Cave Development in Central Scandinavia

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Abstract

Metacarbonate outcrops occur in most nappes of the central Scandinavian Caledonides, but their numbers, lengths, areas and foliation dip-angles decline to the east. Caves of all complexities occur in the higher metalimestone-bearing nappes, from valley shoulder positions down to valley floors, and in (commonly homoclinal) *Vertical, Angled,* and *Non Stripe* karst types that guide internal morphologies. Total cave dimensions show no systematic trend when normalised against the *length* of outcrops, and are not related to catchment areas. Vertical distributions of outcrops and cave entrances are essentially random. Cave depth is always much smaller than the outcrop vertical range: caves in *stripe karst* have formed entirely within an upper 50m-thick zone of fractured rock. Similar cave inception, development and removal processes may have operated across the whole area from the time of the Caledonian Orogeny, and under the direct, and indirect, influences of the many glaciations since the late Miocene.

Introduction

The author is studying the caves in the Caledonian nappes of central Scandinavia in a region based on the *Helgeland Nappe Complex* (HNC). The study area extends eastwards from the Atlantic coast via stratigraphically lower nappes to the Caledonian thrust-front in Sweden, an area of some 40,000km^2.

The Central Scandinavian Caledonides

Contemporary geological research indicates that the rocks along the western coastal belt of Scandinavia derive their composition and structure from a highly complex system of mountain building associated with the plate tectonic opening and closing of the Iapetus Ocean, from late Precambrian to mid Palaeozoic times: the Caledonian Orogeny (GEE & STURT, 1985; GAYER, 1985; SOPER *et al*., 1992; VAN STAAL *et al*., 1998). Thus the region is part of the Caledonian - Appalachian fold and thrust mountain belt that once formed a continuous linear chain extending some 10,000km, from what is now Spitsbergen to the modern Gulf of Mexico, with an average width of about 1000km (GAYER, 1985: Editorial). Subsequent orogenies, and the opening and spreading of the Atlantic Ocean, have caused the mountain chain to be broken up into many geographically dispersed and geologically varied terranes, of which 20 have been identified, and which now reside on both sides of the Atlantic (BARKER & GAYER, 1985).

Some of the dispersed terranes include metamorphic carbonates that either contain, or may contain, karst caves. These occur in Spitsbergen, Shetland (FAULKNER, 2000a), Scotland, Ireland (FAULKNER, 2000b), Greenland, Canada and the USA, as well as in Scandinavia. One of the aims of the study is to make comparisons among these various karst environments.

In Scandinavia, the remnant rocks of the Caledonian Orogeny lie along the 1800km-long Scandian mountain chain. Most were originally formed at the western edge of the Baltic craton, on the eastern side of the Iapetus Ocean, although the westernmost probably derive from the Laurentian craton, to the east of rocks that now form East Greenland. The closure of Iapetus produced a complex series of thrust-sheets and nappes as the rocks of the Caledonides were transported southeastwards on to the rocks of the older Baltic craton.

Four major *allochthons* are recognised in Scandinavia: Uppermost, Upper, Middle and Lower. In the study area (STEPHENS & GEE, 1985), the Uppermost Allochthon comprises the Helgeland Nappe Complex and the Rødingsfjell Nappe Complex (RNC). The Upper Allochthon comprises two groups of individual nappes: the Køli Nappes and the Seve Nappes. In general, stratigraphically lower nappes are encountered when travelling west to east. Each major allochthon contains folded combinations of basement and metasedimentary cover rocks of Late Proterozoic to Silurian or even Devonian ages. The metamorphic grade of the nappe pile generally increases from sub greenschist facies at the base, up to medium amphibolite facies (or higher) at the top. The higher nappes also contain granitic emplacements and volcanic dykes.

Following the building of the early Palaeozoic Scandinavian Caledonian mountain range, the Caledonide structures are thought to have been eroded to a peneplane by the Carboniferous. Uplift of the Baltic Shield in the Mesozoic, Scandian uplift during the Cenozoic, and then differential erosion have combined to recreate the Scandes to the form that exists today (PEULVAST, 1985). The study area is practically devoid of post Caledonian sediments. Exposed bedrock is prevalent between about 400m and the present peaks that reach above 1200m. Below the tree line, vigorous summer mountain streams also reveal the underlying lithology in the valley floors.

