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TECTONIC INCEPTION IN CALEDONIDE MARBLES
TEKTONSKA INCEPCIJA V KALEDONSKIH MARMORJIH

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Abstract: UDC: 551.24:551.44(48)
Trevor Faulkner: Tectonic inception in Caledonide marbles
A fundamental difference between caves in sedimentary limestones and those formed in a repeatedly-glaciated 40000 km^2 region in central Scandinavia that contains over 1000 individual marble outcrops and has nearly 1000 recorded karst caves is the metamorphic grade of the karst bedrock and its negligible primary porosity. Allied to this is the fine-scale foliation and consequent lack of 'bedding-plane' partings. Indeed, the foliation is commonly vertical in the western part of the study area, where sub-horizontal openings must be along joints or other fractures. The deepest cave is only 180 m deep, despite outcrop vertical ranges reaching over 900 m. Caves tend to cluster together and are positioned randomly in a vertical dimension, whilst commonly remaining within 50 m of the overlying surface. Additionally, despite some stripe karst outcrops being several tens of kilometres in length, there are no regional scale caves, and karst hydrological system distances are invariably shorter than 3.5 km. Because the caves are relatively short and epigean and there is a complete absence of long, hypogean, cave systems, speleogenesis by the (chemical) inception horizon hypothesis is unlikely.
A tectonic inception model is derived that proposes that it is only open fracture routes that could provide the opportunity for dissolution and enlargement into cave passages in the Caledonide marbles. It is hypothesised that the dimensions of these fractures are related to the magnitude, and perhaps to the frequency, of local earthquakes and commonly-small tectonic movements that arose mainly from the isostatic rebound that accompanied deglaciation at the end of each major Pleistocene glacial. The openings formed along *inception surfaces* between the limestone and adjacent aquicludes and at *inception fractures* that are entirely within the limestone and are commonly (though not universally) parallel to, or orthogonal to, the foliation. The model builds on reports of a 'partially detached' thin upper crustal layer in similar settings in Scotland and is supported by observations of later neotectonic movements, as indicated by sharp edges and slickensides in most present relict cave passages and sporadically on the surface.
Keywords: Caledonide, epigean, foliation, ice margin, inception fracture, inception surface, marble, near surface aquifer, neotectonics, seismicity, tectonic inception, stripe karst, Weichselian.

Izvleček: UDC: 551.24:551.44(48)
Trevor Faulkner: Tektonska incepcija v kaledonskih marmorjih
V centralni Skandinaviji je več kot tisoč izdankov marmorja v katerih je znanih preko tisoč jam. Razlika med temi jamami in tistimi v apnencih, je pogojena s procesi metamorfoze in zanemarljivo primarno poroznostjo prvih. S tem je povezano drobno plastenje (foliacija) in posledična odsotnost lezik. Najgloblja jama je globoka 180 m, kljub temu, da vertikalni razpon izdankov znaša do 900 m. Jame največkrat najdemo v skupinah in so v vertikalnem merilu precej naključno porazdeljene, pri čemer jih redko najdemo več kot 50 m pod površjem. Kljub temu, da so nekateri izdanki pasastega krasa dolgi več deset kilometrov, zelo dolgih jam ne poznamo, kraški hidrološki sistemi pa ne presegajo dolžine 3.5 km. Ker so jame kratke in blizu površja, je kemijska incepcija manj verjetna. Zato predlagam model tektonske incepcije, ki predvideva, da so jame v kaledonskih marmorjih nastale zgolj vzdolž sistemov odprtih razpok, pri čemer je dimenzija in frekvenca teh razpok povezana z magnitude tektonskih premikov, ki so nastali kot posledica izostatičnega uravnoteženja ob umikih ledenikov po ledenih dobah. Sistemi takih razpok so nastajali vzdolž incepcijskih površin med marmorji in neprepustnimi plastmi in vzdolž incepcijskih razpok v marmorjih, ki so vzporedne ali pravokotne s plastenjem. Model gradim tudi na poročilih o delno odcepljenem tankem vrhnjem delu skorje v podobnih okoljih na Škotskem. Model podpirajo tudi opažanja kasnejših neotektonskih premikov, na katere kažejo ostri robovi in tektonska zrcala v jamah in na površju.
Ključne besede: Kaledonidi, plastenje, rob ledenikov, incepcijska razpoka, incepcijska površina, marmor, plitvi vodonosnik, neotektonika, seizmičnost, tektonska incepcija, pasasti kras, Weichelij.

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INTRODUCTION

Central Scandinavia is a repeatedly-glaciated 40000 km^2 region that contains over 1000 individual Caledonide marble outcrops and over 1000 karst caves with a total passage length >72 km, within an area about the size of Switzerland (Fig. 1). A factual review of data assembled into karst and cave databases (Faulkner, 2001 and 2005a) revealed that cave development has been predominantly phreatic, so that, commonly, just a single vadose streamway underlies upper-level relict phreatic passages with few vadose elements, creating an *upside-down* morphology. Recharge to the karst is primarily allogenic and discharge commonly remains unsaturated with calcite; autogenic recharge is relatively insignificant, mainly occurring during the spring snowmelt. These caves have their own morphological style, recognisable right across the area, which differentiates them from caves formed in 'classical' karsts in sedimentary limestones. A key question to address is "Why do these caves exist at all?"

THE INCEPTION PROBLEM

The Inception Horizon Hypothesis (IHH; Lowe, 1992; Lowe and Gunn, 1997) proposed that the initiation of proto-conduits occurs as a syngenetic cave formational process during diagenesis. The long, slow, *non-karstic*, inception phase is driven by capillarity, earth tides or ionic diffusion at great depth and over great distances *within stratigraphical partings* or *adjacent porous or fractured rocks*. Eventually, chemical dissolution increases conduit sizes to explorable dimensions. How does this hypothesis stand in relation to the karsts and caves of the study area?

LACK OF PRIMARY POROSITY

Most of the high (up to amphibolite) -grade metalimestones of the study area exhibit little memory of their original diagenesis, after their subduction and metamorphism to marble at elevated temperatures and pressures: any proto-conduits formed syngenetically during diagenesis were closed as the rock experienced chemical and physical changes in lithology. The recrystallisation to metacalcite produced a rock with a fine-scale foliation and a primary porosity that can be regarded as negligible, even over the long timescales available for 'conventional' inception. The same applies to any mica schist, amphibolite, granite or gneiss lying adjacent to the marble: these rocks could not have sufficient primary porosity to act as aquifers carrying water to the limestone surface.

