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# MARBLE STRIPE KARST OF THE SCANDINAVIAN CALEDONIDES: AN END-MEMBER IN THE CONTACT KARST SPECTRUM

# MARMORNAT PASASTI KRAS SKANDINAVSKIH KALEDONIDOV: SKRAJNI PRIMER KONTAKTNEGA KRASA

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**Stein-Erik Lauritzen: Marmornat pasasti kras Skandinavskih Kaledonidov: Skrajni primer kontaktnega krasa**

Kadar je obseg alogenega dotoka velik v primerjavi s površino kraškega izdanka govorimo o "pasastem krasu" (=stripe karst). V metamorfnih marmorjih Skandinavskih Kaledonidov je to najpogostejši tip krasa. Izraz "Norveški tip krasa", kot se za tak kras uporablja v terminologiji, je uvedel norveški geolog Gunnar Horn. O pasastem krasu govorimo, ko je razmerje med dolžino in širino (γ) kraškega izdanka večje od 3, o popolno razvitem pasastem krasu pa v primeru, ko to razmerje doseže vrednost 30. Pasovi marmorja so vertikalni ali nagnjeni pod različnim vpadnim kotom, vodonosnik v marmorju je lahko zaprt ali viseč.
**Ključne besede:** kontaktni kras, pasasti kras, Norveška, Kaledonidi, speleogeneza.

**Abstract** UDC: 551.44(48)

**Stein-Erik Lauritzen: Marble stripe karst of the Scandinavian Caledonides: An end-member in the contact karst spectrum**

Stripe karst is an extreme case of contact karst, where the allogenic contact perimeter is very large relative to the area of the karst outcrop. This is the dominant karst found in metamorphic marble outcrops of the Scandinavian Caledonides, and is named *the Norwegian karst type*, as it was first described here by the Norwegian geologist Gunnar Horn. Analysis of the geometric properties of a stripe suggests that stripe karst can be defined as a narrow karst outcrop with length to width ratio (γ) greater than 3 and is fully developed when γ =30. Stripe karst contacts are either sub-vertical, or inclined with confined or perched contacts.
**Key words**: contact karst, stripe karst, Norvay, Caledonites, speleogenesis.

## INTRODUCTION

Contact karst is an *interface phenomenon*, which we may define as karst where the direct contact of a non-karstic country rock changes the intensity and / or the spatial pattern of karstification. Most commonly, contact karst display intensified corrosion. This may be through allogenic waters focussed at the upstream contact boundary as well as the damming effect of an insoluble baselevel at the downstream end. Moreover, chemical and physical alterations of the lithologic contact interface by diagenetic, tectonic, or metamorphic processes contribute to increased affinity for karstification. In its widest sense, since all karst areas have a finite extent, contact phenomena would exist in all karsts. However, the fraction of contact karst in a given situation is directly proportional to the perimeter / area ratio and therefore the *geometric shape* of the karst outcrop. A circular area (approximated by carbonate island karst, 'Klippenkarst', etc.) would therefore display least contact effects of all possibilities.

Therefore, being bilateral or double-sided contact karst; *Stripe Karst* is the extreme end-member at the other side of the geometry spectrum where the perimeter/area ratio is highest. It may be tentatively defined as stratigraphically thin outcrops of karstifiable rocks that intersect the land surface at an angle, thereby producing long and narrow 'stripes'. The extreme case is when the contact phenomena at each side meet, Fig. 1a. Extremely elongated outcrops are almost always a product of tectonic and/or erosional modification of originally flat-lying strata. In this context, orogenic tectonism is the most common and effective process to create stripe karst, and therefore some degree of metamorphosis is always a secondary effect.

