a karst-type aquifer throughout massive ice deposits which would behave in similar ways. The morphology of cave passages (Fig.18) further confirms the analogy with karst caves.

Fig. 18
Deliverance Cave in the Ngozumpo Glacier, Khumbu Himal (Himalaya), Nepal. (from Ben & Gulley, 2006).

Another, somewhat more complex type is the subglacial thermopseudokarst like the one in Iceland, which is connected to the surface through massive shafts created by steam from geothermal vents but also through an intricate network of englacial conduits (Sjogren et al., 2002; Vander-Molen, 1984). Such a superposition would increase the amount of water circulating through the ice and extend the network of conduits, because warm water and air is added to the system. The situation would have been much more dramatic if lava flowed underneath the ice!

It is known that the volume of water that circulates from the top of ice sheets to the bottom is staggering. Sneed & Hamilton (2006) have calculated that a surface of ~172 km^2 of the Greenland Ice Sheet, during the month of August, produced a volume of meltwater of 3.4 x $10^7 m^3$. One can imagine the volume of meltwater running through englacial pseudokarst at the peak of melting at the end of the Pleistocene! Thus, englacial pseudokarst could have provided a significant number of concentrated inputs (point recharge) into the pre-existing subjacent karst. This is a plausible explanation for the unusual geomorphic setting in which Dreamtime Cave entrance is found (Fig.15)

6.3 *A case for subglacial karsting*

At the foot of the CIS, such volumes of water would have caused a number of different effects on the subjacent karst. First, the pressurized flow (confined between the bottom of the ice cap and the bedrock) would force drainage through the caves (and any interconnected fractures), even if they were plugged with sediment, in a manner not common to normal, subaerial floods and floodwater caves (Palmer, 2007, pp.198 – 204). Let us provisionally call this "high pressure flushing" which could be added as a 10^{th} effect in Ford & Williams' list above. Of course, the 7^{th} effect on that list would also be considerable as the hydraulic head would have been significantly increased by this confined flow. Inflowing water would not only flush, it would also bring its own sediment load, elements of which are still present in caves today even at high elevations and pure alpine settings like the Holely Mt. karst. The sediment load on the other hand, especially at the high flow velocities during high pressure flushing episodes, would also cause significant abrasion of the karst conduits and thus enlarging them. The massive input of aggressive water (see above) would have dramatically accelerated solutional karsting. High velocity, high pressure flow and massive sediment load could well explain how cave passages can cut through igneous dykes.

Subterranean point recharge with aggressive allochthonous waters coming from within igneous rocks have been recorded at the boundary between karst and non-karst rocks (Silvestru *et al.*, 1995).

Traditional karst science (known as "karstology" in Europe) maintains that cold, sub- or periglacial meltwater is incapable of dissolving much carbonate. Lauritzen (1986) has found CO_2-depleted water beneath glaciers concluding karsting is negligible in such conditions. The author obviously assumes that carbonic acid corrosion of limestone was the predominant karsting agent. However, the chemistry of solutes in glacial meltwaters points out that it may have other sources of acidity. Thus HCO_3 solute flux in $kgkm^{-2}$ of bulk meltwater runoff at Longyearbreen, Svalbard in 2004, was 5410 whilst the SO_4 was 11400 (Yde *et al.*, 2008). The source of sulfate is both atmospheric (aerosols) and crustal (the rocks). H_2SO_4 karsting is significantly faster than H_2CO_3 so if the meltwaters underneath the Vancouver Island section of the CIS had at least periodic sulfate pulses, due to subglacial volcanic activity, karsting would have proceeded with CO2-depleted meltwaters. Cooley and Rockslide lakes in south-central British Columbia have recorded up to 15 layers of tephra originating from known volcanoes in the Holocene alone ranging from 2100 to 6060 calibrated years BP (Franklin *et al.*, 2004). Many more Late Holocene layers of tephra have been found in northern BC (Lakeman *et al.*, 2008). It is safe to assume a similar level of volcanic activity during the Pleistocene. Rounded gravel I found at higher elevations on the lower mainland BC, in the Okanogan Valley, near Summerland (and which was almost certainly transported by subglacial drainages) is also present in volcanic agglomerates in the area which suggests subglacial eruptions. The CIS almost certainly contained layers of ice with tephra impurities which could have also contributed to the acidification of meltwater. Unfortunately there are no direct ways to test such a case because at the time there were no lakes (like in the Holocene) to preserve tephra and the ice that once may have contained significant amounts of it is long gone.

Sulfuric acid karsting in the cold subglacial conditions, especially in flooded and drastically flushed caves would have not left the classical signatures of known sulfuric acid karst: spongework and network mazes and secondary sulphates minerals.

All the above are building an acceptable case for subglacial karsting as the main geomorphic agency of VIK. If that was the case, one would expect a slight difference in the way subglacial karsting unfolded on Vancouver Island, according to location.