LACK OF STRATIGRAPHICAL HORIZONS

The foliation is commonly vertical in the western Helgeland Nappe Complex (HNC; Fig. 1), but caves in such vertical stripe karst (VSK; foliation dip 81–90°) commonly display morphologies similar to those in horizontally-bedded limestones, with many horizontal passages orthogonal to the foliation (Faulkner, 2005a), despite the lack of inception horizons to guide their formation along particular bedding plane partings. There are also no consistent systems of sills or other intrusions to act as inception horizons, so that the horizontal openings must be along joints or other fractures.

LACK OF REGIONAL-SCALE SYSTEMS

The IHH suggests that inception takes place over extremely long timescales, at great depths and over great distances. There is no evidence that such a mechanism has taken place in the study area, despite some of the *'stripe karst'* outcrops exceeding 50 km in length. There are no regional-scale caves; there are no known allogenic or autogenic sink-to-rising hydrogeological drainage systems longer than the 3.5 km that occurs at Vallerdal on the border between Norway and Sweden; and there is no evidence of very deep cavities or wells in the metacarbonates. The steep foliation and metamorphic history have left many completely separate stripe karsts. Their contained caves are, by necessity, commonly short (mean length = 85 m) and completely unrelated to each other internally, even if proximate in the field, so that regional-scale inception is not possible.

EXISTENCE OF SHALLOW SYSTEMS

Despite the large vertical range (VR) of some of the metalimestone outcrops (up to 956 m), the deepest cave is only 180 m deep, and only four others are more than 100 m deep. The mean cave VR is only 8.8 m and it rarely exceeds 15% of the local outcrop VR. Thus, the caves are commonly extremely epigean and there is a total absence of long, hypogean, cave systems. It is self-evident when visiting such systems (e.g. a short shallow 'through cave' that carries a stream along a vadose passage from one

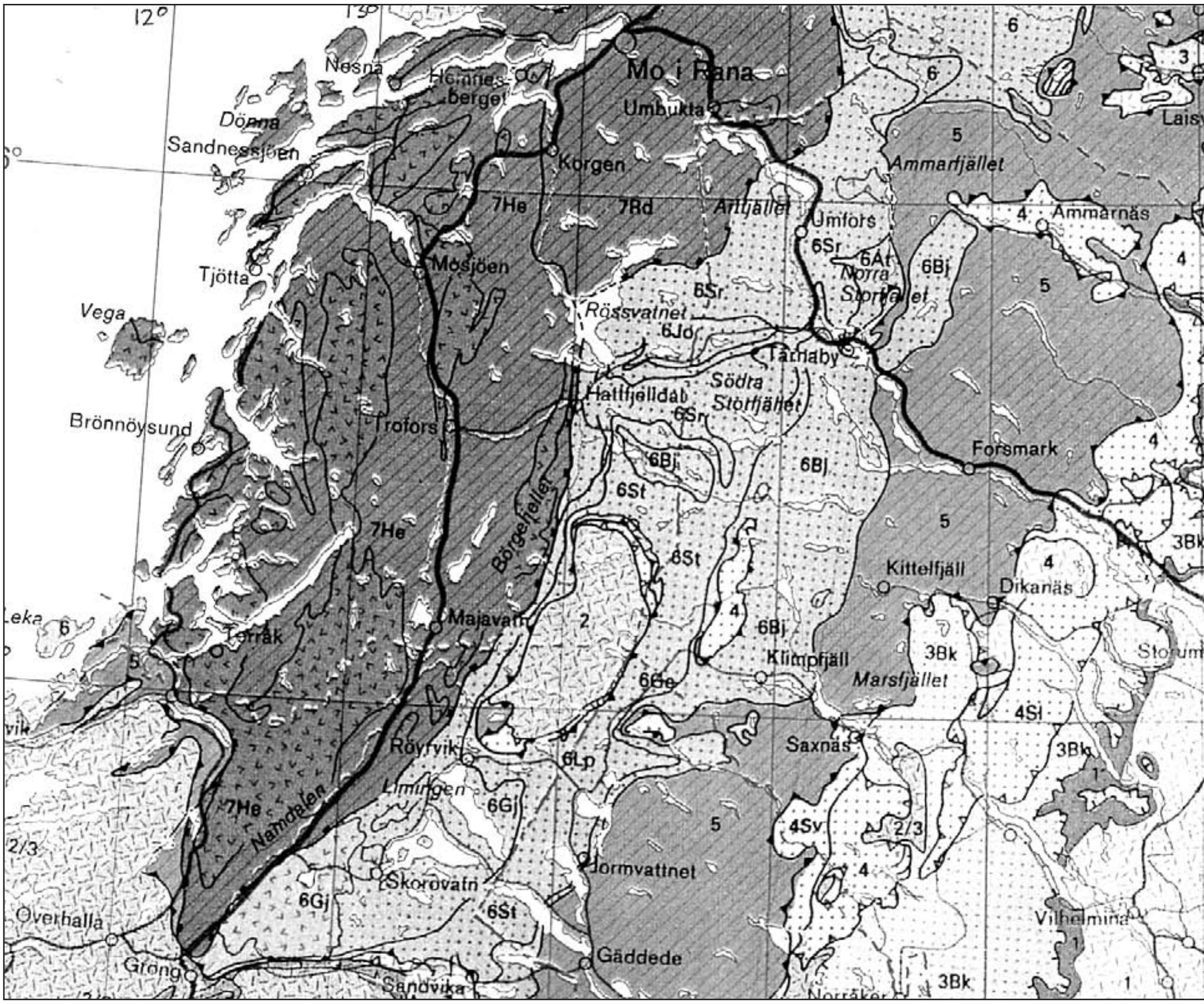

Fig. 1: Tectono-stratigraphic map of central Scandinavia, from Gee and Sturt (1985). The numbers indicate the area's various allochthons and nappes. Most nappes contain metacarbonate outcrops that are commonly aligned N–S and decrease in size (along with a common reduction in metamorphic grade) in an easterly direction. Caves are only recorded in metalimestone outcrops in the Uppermost Allochthon (7; i.e. in the Helgeland Nappe Complex, HNC and the Rødingsfjell Nappe Complex, RNC) and in the Køli Nappes of the Upper Allochthon (6). Small marble outcrops occur in the Seve Nappes of the Upper Allochthon (5) and in the Lower Allochthon (3), without recorded caves. The Middle Allochthon (4) does not contain metacarbonates.

entrance to another) that such passages have no relationship to any deeper, regional-scale, hydrogeology, even if it existed. Whereas it could perhaps be considered as a possibility that *all* such short and shallow caves are the lowest remnants of much longer systems formed deep below landscapes that have since been eroded away, this seems most unlikely as the carbonate outcrops would not have been consistently longer in the past than at present.