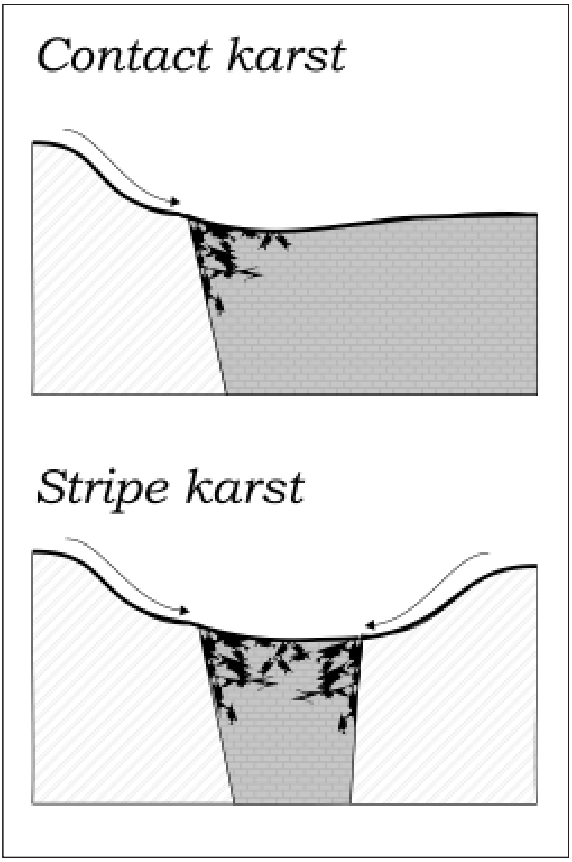



*Fig. 1a: Stripe karst is a special case of contact karst, where allogenic corrosion occurs along a narrow band of karstifiable rock. In very narrow stripes, or when allogenic runoff is large, the two contact zones may merge and form a continuous zone of intense karstification. In the extreme case, all karst rock in narrow stripes may become dissolved, so that only the wallrock remains.*

## STRIPE KARST, THE NORWEGIAN TYPE KARST

The term stripe karst, or 'Streifenkarst' was first introduced by the Norwegian geologist and speleologist Gunnar Horn (1937) in his discussion of caves in north Norway. Horn (*op cit*) defines 'Stripe Karst' as laterally extensive, but stratigraphically thin bands of limestone with various degrees of dip, which is interbedded with schist aquicludes:

> *'Das verkarstungsfähige Gestein tritt wegen der gewöhnlich schrägen Lagerung in schmalen Zonen auf mit einer Breite von einigen hundert m (aber auch weniger) bis 1-2 km und einer Länge von vielen kilometern. (...) Wir haben also in unserem Gebiet Packete mit verkarstungsfähigem Gestein zwischen wasserunlöslichen Schichten, und wir erhalten demnach einen Typus der Karstlandschaft, den wir als Streifenkarst bezeichnen können.'*

Horn suggests dimensional boundaries of individual bands of 'some hundred meters to 1-2 kilometres thickness (but also much less) and several kilometres lengths', Fig. 1b. The distinctive criterion is that these bands are interbedded with insoluble aquicludes, which provide contact effects and a clear hydrological boundary of each individual karst outcrop. This criterion distinguishes stripe karst from limestones that are interbedded with less pure, argillaceous bands that do not provide efficient aquicludes. Because stripe karst was first described by Horn on his obser-

*Fig. 1b: Pikhaugene stripe karst, Svartisen. For location, see map Fig. 3. This stripe is only 20 m thick, steeply dipping, and continue for several kilometres. Note the rounded, whaleback forms due to glacial erosion. Photograph: S. E. Lauritzen.*

vations in rock formations in the Norwegian Caledonides, and since this outcrop geometry is very abundant in Norway, it is justified to claim stripe karst to be the '*Norwegian Karst Type*'[1] (Lauritzen, 1991a). In the following, stripe karst will be discussed in relation to the geological conditions prevailing in Caledonian metasediments of Central Scandinavia.