6.3.1 *East coast karst*

At whatever elevation the resurgences of karst drains were placed (above or below the virtual sea level) each one had the bottom of the CIS as base level. As previously mentioned, there are indications that in what is now the Strait of Georgia, CIS was cold-based so that most of the subglacial karst waters would freeze by the time they reached the bottom. Thus karst drains would be sealed or at least forced to accumulate large volumes of water and flood. Increased hydraulic head would have resulted from this. As long as the bottom of CIS was stable, the transit of meltwater through the flooded caves would have been slow but active, given the massive hydraulic head caused by the superjacent englacial pseudokarst. However, it is quite possible that seismic activity (the whole area is seismically active) and volcanicity could have caused sudden episodic draining/flushing of the flooded karst aquifers. These episodes would have increased karsting rates. As a consequence one would expect cave systems to be quite well developed and drains established.

6.3.2 *Interior karst*

The fact that today the karst in this area has rivers or lakes as base level suggest that when CIS was covering it, the base level was controlled by glacial erosion so that subglacial geomorphology would be less favorable to karsting except where the pre-glacial landscape already created sufficient hydraulic head i.e. karstic rocks high above pre-glacial valleys. In the case of ECK the hydraulic head resulted from the proximity of a very large depression – the Strait of Georgia. If, as one would expect, the surface of CIS was not perfectly flat but rather followed the subjacent morphology, it was lower over the strait and higher over Vancouver Island, only to lower again close to the Pacific Ocean. That would have normally directed drains in the englacial pseudokarst towards the strait and the ocean i.e. ECK and WCK leaving the center (IK) with less meltwater reaching the karst rocks. Significant dislevelment was present in the Gold River area where the Q5 system is located well above 1000 m. Indeed, of all the IK, this is the only karst area with a significant cave system (see Table 2).

6.3.3 *West coast karst*

As mentioned before, on this side of the island the CIS thinned significantly, becoming an ice shelf. Such a setting would make the ocean an effective base level even for subglacial karst. With the particular geological setting (Fig. 10) of the limestones in the area and vast amounts of meltwater draining toward the ocean, the establishment of extended karst drains was unavoidable.

7. The age of VIK

The existing radiometric data from VIK speleothems places the oldest speleothem (from Cascade Cave in the Port Alberni area) at 18.5 ka with a continuous precipitation until present (Latham et al., 1987). The calculated growth rates range from 7 to 24.1 mm/ka. A more recent study on a stalagmite from Arch Cave (Marshall, *et al.*, 2009) yielded a U-Th age of 12,500 years with growth rates ranging from 6 to 41 mm/ka. The same study provided paleoclimate reconstructions based on $\delta^{13}C$ and $\delta^{18}O$ which in many ways is at odds with karstological and especially geological data. It is thus concluded that there were warmer, wetter conditions at the end of the Younger Dryas, during the Holocene Maximum and the Medieval Warming. The warm peak is placed at 8000 y BP. Cooler periods were inferred at 3500, 8200 and 11,500 y BP and during the Little Ice Age. However, none of the studies above have addressed the fact that the caves were covered by a thick ice cap and had therefore made no corrections for meltwater. These studies presented data in the same manner as paleoclimate reconstructions in temperate, unglaciated karst areas. The authors even mention that the cave "*was chosen for its proximity to the ocean so as to reflect a global climate history*" thereby overlooking the fact that the VIK (especially Arch Cave with an entrance elevation today of 660m) was undoubtedly a subglacial glaciokarst during the Younger Dryas and maybe periglacial glaciokarst during the Holocene Maximum and it was meltwater transiting through thick, layered ice that dissolved limestone and deposited speleothems. The isotopic contents of the melted ice is unknown and so is the isotope fractionation history, so one should be cautious with the interpreted data. However, there is a clear discrepancy between the speleothem paleoclimate reconstructions, the basic glaciological reconstructions, the isostatic and eustatic variations and speleogenesis. And this discrepancy is further accentuated by a marine abrasion cave on the west coast of the island – Port Eliza Cave located at 85 meters a.s.l. The radiocarbon age of bone remains in this cave range from 18,010 y BP to 9,500 y BP; U/Th dating of dripstone fragments (in a non-karstic cave) found inside clay and silt unbound sediments in the cave yielded an age of 16,500 y BP. A stalagmite and fragments of a stalactite on top of the cave sediments yielded ages of 5,100 and 3,200 y BP. (Al-Sawaidi, 2006) The data from this littoral cave sediments require repeated episodes of deglaciation during the FG which cannot be correlated with data from other locations. Unless, as mentioned before, this is not a marine abrasion cave.

It is not the purpose of this paper to resolve the discrepancies between speleothem dating and paleoclimate reconstructions but rather to assess speleogenesis in glacial conditions. The data associated with the studies mentioned above reveals that speleothem formation was not really affected by the FG. It is therefore quite probable that karsting itself was not slowed down either, for the reasons mentioned above.