THE IMPLAUSIBILITY OF THE IHH TO EXPLAIN INCEPTION IN SOME METALIMESTONES

From the four arguments presented above, the IHH cannot explain the inception of the overwhelming majority of caves in the study area. However, elements of the Hypothesis may explain parts of the inception process in some caves, or groups of caves. For example, inception that is *guided* along sub-horizontal aquicludes within the foliation of marbles in low angle karst (LAK; foliation dip 0–30°) seems likely, as at **Ytterlihullet** in Bryggfjelldal. Similarly, inception along-strike at lithological boundaries within lower grade metacarbonates in angled stripe karst (ASK; foliation dip 31–80°), as at **Korallgrottan** in Sweden, is also feasible. However, even in these examples, another mechanism is needed to explain an initial porosity.

THE TECTONIC SOLUTION

Despite the difficulty in utilising the IHH to explain the inception of the studied caves, these caves exist and their origins must post-date the last phase of metamorphic activity. The consistent style of the caves suggests that a consistent set of processes guides their inception, development and eventual destruction. Two major clues to the inception process were noted in analysing the cave morphologies: externally, their epigean association with the landscape, and internally, the dominance of relict phreatic passages.

ASSOCIATION OF CAVES WITH LANDSCAPE

All cave passages in both VSK and ASK lie within 50 m of the overlying surface. Even in **Ytterlihullet** (LAK), all parts of its streamway are ≤93 m below the surface. Its stream resurges, flows along a short surface valley, and then sinks again in the same limestone outcrop before finally resurging some 200 m above the base of the limestone, and some 300 m above the valley floor. Thus, this cave and most other active caves act in harmony with local hydrology and have an intimate, *epigean*, association with their local landscape. It seems safe to assume that these caves evolved in association with the shaping of their local topography, whose dominating process is the cycle of glaciation and deglaciation that has been repeated many times since the late Tertiary.

RELICT PHREATIC PASSAGES

The absence of relict vadose caves shows that all relict caves in the area developed phreatically, as did nearly all the higher-level abandoned passages in the active caves. However, it is not possible to imagine present circumstances, even during spring melt, when most of these relict caves could be flooded to create phreatic conditions for their enlargement. It *may* be possible to envisage earlier landscapes where these passages were submerged under meteoric conditions, but a much simpler explanation is that these passages enlarged subglacially or during deglaciation phases, when whole valleys could be inundated by glacial meltwater.

THE TECTONIC INCEPTION MODEL

The development (and destruction) of the present suite of karst caves can therefore be addressed by considering the way that glaciation has eroded the land surface, and perhaps provided sufficiently aggressive meltwaters to enlarge passages by dissolution. But these processes cannot explain the actual inception along proto-conduits. Without such openings, glacial meltwaters would not penetrate into high grade metalimestone, even under pressure.

The *Tectonic Inception Model* hypothesises that, through several separate, but commonly related, mechanisms, the stress release arising from the isostatic rebound and surface erosion that accompanied deglaciation at the end of each glacial cycle, plus longer-timescale plate tectonics, caused the formation of tectonic fractures in the upper (epikarstic) part of the limestone (Fig. 2). Thus, openings are created along *inception surfaces* between the limestone and adjacent aquicludes (which may include dolostones), and by *inception fractures* that are entirely within the limestone, but are commonly (though not universally) parallel to, or orthogonal to, the foliation. This model builds on the observations that "*the continuing seismic and tectonic activity* (in similar settings) *in Scotland may be best understood in terms of a 'partially detached' thin upper crustal layer*" (Davenport *et al*., 1989, p 191) and that near-surface limestones are not very ductile and produce brittle fractures during folding, faulting and removal of overburden stress by erosion (e.g. Doré and Jensen, 1996, pp 426–427). It is also assumed that the maximum thickness of permafrost during glaciation is c. 100 m. Rock above this level is subjected to more severe temperature cycling and freeze-thaw processes than rock below it, and is therefore more likely to form inception fractures when triggered by seismicity. The practical expression of these processes was provided by Boulton *et al*. (1996, p 403), who noted from pumping tests that the crystalline basement rocks of the Scandinavian shield (primarily non-carbonates) have "*a surface horizon of fractured bedrock about 100 m thick which has a hydraulic conductivity of* $10^{-6}ms^{-1}$". This provides a *near surface aquifer* that is commonly found in crystalline rocks worldwide (Gustafson and Krasny, 1994).

The idea of tectonic speleogenesis in karst rocks has a precedent, because Riggs *et al.* (1994) proposed this at

Fig. 2: Marble at Indråsen quarry, Velfjord: Shattered nature of the epikarst in high-quality metalimestone altered by contact metamorphism.

Devils Hole, Nevada, although without subsequent dissolution. The only known paper to discuss the importance of fracturing by stress release in the development of cave passages in sedimentary limestones was by Sasowsky and White (1994), who anticipated some of the processes described herein, but for a non-glacial setting in Tennessee.

THE GLACIAL / TECTONIC CYCLE

Because the tectonically-induced inception fractures are commonly produced at the *end* of each glaciation, there may not always be sufficient time for phreatic passages to enlarge to explorable dimensions during the remaining time of that particular deglaciation. Hence, the cyclic processes of glaciation, deglaciation and tectonic opening combine together to develop cave passages: tectonic inception provides fractures that permit the circulation of meltwaters that can be chemically aggressive even without dissolved CO_2 (Faulkner, 2004a and b; 2005a), both during that deglaciation and during the next glacial and deglacial phases. As the cycle repeats itself, passages near the surface enlarge and become removed by glacial and fluvial erosion (as noted by Isacsson, 1994, at **Korallgrottan**), and new passages form at geologically lower levels.

FORMATION OF TECTONIC FRACTURES

Tectonic inception (and indeed any *inception* hypothesis) is not easy to *prove*. Tectonic fractures may be too narrow to observe visually and may no longer be recognisable after karstic dissolution and enlargements to explorable passages. Thus, the Tectonic Inception Model is supported by several lines of evidence for Caledonide tectonism and fracture formation in the following sections. The *hydrogeology* of fractured rock, including fractured metalimestone, was considered separately by Faulkner (2003 and 2005a).