Scandinavian metacarbonates

The metacarbonate outcrops occur commonly as long and narrow "stripe karsts" (HORN, 1951), and run roughly north to south. Subsequent to carbonate deposition in river estuaries and warm shallow seas that started in Precambrian times, the sedimentary limestones were repeatedly compressed, folded and subducted to depths reaching tens of kilometres as Iapetus closed. The consequent high temperatures and pressures caused the original limestones, dolostones and non-carbonate rocks to flow in a ductile manner and recrystallise. Commonly, the original bedding structures were completely lost. The rocks cooled, and pressures fell, as tectonics and erosion brought them towards the surface, which they reached by early Devonian times. A new *foliation* was formed. The chemistry of the original sediments commonly also changed, depending on the availability of silica and other minerals. The extremes vary from pure calcite and dolomite recrystallising as pure calcite and dolomite marbles, through various calcite to dolomite exchange reactions, to the production of calc-silicate rocks in which all carbonate has been consumed. The marbles can be seen in several forms from pure white to dark grey, but they also occur as bands of alternating colours, for example white/black, white/red, or yellow/ brown.

Cave exploration

Since the first exploration, during geological mapping, of karst caves in Scandinavia in about 1870, a steady increase has been recorded, mostly in the county of Nordland in Norway (ST.PIERRE, 1988). Rates of cave discovery and exploration were intensified by sporting cavers, beginning in the 1950s in Norway, and in the 1960s in Sweden. Many caves up to several kilometres in length have been explored. A recent discovery is Tjoarvekrajgge, in northern Nordland. At over 500m deep and over 12km long, it is now the longest in Scandinavia.

In the central Scandinavian study area, over 840 karst caves have been recorded by the author, with a total passage length of some 74km. Summaries for the south Nordland part of the area were provided by FAULKNER (1987; 1992; 1996; 2000c). The longest caves are Korallgrottan (c. 6km) and Labyrintgrottan (2.5km), which are both in Sweden. In the Norwegian part of the area, two stream caves, Toerfjellhola and Stor Grubblandsgrotta, are both nearly 2km long. The deepest cave is Ytterlihullet. Its depth of 180m is exceptional for the area. Cave cross-sections vary from under $1m^2$ (frequently) up to $100m^2$ (rarely). The caves occur at altitudes from over 800m down to sea level, and many contain powerful streams in spring and summer.

The Central Scandinavian Carbonate Outcrops Database

For convenience, the study area has been subdivided into 20 zones/nappe groups on a geological basis. The zones generally follow the stratigraphically descending sequence down through the Caledonian nappe pile. A computer-based database has been compiled with information from geological maps and other reports, organised by zones. Each separate carbonate outcrop occupies one row in the database tables, and information about the outcrop is held in 25 fields. Topographical maps have also been studied, and all instances of possible mapped karst features have been recorded. These features are predominantly the sinks or risings of surface streams, but may also include such items as lakes without outlets, and individual caves.

Central Scandinavian Cave Databases

Information about the caves from published references, from a Sveriges Speleolog-Förbund database, and from data assembled during field study trips is stored in two databases. Each recorded cave occupies one row in the tables, and data about the cave is held in 38 fields. Each cave is allocated a *Cave Type* from a list defined by the author. The main cave types are quickly identifiable from cave surveys, and do not pre-judge the method of cave or passage formation:

S Predominantly a single shaft, blocked at its base
A Single linear passage, with a simple staircase profile
B Single meandering passage, with a simple staircase profile
C One level rectilinear network
D One level dendritic network, with simple staircase profiles
E Tiered linear passages, connected by shafts
F Tiered rectilinear network
G Multilevel dendritic, with simple staircase profiles
H Complex multilevel network with steeply sloping passages

The topographical position of each cave is recorded in a *Cave Location* field, adapted from LAURITZEN (1981; 1990):

P Paleic surface cave
G Other gently sloping surface cave
S Valley shoulder cave
R Ridge crest cave
W Hanging valley wall cave
F Valley floor cave
C Coastal cave, along the Atlantic-facing strandflat
M Marine cave, above the strandflat, but invaded by the sea at the start of the Holocene

Karsts

The outcrops database presently records almost 950 entries, comprising a total carbonate area of $850km^2$. Only 55 of the outcrops have been identified as dolomite, covering an area of $47km^2$. Metacarbonate outcrops occur in most nappes, but their number, mean length, area (relative, total and mean), and angle of dip generally decline as the nappes are descended. Many of the HNC outcrops are close to vertical. Less than 15% of the total length of 3100km of mapped carbonate outcrops has been visited by cavers looking for caves.