## GEOLOGY OF KARST ROCKS IN THE SCANDINAVIAN CALEDONIDES

Almost all karst in central Scandinavia is developed in metamorphic carbonates. Precambrian and Palaeozoic limestones suffered regional metamorphosis during the Caledonian orogenesis, whilst carbonates distally to the orogen only suffered folding (e.g. the Oslo region of south Norway and limestones in south Sweden). In the Oslo Graben area, contact metamorphosis occurred later from Permian intrusives. In the central Caledonides, orogenic deformation resulted in multiple fold phases and fragmentation into a series of nappes. The various nappes are grouped into four units (lower, middle, upper and uppermost allochton) where metamorphic grade generally decrease eastwards from the granulite to greenschist facies (Bryhni and Andréasson, 1985), although in an irregular manner due to overthrusting (Mørk, 1985).

The 'Caledonian strike direction' is generally NE-SW (Fig. 2) as is evident from the trends of the coastline, outcropping rocks and drainage routes. Sub-


*Fig. 2: Simplified tectonostratigraphy of Scandinavia. The hatched areas represent the Caledonian nappes; hatching direction approximates the average Caledonian strike direction. Dotted area: The Oslo Graben. White areas: Precambrian basement rocks of the Fennoscandian shield.*

[1] *This is similar to plateau glaciers, or icecaps, being first described from Norway and named glaciers of the 'Norwegian type'.*

sequent, episodic uplift and erosion since the Mesozoic exposed carbonates as bundles of narrow, but laterally very extensive marble bands, interbedded with mica or quartzite schists or, less commonly, in contact with granitic intrusives. The carbonate outcrops illustrate this as they appear in two sections from karst maps of Norway (Lauritzen, 1991b, c, d), Fig. 3 & 4. Metamorphic grade do not appear to have much influence on karstification affinity, since even the most low-grade carbonates within the study area are recrystallized into marbles. Even under quite low P, T conditions, carbonates recrystallize and float around more competent rocks. This process leads in turn to annihilation of primary sedimentary or diagenetic structures (e.g. bedding planes), which are important targets for speleogenesis in non-metamorphic rocks (Ford and Williams, 1989a; Klimchouk and Ford, 2000; Lowe, 2000). As a consequence, water penetration through marbles is entirely dependent on post-metamorphic deformation in the brittle regime, close to the land surface. Chemical composition ('purity'), combined with fracturing are the single two most