CALEDONIDE EVIDENCE FOR TECTONIC ACTIVITY

Faulkner (1998) reviewed recent ideas on the importance of tectonic activity to cave development in sedimentary limestones. The idea that tectonism *sensu lato* has influenced karst cave development in Norway has been suggested, or hinted at, by several authors. Thus, Hoel (1906, p 8) raised the possibility that **Aunhattenhullet 1, 2 and 3** and **Langskjellighattengrotta** in Velfjord in the study area were formed by "dislocations". Horn (1947: McGrady translation, 1978, p 135) noted that the Norwegian coastal area at the Arctic Circle is still unstable tectonically, which should favour joint formation, or the widening of old joints. Kirkland (1958) thought that collapsed blocks on the floors of chambers in the Svartisen area could have resulted from movements along faults and from seismic disturbances. Lauritzen (1989a, 1989b and 1991b, p 122) suggested that cave passages in Norway are almost always guided by the line of intersection between two planes (but see section 4). His statistical analysis revealed that commonly shear fractures (faults and shear joints) and less commonly tension fractures are utilised as primary guiding voids for speleogenesis. Onac (1991) noted caves formed by gravitational mass movement near Narvik, and the influence of tectonic faults in guiding subterranean streams.

Randall *et al*. (1988) reported on the hydrogeological framework of the NE Appalachians (USA), a region with a comparable metamorphic Caledonide geology. They noted high hydraulic yields from fractured non-porous bedrock, especially from wells that intersect contacts between different lithologies. Earlier work was quoted that showed that fractures decrease in size and frequency some 50–75 m below the surface. The water-table configuration in uplands nearly replicates the topography throughout the region, so that inter-basin flow systems involving significant flux have not been shown to exist, as in central Scandinavia. Carlsten and Stråhle (2001) reported that open, and partly-open, fissures were found in a borehole at Bodagrottorna in non-carbonate rock on the Swedish Baltic coast at depths at least down to 150 m, in an area that was very active seismically in the early Holocene.

TECTONIC MECHANISMS

Seismic and aseismic tectonic processes that create fractures can arise from several separate mechanisms. The evidence for considerable isostatic uplift during the melting of the 2–3 km-thick Weichselian icesheet is well documented. That part of the evidence for uplift that is associated with caves includes Sjöberg (1981a and b), who discussed 50 elevated caves in east Sweden formed by cobble abrasion at the coast of the Baltic, and Sjöberg (1988) who discussed elevated coastal caves in central Norway. That seismic tectonic activity accompanied the uplift was documented by: Husebye *et al*. (1978); Mörner (1980); Stephansson and Carlsson (1980), who discussed a Caledonian Zone of seismicity; Anderson (1980), who suggested that the maximum number of earthquakes after deglaciation would occur just inland along the coast, especially in regions of large elevation differences perpendicular to the coastline; Sjöberg (1987), who classified Swedish neotectonic cave types as occurring a) in split roches moutonées, b) in collapsed mountain slopes, and c) in sub-horizontally displaced mountain tops, and who postulated that talus caves in Sweden were formed by earthquakes caused by the early and rapid Holocene uplift that Mörner (1979) estimated at 20–50 cma^{-1}; Sjöberg (1996a), who dated the formation of scree and talus caves by a huge tectonic event at 9400–9200a BP; Sjöberg (1996b) and Mörner (2003), who recorded that the Swedish nuclear industry now accepted that Sweden suffered heavy earthquakes immediately after the Weichselian glaciation; Sjöberg (1996c), who listed Swedish Holocene earthquakes with magnitudes from 5–8 and showed how the formation of seismotectonic caves could be dated by studying soft sediment deformation in varved clay, as also discussed by Sjöberg (1999a and b); Kejonen (1997), who described seismotectonic crevice caves in Finland that developed from 12–8 ka BP; and by Mörner (2003) who presented 15 papers to demonstrate that Scandinavia was an area of high seismic activity at the time of deglaciation.

Mörner *et al.* (2000) noted that palaeoseismic events occurred in the Stockholm area about every 20 *varve years* from ~10490 to ~10410a BP, and listed 15 events in Sweden with magnitudes between 6 and >8 from ~12500 to ~1000a BP, some being associated with tsunamis. Because the records came from the whole of Sweden, no region was aseismic during the deglaciation period. The formation of the Bodagrottor talus cave (close to the borehole discussed in section 3.1) by the 'blowing-up' of a roche moutonée occurred at 9663a BP, by the dating of a varve that arose from a synchronous earthquake-generated tsunami that swept across the Baltic sea 33 varve-years after local deglaciation. From the size of the individually moved blocks, this earthquake may have had a magnitude >9–10. A map produced by Mörner *et al.* (2000) shows that each seismic event occurred as the ice margin passed overhead, commonly from west to east during deglaciation. Thus, from all this evidence, it is sensible to suggest that some fractures in the metacarbonates of the Caledonides were caused by surface strain release, or by deeper seismic activity, associated with the fast, early Holocene, uplift, at a time roughly coincident with the passing of the ice margin.

The uplift was not necessarily uniform, even at a local scale. Differential uplifts caused crevasses and other changes of slope, particularly along ridges. Braathen *et al.* (2004) described four types of failure of rock slopes that occur especially in valley shoulder locations, where Faulkner (2005a) showed that cave dimensions are maximised. Additionally, Warwick (1971), Ford and Ewers (1978) and Lauritzen (1986) suggested that pressure release at the sides of valleys could create fracture zones, including after melting of the local valley glacier (e.g. Fig. 3).

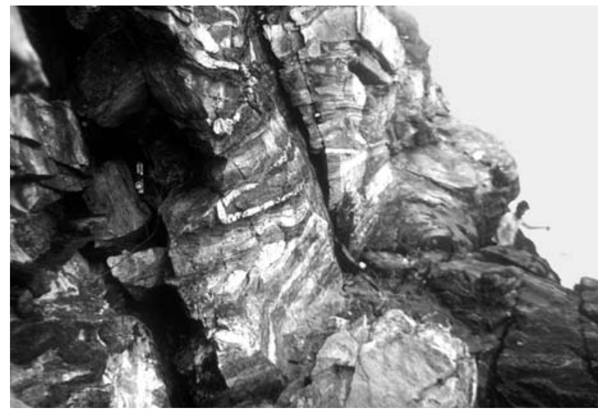

Fig. 3: Entrance to Johngrotta, Tosenfjord: Tectonic openings caused by pressure relief at side of fjord. Caving lamp for scale, at entrance to 15 m-long fissure.