Above the Seve Nappes, exokarst and endokarst are relatively common phenomena. This is demonstrated by the number of karst features shown on topographical maps, by the number of caves recorded in the Cave Databases, and by the relative ease of their discovery. The means for the study area are 1.3 mapped karst features per 10km length of carbonate outcrop, and 1800m of passages in 20 caves in every 10km visited outcrop length.

The study area provides a natural laboratory for studying the effect of outcrop dip on karst geomorphology. A classification of the karsts into 4 main *Karst Types* has been utilised:

V: *Vertical stripe karst* in which the generally homoclinal angle of dip varies between 80^o and 90^o

A: *Angled stripe karst* where the homoclinal angle of dip varies between 45^o and 80^o

C: *Complexly folded karst* where the folds are visible in cave passages

N: *Non-stripe karsts* where the angle of dip is less than 45^o and the outcrop is broad in relation to its length.

Type C is rare. Type N includes sub-horizontally foliated outcrops, and outcrops refoliated by contact metamorphism.

Caves

The mean length of the explored caves is 87m and the mean vertical range is 9m: there are over 400 recorded caves that are less than 100m long and less than 10m deep. Many of these consist of a single passage. However, several caves over a kilometre in length and over 100m in depth occur in the area, and some of these display an extremely complex arrangement of inter-linked passages at several levels.

A distinctive suite of *internal* cave features can be recognised especially for caves in *vertical stripe karst*. Vertically tiered passages that may be connected by vertical shafts only occur in vertical stripe karst. It is seen from inside such caves that the vertically foliated limestone supports three main orthogonal joint systems. Thus vertical stripe karst can support cave morphologies that are similar to those in horizontally-bedded limestones, within the confines of the narrow outcrop. They include such features as anastomoses, phreatic tiered passages, vertical shafts and avens, vertical meandering vadose streamways and small networks of joint-aligned vertical rifts. The survey sections show a tendency for tiered shallow and fairly symmetrical phreatic loops to form along the strike. Below these abandoned phreatic loops there is commonly a vadose passage that carries the present allogenic stream from its sink-point entrance towards the resurgence. Along this stream passage there may be one or more sumps that occupy the lowest levels of the cave. The distinctiveness of vertical stripe karst may be compared to that of horizontal sedimentary limestones with a dip between 2 - 5^o. According to FORD & EWERS (1978, p1793), there are important probabilistic differences between such flat-lying strata and strata which dip more steeply.

The widths of the vertical carbonate outcrops in the study area vary from the infinitesimally small up to c. 1000m. However, as the vertical outcrops are almost entirely within the Uppermost Allochthon, which contains many aquiclude layers within the carbonates, the effective width of the vertical stripe karst rarely exceeds a few tens of metres.

In angled stripe karst, passages at different levels are typically offset down-dip. Shafts and avens are steeply inclined. Phreatic loops are less symmetrical and utilise aslant dip and joint directions. In stripe karst caves, water flow is almost always either directly or generally *along* strike. The non-stripe karsts support a variety of passage forms and linkages. Water flow may be generally *across* strike. Very few horizontal outcrops are known, but in one, a single-level rectilinear network cave has formed in sub-horizontal metacarbonates below a mica-schist caprock. Its plan morphology is probably guided by two sets of fairly widely spaced vertical joints that are orthogonal to each other.

Observations

1 Approximate dimensional consistency across the zones

Karstic frequencies and total cave dimensions tend to follow the trend of declining carbonate outcrop extent when traversing the zones from west to east. It is suggested that a simple normalising geological parameter that can be invoked to model and predict the numbers of mapped karst features and the total length and volume of caves is the total *length* of carbonate outcrop in each zone. Karst caves have formed in all carbonate-bearing nappes down to the lower Køli Nappes. None have been reported in the Seve Nappes nor in the lower allochthons, where there are only relatively few, small, carbonate outcrops.