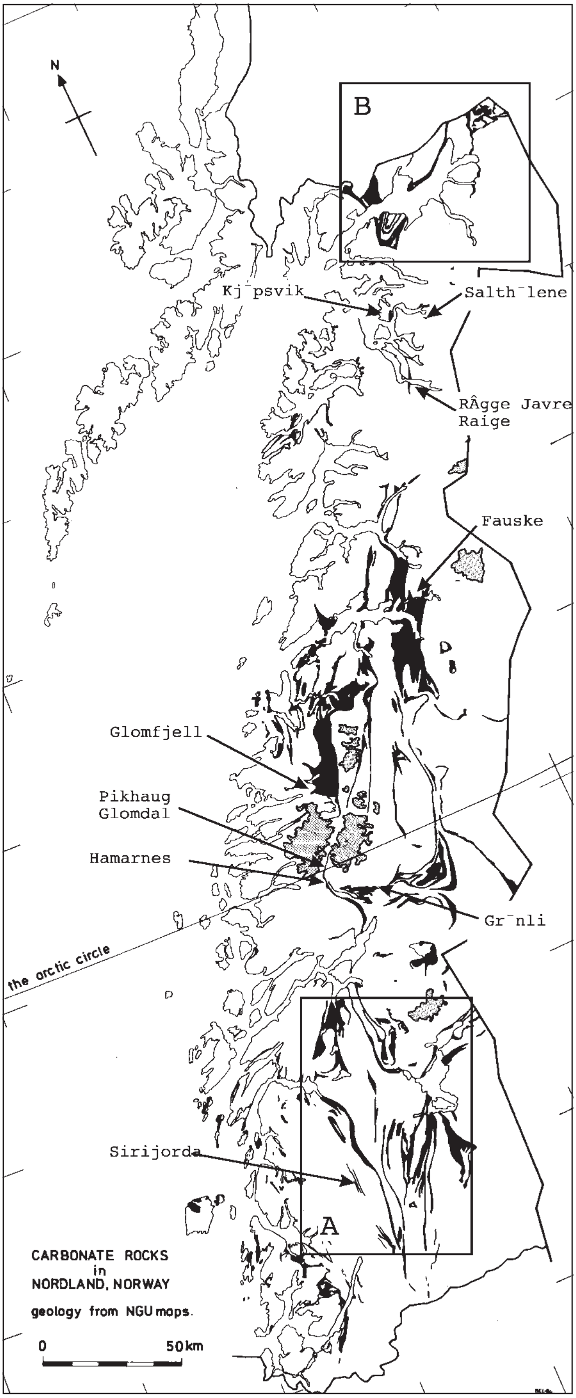



*Fig. 3: Karst map of Nordland County, Norway with carbonate rocks in black and glaciers in grey. Insets A) and B) corresponds to maps in Fig. 4. Location of cave examples and areas discussed in the text is shown. For location with respect to the map in Fig. 2, consider position of The Arctic Circle.*

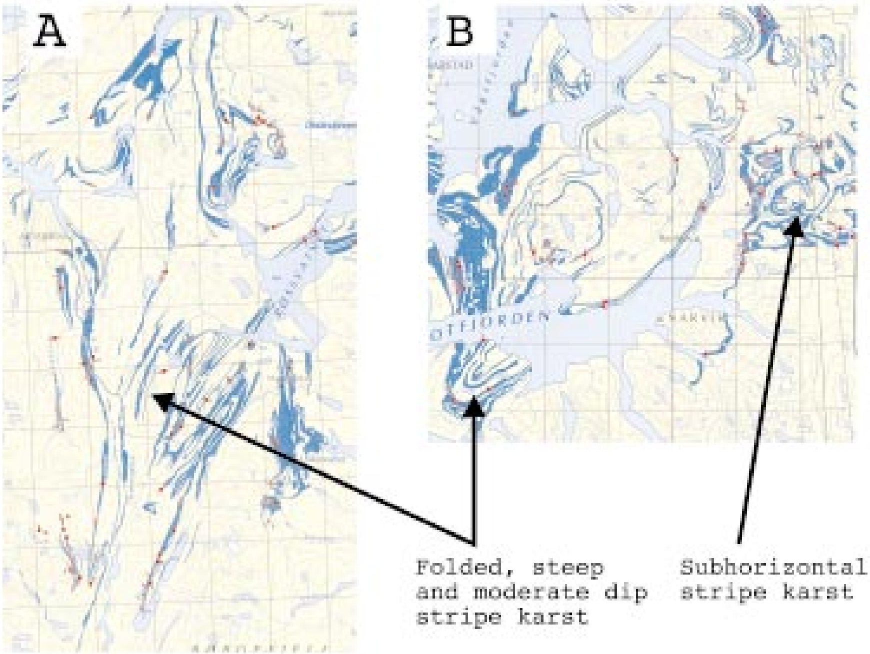



*Fig. 4: Carbonate outcrops in north Norway. A: south Nordland, B. north Nordland and Troms County. Blue outcrops are karst, red dots, karst forms. Each grid unit is 10 km. From Lauritzen (1991b, c, d).*

important necessary rock conditions for karstification, see Lauritzen & Lundberg (2000) Fig. 2, p409). The history of brittle tectonics and water availability dictate karst development in metamorphic rocks (Lauritzen, 1991a). The *Type Stripe Karst* therefore represents a metamorphic and orogenic setting where wallrock consists of phyllite, schist, gneiss or granite.