Rohr-Torp (1994) found excellent linear relationships (R^2>0.85) between the local present rate of uplift (which itself is positively correlated with the total Holocene uplift) and the mean and median of both borehole yield and the reducing depth required to achieve an adequate yield, at sites across southern Norway. Concluding that young tectonic events have rejuvenated old fractures, he proposed a simple rule to predict the typical yield of a randomly-placed drilled well in Precambrian rocks in Fennoscandia: the yield is 180 Lh^{-1} at a place with 0mma^{-1} uplift from a well at 80–85 m depth, increasing by 100 Lh^{-1}, from a required depth of 6 m less, for each extra mma^{-1} of uplift. Present study area uplift rates vary from 2.5–5.5 mma^{-1}, going inland. The fracture patterns and dimensions that may support this groundwater storage and flow in Norway were discussed by Banks *et al.* (1996) and by Gudmundsson *et al.* (2002). Ford (1983, p 157) referred to this mechanism in Canada as *"isostatic groundwater pumping"*.

Thorson (2000) noted that there is now a blurring between the study of basic tectonics, and the study of *glaciotectonics*, and further, that seemingly trivial changes in stress may be sufficient to nucleate earthquakes, especially if there is a change in *crustal pore pressure*. Muir-Wood (2000, p 1410) stated that, at deglaciation, the tectonic strain energy that was accumulated during the whole period in which the icesheet had been in place "*can be liberated in a major seismic outburst*". Stewart *et al.* (2000) noted that horizontal plate motions normally drive crustal deformation, but with the onset of glaciation, this style is overprinted by the glacial stress, and new horizontal crustal motions increase outwards from the icesheet centre. They showed that subglacial water penetrates into the crust below enhanced icemelt in topographic hollows, increasing the pore-water pressure, and that large icesheets stabilise underlying crustal faults, whereas deglaciation destabilises the faults. Periods of cover by maximal Scandinavian icesheets represent times of seismic quiescence, due to the muffling effect of the weight of ice, as the land is gradually compressed and isostatically depressed (Johnston, 1987). In Fennoscandia, faulting is linked to zones with very steep ice gradients, or to the final stages of recession, when the bulk of seismic activity probably occurs within a few hundred years. During the similar deglaciation of Scotland, local movements were caused by differential glacial load flexure stresses (Davenport *et al.*, 1989; Ringrose *et al.*, 1991), at places with the steepest ice gradients (Stewart *et al.*, 2000). Johnston (1987) also noted that artificial reservoirs can trigger earthquakes by increasing hydrostatic pressure. It occurs to this author that local deglacial earthquakes may similarly be triggered by the formation of ice-dammed lakes. Fjeldskaar *et al.* (2000) suggested that stress-generating mechanisms can be grouped into three classes: first-order stresses across *Fennoscandia* that arise from the longer-term plate tectonic NW–SE compression ridge-push forces caused by oceanic spreading from the Atlantic Ridge; second-order stresses that are limited to *Scandinavia*; and third-order stresses that relate to *local* features (e.g. topography) and rarely extend beyond ~100 km.

Any of the above mechanisms may result in fractures open to the surface. They may fill with water in summer, so that any winter freezing would subject the rock to increased stress. The magnitude of any widening is proportional to the sub-zero (°C) temperature at the surface (Matsuoka, 2001). Although most widening is reversed on thawing, there is a tendency for the fracture to be permanently enlarged, and then to admit a higher volume of water during the next freezing cycle. The temperature cycling of rocks of differing lithologies that have unequal coefficients of thermal expansion would also promote fracture enlargement along contact zones. Indeed, Gudmundsson *et al.* (2002, p 64) stated that "*stresses tend to concentrate at the contact between dyke rock and the host rock and generate fractures that may conduct groundwater*". Thus, tectonism commonly leads to a growth in the size of the near-surface fracture network, even without invoking karstic processes. If ice-dammed lakes completely froze in winter or during a period of local permafrost, then submerged fractures would also be subjected to further stress and widening.

Another mechanism to increase fracturisation is *hydrofracturing* (e.g. Gudmundsson *et al.*, 2002). This process forces groundwater upwards through bedrock at gaps in permafrost, which may apply to metacarbonates during parts of the glacial cycle. At the base of a 500 m-deep ice-dammed lake, the excess pressure would be 50 atm. Thus, water can be injected into fractures that may occur within any underlying metalimestones, and, according to Banks *et al.* (1996, p 230), such pressures in a borehole may be sufficient to stimulate already fractured bedrock and to create new fractures. Lubrication by water would also amplify the effects of local seismicity.

There is no reason to suppose that the concentrated seismic creation of fractures during the Weichselian deglaciation was unique: similar processes must have occurred during the demise of all previous Cenozoic glacials (and perhaps stadials). However, from the speleothem chronozones proposed for Norway (Lauritzen, 1991a), there are long intervals of several 10 ka when speleothems did not grow, and full glacial coverage can be inferred. It therefore seems likely that the largest magnitude earthquakes only occurred once per 100 ka glacial cycle.

NEOTECTONICS

In addition to the postglacial uplift, there are two main sources of evidence of *neotectonics* in Scandinavia: the recent earthquake record, and the observation of movement along faults (e.g. Husebye *et al.*, 1978; Olesen, 1988; Bungum, 1989; Olesen *et al.*, 1992 and 1995). Local instrumentation can now record small earthquakes of magnitude 2, as summarised on a neotectonics map by Dehls *et al.* (2000a). The seismic events tend to follow N–S alignments at depths commonly focused above 15 km at the Atlantic Ridge, along the Continental Shelf edge, along the Norwegian coast, rather randomly along the border and onto the Swedish shield, and along the Swedish Baltic coast.