2 Dimensional independence from metalimestone lithology

Each carbonate outcrop has undergone various complex and individually uncertain processes of diagenesis, dolomitization, prograde and retrograde metamorphism, dedolomitization and partial conversion to calc-silicate skarns. Predominantly, the outcrops are of Low Magnesian Calcite (LMC) composition. Yellow/brown layers of a presumed (more soluble) High Magnesian Calcite (HMC) composition occur uniquely in Zone 4 of the HNC, and contain cave passages. The declining frequency of interlayered aquicludes follows a similar pattern to the decreasing metamorphic grade down through the nappe pile. As this pattern cannot be detected in the normalised frequencies and dimensions of karst features and caves in each zone, it is concluded that cave dimensions are independent of the lithological history and chemical purity of the limestone outcrops. Thus the number, length and volume of karst caves and the frequency of underground drainage are governed primarily by the solubility in acidic waters of calcitic limestone (both LMC and HMC), however it has been derived, and are little influenced by, for example, crystal size or interlayered impurities.

This independence of limestone chemistry certainly does **not** extend to pure dolomite outcrops. Although exokarst features and one short cave have been found by the author in dolostones, no *significant* caves are found in dolostone rocks (i.e. those with more than 20% of $MgCO_3$).

3 Internal morphological guidance by limestone dip

Within the general west to east decline in the angles of dip of the limestone outcrops, the dips can be very varied within each zone. The longer and deeper caves seem to form in limestones with rather shallow angles of dip. The angle of dip is a major influence on internal cave passage shapes, orientations and relationships, as discussed above.

4 Internal morphological guidance by aquicludes

Where aquicludes occur, they have a very strong influence on internal cave morphologies. Additionally, many cave entrances are situated at the along-strike junction of the limestone with an aquiclude country rock, and this contact is commonly observed to form a wall of the internal cave passages.

The morphological effect of the aquicludes is most pronounced in caves in vertical stripe karst in the HNC. These are commonly formed as straight linear passages or as vertically tiered passages alongside a vertical wall of non-carbonate rock. The other wall of the passage may similarly be formed alongside another aquiclude, with the intermediate limestone being removed. The non-carbonate layers typically act as complete aquicludes if they maintain a thickness greater than c. 30cm. Where their width reduces, they can be breached by karst waters and provide "doors" or "windows" that can be walked or crawled through into passages formed in the next vertical layer of limestone. Typically, waterfalls and short, passable, sumps in the caves in vertical stripe karst occur at places where a stream flowing under mainly vadose conditions has breached a non-carbonate layer.

5 Independence of altitude and catchment area

The vertical distribution of the carbonate outcrops is essentially random, and cave entrance altitudes are scattered randomly within the overall constraints of the local topography and carbonate outcrops. Furthermore, cave lengths, cross-sections and vertical ranges are essentially independent of altitude, unrelated to the local tree line and are not related to the contemporary cave catchment area. Relict caves occur randomly within the set of all caves, both in terms of entrance altitude and in geographical position. However, they are generally shorter and less deep than the active caves.

6 The shallow nature of most cave systems

The vertical ranges of the carbonate outcrops (which can exceed 900m) do not appear to influence the depth of cave systems that have a study area mean of only 9m. The surveyed sectional profiles of the 18 deepest systems in the study area reveal that the rock thicknesses directly above the lowest parts of each cave are commonly much less than the cave vertical range, especially for the deeper systems. Only Ytterlihullet (Non stripe karst) has a rock thickness (80m) greater than 55m above the lowest parts of its streamway. The greatest rock thickness above any cave formed in vertical or angled stripe karst is about 50m.

Hence many caves in the study area gain depth below a gently descending surface slope to which they keep within a relatively close range. This suggests that caves in vertical and angled stripe karst have formed entirely within an upper zone of fractured rock which has a maximum thickness of 50m. This may be compared to the epikarst or subcutaneous zone of sedimentary limestone, but in the case of metamorphic stripe karst, there is no lower "percolation" zone and perhaps no cave development below the level of fracture porosity.