Trying to estimate the age of the caves themselves however turns out to be more difficult. One thing seems certain though: the caves – at least the ones with dated speleothems - predate the Fraser Glaciation. Port Eliza Cave was definitely fully formed before the FG in order to receive and store the complex set of glacial sediments it still preserves. Furthermore, it had to be 85 meters lower than it is today which could have only happened at the peak of some older than FG glacial depression. But in order to have marine abrasion, the rocks in which the cave were excavated had to be directly exposed to open sea, even if the land was depressed 85 meters by the ice sheet! Unless at that particular moment in time the sea level was 85 meters higher than today which of course should have caused many other karstic caves to be invaded by the sea which, as mentioned before, is not the case. I would contend that the Port Eliza Cave data is so different from the rest of the karstological, geomorphological and sedimentary data from Vancouver Island that it should be used with caution or even ignored for the time being. An alternative would be to reinterpret it as a type of parakarst (Silvestru, 1990) formed not by marine abrasion but by hydrothermal alteration of the parent rock followed by subglacial wash-out.

As mentioned before, one can use a morphogenic and geomorphic proxy - Castleguard Cave (CG) in the Canadian Rockies - which is very similar to the VIK caves (Fig.19). In fact the upper sections of CG run under the Columbia Ice Field and many passages end in the ice itself, situation that must have existed in VIK during the FG. Radiometric dating coupled with paleomagnetic data has led Ford et al., (2000) to believe CG was already relict well before 780 ka. The authors infer the cave has survived with a juvenile morphology through the whole of Quaternary. However, if karsting processes were not hindered much by the FG – the most intense stadial – there seem to be no reasons to assume previous stadials did. If such is the case, why would such a major cave not mature, unless it is much younger than stated by Ford *et al.*, (2000). How much younger though? This is where VIK can lend a … cave.

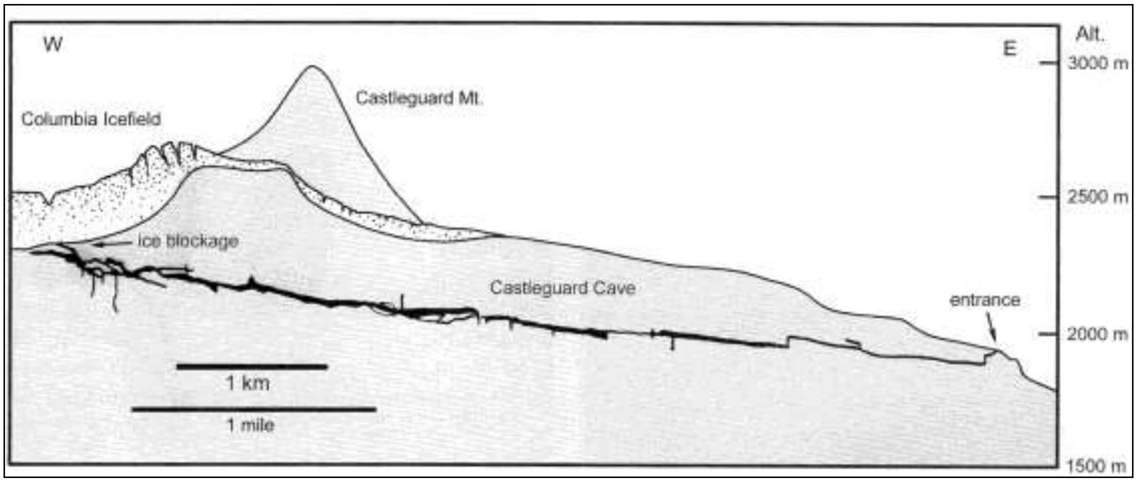

Fig. 19
Simplified cross-section through Castleguard Cave, Alberta, Canada (from Palmer, 2007, p.47).

Based on the facts and inferences mentioned before, it is reasonable to assume VIK caves speleogenesis was triggered sometime before the FG when most of the karst rocks were exposed by glacial erosion during the Semiahmoo Glaciation. During the FG the caves were enlarged dramatically and extensive subterranean drainages were established. This would mean that the assembly of VIK was created in no more than 50 ky, possibly even less.

One puzzling element, given the paleogeography of the island is the absence of any paleokarst. As shown in Fig. 3, according to the standard interpretation there have been extensive periods of subaerial erosion on the island and for most of the time the island's climate has been ideal for karsting. In addition to favorable exogenous karsting conditions, the ubiquity of igneous and volcanic rocks has undoubtedly provided an abundance of hydrothermal activity which could have generated copious endogenous karst. Mineral deposits on the island include porphyry copper in the Jurassic Bonanza Group rocks (Yorath, 2005), colloform magnetite in metasomatic deposits in the QL (Stevenson & Jeffrey, 1964) as well as placer gold (of hydrothermal origin).

One can of course appeal to the imperfection of the rock record and glacial erosion as having completely obliterated paleokarst features, but given the complexity of the island's topography and geological makeup, that would be simplistic and it does not adequately meet the burden of proof.

This is a preliminary assessment of karst features on Vancouver Island. It aims to provide a general framework which can then guide further detailed investigation and possibly help focus it in a correlative way rather than the disjointed in which it seems to have been unfolding thus far. Future data may of course confirm or reject this framework but I believe the glaciokarstic label will withstand all future scrutiny.

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