Many earthquakes have occurred in northern Norway and along the coast of southern Norway since 1750 AD, but lower frequencies and magnitudes coincide with the study area, which occupies a 'saddle' position between higher mountain ranges. Central Scandinavia probably acted as a focus for ice flow during late Cenozoic glaciations. With thinner icesheets, there was less stress relief and lower seismicity at each deglaciation. Additionally, increased ice flow increases glacial erosion, leading to less surface relief and less differential stress, and the increased sedimentation on the Vøring Plateau, off the coast of the study area, may have a dampening effect. The historical record of significant, but comparatively smaller and less frequent neotectonic earthquakes in the study area (Fig. 4) *may* be representative of relative seismic activity during the whole Holocene, although, following the 'pulse' of deglaciation seismotectonics, the style of seismicity does change, as noted by Stewart *et al.* (2000, p 1381): "*Whereas present-day seismicity is concentrated around the margins of the former icesheet, on deglaciation, earthquakes predominated at the centre of the rebound dome*". However, neotectonic earthquakes do follow the *Rana Fault Complex* south along the coast of the study area, and the largest recorded Northern European near-shore earthquake, of magnitude 5.8, occurred on 31 August 1819 AD in Rana, just north of the study area. Some 10000 micro earthquake shocks were recorded instrumentally at Meløy, 70 km north of the study area, during 10 weeks in 1978 (Bungum *et al.*, 1979). These were up to magnitude 3.2, were heard and felt locally, and caused cracks in walls and chimneys.

The documented active postglacial faults are commonly NE–SW-trending reverse faults that lie within a 400 km x 400 km area in northern Fennoscandia (e.g. Arvidsson, 1996). Their lengths and maximum scarp heights vary from 3–150 km and from 1–30 m. Fault offsets range up to 13 m (Dehls *et al.*, 2000b). A magnitude 4 earthquake occurred near one of these faults in 1996, when large amounts of groundwater poured out of the escarpment. The fault length to offset ratio indicates that the structure itself resulted from an earthquake with a magnitude above 7. The work of Olesen *et al.* (2004, p 17) *"supports previous conclusions regarding a major seismic 'pulse' (with several magnitude 7–8 earthquakes) which followed immediately after the deglaciation of northern Fennoscandia".*

The earthquakes may not just be caused by isostatic rebound after the removal of ice. They may also indicate the opportunity for adjustment to glacial erosion after the 'muffling' effect of the ice cover has gone. The 2 km-wide W–E Båsmoen Fault zone is just north of the junction between the HNC and the Rødingsfjell Nappe Complex (RNC) and can be traced for 50 km along Ranafjord (Fig. 4). It has a maximum displacement of 10 m, escarpments up to 80 m, provides evidence of recent movements (30–40 cm between 8780 and 3880a BP: Hicks *et al.*, 2000), and was associated with the 1819 earthquake. The Rana area was the subject of an in-depth seismic study, NEONOR, from 1997–1999, when some 267 local earthquakes were recorded with magnitudes up to 2.8 by Hicks *et al.*, (2000), who stated (p 1431): "*The Rana area has a significant amount of the total seismic activity in onshore northern Norway*" and concluded that postglacial uplift is the most likely cause for this continuing high level of seismic activity.

Muir-Wood (2000) discussed postglacial very shallow stress-relief phenomena, known as 'pop-ups', which are prevalent along the margins of the Laurentian icesheet, but relatively unknown in Scandinavia. However, Roberts (2000) reported offset structures in boreholes at road-cuts that are regarded as stress-relief features initiated by blasting. Within road tunnels there is anecdotal evidence that civil engineers report the sounds of rock moving, and 'rock bursts' occur when rocks fall from the roof, after blasting is complete. At the surface, crushed rocks and slipped blocks and notches on skylines may indicate postglacial movements along faults and nappe boundaries.

Olesen *et al.* (2004, Appendix A) included 54 classified claims of neotectonic movements from onshore mainland Norway, prior to new evidence discussed here (section 3.4). The earthquakes and fault movements are commonly parallel manifestations of neotectonic activity that arise from both glacial isostatic uplift and the longer-term plate tectonics. Olesen *et al.* (1992) reported that the earliest detectable displacement in Finnmark (the northernmost county in Norway), is of *Proterozoic* age, indicating an extremely long-lived fault zone. Such fault zones and their adjacent sub-parallel accommodation faults lie parallel to the strike of the foliation, and give low resistivity readings *due to ingress of water into fractures*. Whereas the plate tectonic processes constitute the most important fault-generating mechanism in Finnmark, stress relief could still have been *triggered* during the deglaciation period.

There are no known *extensive* faults wholly within the study area, which, as noted above, is less seismically active, although Olesen *et al.* (1995) showed an earthquake zone that extends NE across the north of the study area, passing through Mosjøen and Korgen (Fig. 4). Because the Weichselian icesheet had melted by 8500^{14}Ca BP, the present pattern of neotectonic seismic activity corresponds more to the *horizontal* stress field. As well as being concentrated at the centre of the rebound dome, the earthquake pattern from $10000–8500^{14}$Ca BP was probably aligned along the mountain ranges, and represented the *vertical* isostatic rebound.

A conclusion from this review of neotectonic activity is that the seismic and aseismic creation and enlargement of near-surface fractures continued throughout each interglacial, to supplement the more intense fracture sets produced at each deglaciation. These processes probably combine to create a spectrum of fracture apertures, lengths, frequencies and interconnectivities within the metalimestones. Such fracture systems may include subsystems that vary from being too small to transmit water, to those that are great enough to permit turbulent flow (without requiring karstic dissolution) over path lengths that in the study area reach up to 3.5 km.

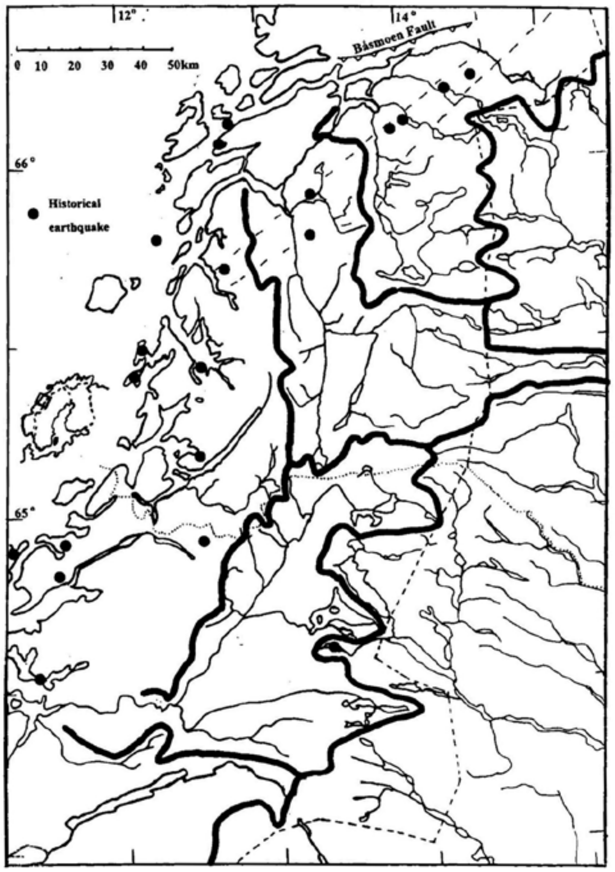

Fig. 4: Historical earthquakes in the study area (Various sources).