7 Consistent pattern of cave types and morphologies

The distribution of Cave Types is fairly consistent across all zones. All Cave Types can occur in most Karst Types, and in most Cave Locations. In all zones, two thirds of all caves consist of a single linear or meandering passage, and these commonly represent the shorter caves. The longest cave in each zone commonly has the most complex type of passage arrangement. Relatively few caves have more than one active stream. High-level static sumps are rare, as are abandoned vadose passages. There is a high frequency of multiple entrances for the caves (the area mean is 1.5 entrances per cave), although many of these are relict, and even short caves can have many entrances. There is a very low frequency of significant chambers, and it is expected that these are concentrated in the more complex caves. There are also very few large boulder chokes in the caves, and only 34 unpassed boulder chokes have been counted in the whole study area. Only about 5% of the caves contain significant speleothems or other chemical deposits. These must therefore be regarded as consistently rare, although those that do exist can be very distinctive. Some 21% of the caves are reported to contain significant clastic deposits. There is much evidence for the complete inundation of some caves during large modern flood events, and the consequent progressive movement and flushing of earlier deposits down, and eventually out of, the caves.

Discussion

The above observations confirm that the major dimensions and much of the internal cave morphologies are independent of zonal geographic position and individual cave altitude. This suggests that similar cave inception, cave development and cave removal processes operate, and have operated, across all zones of the whole study area, and for similar periods of time.

This outcome is hardly surprising, as all the zones share a common geological history after the Devonian, as discussed above. The whole area has since suffered multiple glaciations during the late Miocene, the Pliocene and, especially, the late Pleistocene, when huge ice caps formed over the whole of Scandinavia. (JANSEN & SJÖBERG, 1991, deduced from studies of ice-rafted detritus (IRD) in the Norwegian Sea that small scale glaciations started as early as 5.5 Ma b.p. MANGERUD *et al*., 1996, p22, noted that small, but significant, IRD pulses dated from 11 Ma b.p., i.e. early in the late Miocene). These glaciations have dominated the evolution to the present landscape that is still shaped by the geological structures. The climatic changes since the start of the Holocene have been fairly uniform across the whole study area. Any moderating influence of varying tree line, mean annual temperature and mean annual precipitation on karst development is considered to be slight.

As the whole area is almost devoid of post Caledonian sediments, the timescale of possible karst development is very long. Carbon dioxide was available in rainwater from before the original formation of the Caledonides, and BASSETT (1985) mentioned palaeokarst in northern Norway dated from the mid-Ordovician. Thus, the various cave processes may possibly be normal components of landscape development since the Caledonian Orogeny. Within the continuum of processes, individual caves may develop relatively quickly or slowly, and persist in the landscape for short or long time periods, depending on geological constraints and topographical inheritance. Hence the known caves may represent a range of examples from long persistence caves through to more recently developed caves.

Many kilometres of bedrock have been eroded from above the present surface since the Caledonian Orogeny, but due to the random nature of the vertical distribution of the present carbonate outcrops and their general alignment with tectonic structures it seems likely that the distribution of such outcrops in previous landscapes would be similar to that of today. (That is, they would occupy about the same proportion of land area and have a similar distribution of length, width and area as today. They would generally be aligned north to south or NNE to SSW, and occupy all parts of the vertical range). The vertical range of each outcrop would however depend on the degree of uplift applicable at the time. Additionally, they would comprise similar lithologies and contain similar amounts and types of non-karstic impurities. Thus, at the zonal scale, the geological distribution of lithologies can be regarded as roughly a constant since the Caledonide events. The conclusion that each zone represents a continuum of processes of cave inception, development and removal with a distribution of timescales being represented for each phase, may perhaps be extensible to any time period back to the early Devonian. For all this time, the whole area can be regarded as a single entity regarding climate and uplift so that at each point in time the same karst processes should apply across the whole region. As arid periods would slow down all erosional and solutional processes and very wet periods would speed them up, these effects would moderate the age distribution of the caves. However, at any one point in time, the physical distribution of caves, their total lengths and volumes should remain roughly related to the contemporary lengths of the carbonate outcrops.

The effects of uplift, peneplanation and glaciation may moderate this general model as erosional processes could generate a deeper and a longer set of caves during times of high uplift, and a total destruction or total infilling of caves would occur during peneplanation, tectonic sinking or marine invasion. Internal cave morphologies across the whole study area may also have varied across geological time due to the effects of the multiple glaciations. It has been shown that Scandinavian karst caves became flooded and acted as component parts of glacial hydraulic regimes during the onset, maturity and recession of the Scandinavian ice caps (e.g. LAURITZEN, 1986). Thus total cave dimensions, and the proportion of phreatic to vadose passage elements across the study area, may have increased in a consistent fashion across the whole area during periods of glacial activity.

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