EVIDENCE FOR TECTONIC ACTIVITY FROM THE STUDY AREA

None of the 54 claimed examples of Norwegian neotectonic movement (section 3.3) lie within the study area. The lithologies of affected or adjacent rocks are rarely given, but there is no indication that any are in carbonate rocks. Thus, a list of 56 possible examples of tectonic movements in metalimestones presented by Faulkner (2005a, Appendix D1) may be the first recorded for the study area, and the first observed in both exokarstic and endokarstic situations. Altitudes range from near sea level to 770 m. Elgfjell provides many good examples. Most underground observations are intended to provide direct evidence of movement, after formation of the observing passage, rather than direct evidence of tectonic inception.

Only one observation concerns fallen, broken or curved stalactites and stalagmites, which can be diagnostic of earthquakes and relative roof movement. A few more unrecorded examples probably do exist, but speleothems are rare in the study area anyway, and most of those that do exist are small and probably grew in the Holocene, *after* the large earthquakes occurred. Speleothems that grew in earlier interglacial periods have commonly been removed by subsequent deglacial outflows. The few chambers with roof spans greater than c. 6 m commonly contain fallen blocks, which almost universally comprise limestones with clean, sharp, angular surfaces. This suggests that they fell after any deglacial deposition, and are situated high enough above streamways not to have been eroded by Holocene flood waters. Only two of the chambers are lit by daylight from nearby entrances, so that only these two may experience severe, seasonal, frost action. The others are not in entrance areas, and their disturbance by seismic shock seems the best explanation (e.g. Fig. 13). Human intervention is most unlikely, because of the common inaccessibility. However, all the large chambers are within 30 m of the overlying surface, and most within 15 m, so that a second possible process is downward flexing of the roof by the weight of an overriding icesheet (providing the cave was not filled by ice or water), as proposed by Warwick (1971), and upward flexing when the ice melted. A third explanation based on the freezing to a total ice fill during glacial conditions also cannot be ruled out.

It is the author's opinion, made after field trips to marble caves in central Scandinavia, northern America and Scotland, that evidence of small Holocene tectonic movements (e.g. bedrock movement that displays sharp edges or slickensides, without subsequent calcite dissolution or deposition) can be found in all relict passages in metalimestones in the Caledonides. Movements in VSK seem to occur in either vertical or horizontal slabs that are typically 1–3 m thick. The movements, presumably caused by W–E compressive stress, are commonly horizontal, normal to the strike, and have typical moved distances of only a few centimetres (and, rarely, several tens of centimetres), as expressed at the surface and within cave passages. The horizontal movement of vertical slabs of limestone 1–3 m thick is compatible with the survey leg length of many caves in the study area, suggesting that joint systems (in, e.g., VSK) are produced by this process (Figs. 5 and 6). Longer straight passage elements, and very wide, but low, passages, may arise from the horizontal movement of horizontal slabs of limestone (Figs. 7, 8 and especially 9 and 10). These observations agree with those of Olesen *et al.* (2004, p 13): *"the Norwegian bedrock consists of individual blocks that, to some degree, move independently of each other"*. According to Mörner (2003, p 72), a passing seismic wave can cause bedrock to lift up and then sink back, whilst the ground is being severely shaken. This probably happened at **Cliff Cave** in Jordbrudal (Figs. 9 and 10). Because most tectonic movements are of only a few centimetres, explorable cave passages are unlikely to be truncated along faults, and few such blind passages are known in the area.

Fig. 5: Scallop in Elgfjellhola: 11cm tectonic movement at scallop (highlighted), which occurred after formation of the passage, probably synchronously with movement in the nearby Paradox Cave (Fig. 6).

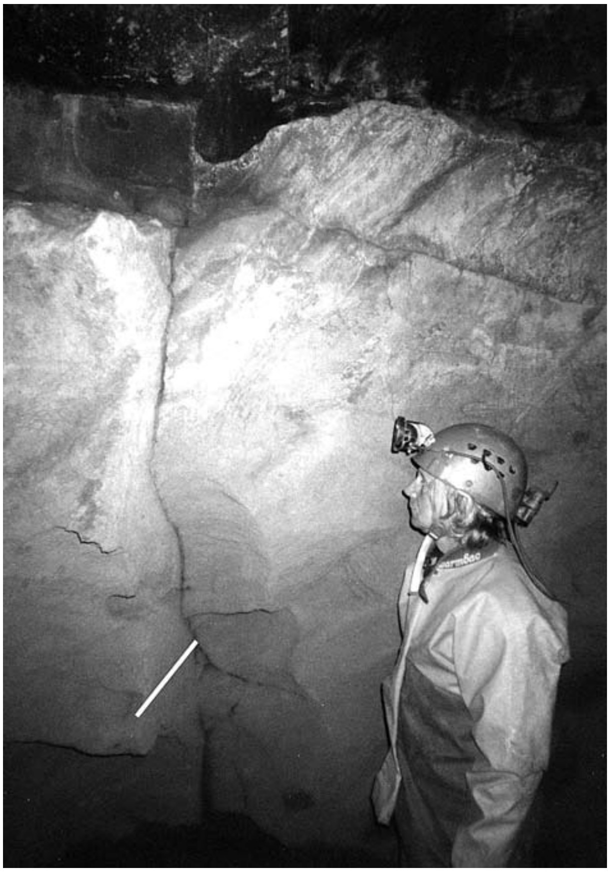

Fig. 6: Slickensides in Paradox Cave, Elgfjell: Tectonic movement of ~20 cm after enlargement of passage to its present size.

Fig. 7: Kidney Lake Cave, Jordhulefjell: Relict phreatic passage, with ~2 m diameter. A prominent horizontal tectonic movement bisects the passage, probably resulting from seismic amplification, because the cave lies in a ridge. Although this movement occurred after the passage enlarged to it present size, cave inception probably took advantage of a similar movement at the end of the Saalian deglaciation. Photo by P. Hann.

Fig. 8: Horizontal tectonic movement on Elgfjell: Mass movement outward (after glacial smoothing) of 2 m-thick slab of metalimestone, with proto-conduits at upper fracture.

A possible alternative explanation is that there has not been any movement, but that differential erosion or corrosion has given the appearance of movement. This could arise particularly if the apparent movement is aligned with the foliation. However, the photographic evidence for tectonic movements discussed above is compelling. The evidence provided at **Elgfjellhola** (Fig. 5) is particularly convincing, because the movement is *across* the foliation, is seen all the way around the passage walls, has a 1 mm-thick fault gauge wafer protruding up to 50 mm, and includes an 11cm step across a wall scallop. The evidence of protruding fault gauge wafers at surface sites (e.g. Fig. 11) that appear to cross-cut karren and stream channels suggests that these movements occurred in the Holocene, after the transport of ice across the area. The wafers could have been extruded beyond the faces of the limestone blocks by the seismic movements, or else Holocene chemical dissolution of the surface has left the more resistant wafers exposed to a height that indicates

Fig. 9: Cliff Cave entrances: Shattered cliffs and towers of limestone near the Rockbridge, Jordbrudal.

Fig. 10: Cliff Cave entrance from inside: Horizontal opening of c. 1 m to both left and right that split floor of phreatic passage to create a box-like profile. This is the largest known tectonic movement in the study area.

the extent of local surface lowering, or wall retreat in a cave. The wafers are calcitic, with polished surfaces and unknown dissolutional characteristics.

The observed tectonic movements in karst caves commonly follow the plane of the supposed inception fracture. Additionally, caves commonly display a high concentration of joints and fractures (c.f. the epikarst in sedimentary limestones) that lie parallel to, or normal to, the plane of foliation, and in some cases at other angles. These openings may not show lateral movement, but the variable degree of sharpness or smoothing by dissolutional water indicates that they probably represent a general settling upwards of large superficial carbonate blocks after seismic shocks. The sporadic lines of speleothems beneath roof joints indicate 'failed' vertical inception fractures, which transmit water more readily in vadose rather than phreatic conditions.

Fig. 11: Diverging flow on Elgfjell: Diverging flow of coffee across vertical fracture with fault gauge, suggesting that movement occurred after the surface flow was established.

Fig. 12: Fountain at Litl Hjortskar, Svenningdal: Spring at high stage from metalimestone fractures 1 m above level of adjacent stream.

Fig. 13: The Blockpile, Kvannlihola 2: Well-away from freeze-thaw influences, this collapse likely occurred during early Holocene earthquakes.

Fig. 14: Secret Stream Cave, Elgfjell: Primarily a tectonic cave, formed at junction of mica schist and marble. The mica schist has split and rotated upwards. The pick-axe is a relic of small-scale mining activity.

EVIDENCE FOR TECTONIC INCEPTION

It is self-evident that if tectonic caves can form in non-carbonate rocks, such as the entrance to **Secret Stream Cave** in mica schist (Fig. 14), then, despite metalimestone perhaps being slightly more ductile than some other local lithologies, there almost certainly exist natural conditions that promote the creation of tectonic caves in marbles, as listed by Faulkner (2005a). Such caves may be recognised by their angular or triangular passage profiles, especially at roof level. (Sediments, clastic materials and fallen rock may provide a flatter, sub-horizontal, floor). Whereas the movements along fractures in caves primarily formed by karstic dissolution are commonly small (the c. 1 m movement in **Cliff Cave**, Figs. 10 and 11, is exceptional), the movements at purely *tectonic* caves could be much greater. It is also self-evident that if a limestone tectonic cave later became part of a drainage route, under vadose or phreatic conditions, then normal karstic chemical and mechanical erosion processes would apply, and, over time, the passage would enlarge. If the drainage was phreatic, then eventually the evidence of its tectonic inception could dissolve away. Even in vadose conditions, the signs of an original tectonic movement may be destroyed in all but the highest, perhaps inaccessible, levels. The only known examples in the study area of caves in metalimestone that possibly enlarged tectonically to explorable dimensions and later enlarged significantly by karstic processes are the adjacent caves **Nordlysgrotta** and **Marimyntgrotta** in Velfjord, which may also have passages truncated by tectonic movements (Faulkner, 2005b).

Whenever a Caledonide karst passage has been studied by the author, it has always been found to follow either the contact between metalimestone and another, non-carbonate, rock, or a narrow (commonly horizontal in VSK) fracture plane in the limestone. Because there are likely to be rheological differences between rocks of differing lithologies, tectonic fractures are particularly likely to form at lithological contacts, under all conditions of seismic and aseismic tectonic movement. It is not necessary to have intersecting fractures for tectonic inception: apertures are uneven, and channel flow follows the widest part of the opening (Hanna and Rajaram, 1998). Nor is movement along the plane of the fracture necessary: a separating aperture adjacent to, or within, the limestone is sufficient. Such local rock splitting, especially vertical, may arise near the surface from deglacial and erosional unloading, without necessarily being triggered by seismic or aseismic processes.

CONCLUSIONS

On the basis of the accepted facts of seismic and slow tectonic activity in Scandinavia (section 3), it is argued here that all the solutional karst caves of the study area were initiated by tectonic inception. Tectonic activity creates fractures and some of these fractures must be open, as shown by the extreme cases of explorable tectonic caves. For the vertical stripe karsts in the HNC (at least), it seems probable that horizontal movements produce sub-linear sections of horizontal and vertical fractures with apertures that match the mm- and cm-scale banding of the foliation. The availability of chemically aggressive waters during meteoric and glacial conditions (Faulkner, 2005a) that can pass easily through connected fissures that lie close to the surface, and that commonly have high hydraulic gradients (Fig. 12), promotes karstic enlargement. Indeed, just as it seems impossible for karst caves to exist in the metalimestones of the study area without tectonic inception (section 1), it also seems impossible for them not to exist, given the tectonic history and the availability and flow regimes of chemically aggressive waters. Hence, all the karst caves are hybrids. After tectonic inception, conduits enlarged by dissolutional karstic processes, some with marine modification, and some with observable tectonic modification subsequent to inception. Monogenetic cave types in metacarbonate rocks are limited to wholly tectonic caves, wholly sea caves (formed by wave action), and jettegryter (rock-mills, formed by mechanical action during deglaciation).

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