## HYDROLOGICAL AND GEOMETRIC DEFINITIONS OF STRIPE KARST

**Aquiclude constraints.** Impermeable side rocks makes each marble band into an individual aquifer. Sometimes, when two or more marble bands are adjacent, water may break through thin schist walls, especially when they are crossed by fractures. In many cases, hydrological communication indicates that schist horizons taper out laterally as cores of very tight folds, or become bodinaged. Fracture-guided breakthrough in mica schist has been observed in up to half-meter thick mica schist, in accordance with Faulkner's (2001) observations of 30 cm as the maximum thickness for broken aquicludes. Under vadose conditions, erosive streams may cut through much thicker schist layers. *Aquicludes make stripe karsts to individual, often confined aquifers that may exist side by side without underground communication.*

**Geometric properties.** Stripe karst is characterised by having an unusually large allogenic perimeter relative to its area. However, all karsts do have a perimeter to area ratio, and it is desirable to look for a criterion by which stripe karsts can be distinguished from other karsts. Since the perimeter / area ratio of a rock stripe do increase with decreasing outcrop thickness, this can be investigated mathematically to see if there is some geometric threshold at which this ratio changes. For a rectangular approximation of the stripe with width (*w*) and length (λ), Fig. 5, the perimeter (P) to area (A) ratio (r) is:

$$r = \frac{P}{A} = \frac{2(\lambda + w)}{\lambda w} \qquad \Rightarrow \qquad r = 2(\lambda + w) \quad for \quad A = 1 \tag{1}$$

The normalised ratio approximates 2 λ when *w* becomes much smaller than λ, i.e. for very long and narrow stripes. If we image the stretching of a rectangular piece of 'rubber' of constant area equal to unity, we may observe the change of r as stretching proceeds, see Fig. 5a.

For $A = \lambda w = 1$, then $\lambda = 1/w$, $\lambda = (\lambda/w)^{1/2}$ and $w = (\lambda/w)^{-1/2}$. Hence, expressing r as a function of the length-to-width ratio of the stripe, $\lambda = (\lambda/w)$, yields:

$$r = 2(\sqrt{\gamma} + \frac{1}{\sqrt{\gamma}}) \tag{2}$$

The function in eqn. (2) is sigmoid (s-shaped) so that its slope goes through a maximum. Differentiating with respect to γ, one gets the *sensitivity* of the perimeter-to-area ratio of a (rectangular) stripe as a function of its length-to-width ratio:

$$\frac{dr}{d\gamma} = \gamma^{-1/2} - \gamma^{-3/2} \tag{3}$$

This function has a maximum at $\gamma = 3$, see the graph in Fig. 5b. With increasing γ, the sensitivity of r decreases rapidly: i.e. some 5 times within the range of realistic values of γ, Fig. 5c. In other words, stretching a rectangle always increases r, with optimum sensitivity when length is 3 times width. Since the graph of eqn. (3) resemble a hyperbola for $\gamma > 3$, so that the sensitivity undergo a transition, or 'switch', from high to low sensitivity, we may approximate this graph into two linear components as depicted in Fig. 5c. The two linear approximations of the 'hyperbola' intersect at $\gamma \approx 22$, and the high sensitivity limb becomes zero at $\gamma \approx 30$, (Fig. 5c), indicating that for stripes with $3 < \gamma < 30$, r = P/A is most sensitive to small changes in γ. We may call this a *region of development to full stripe geometry*. For $\gamma > 30$, P/A is much less sensitive, because the stripe geometry is now established, and P/A grows approximately linearly with continued stretching. (For $\gamma > 30$, w is less than 3.3 % of λ so that eqn (1) approximate to $r \approx 2\lambda$ with less than ~5 % error).

*Fig. 5 (on page 55): Geometric properties of a karst stripe. a) Most stripes are lenticular to some extent; here we use a rectangular approximation with average width and same length. By stretching a rectangle of unit area, we may investigate how the perimeter-area relationship changes with increased stretching. b) Eqn. (2) and (3) plotted, showing that stretching a square has maximum sensitivity at length-to-width ratio (γ) of 3. c) The sensitivity of P/A with increasing γ die out above γ = 30, i.e. stripe geometry is fully developed. Most stripe karsts display γ in the interval [10 < γ < 200]. See text for further discussion.*

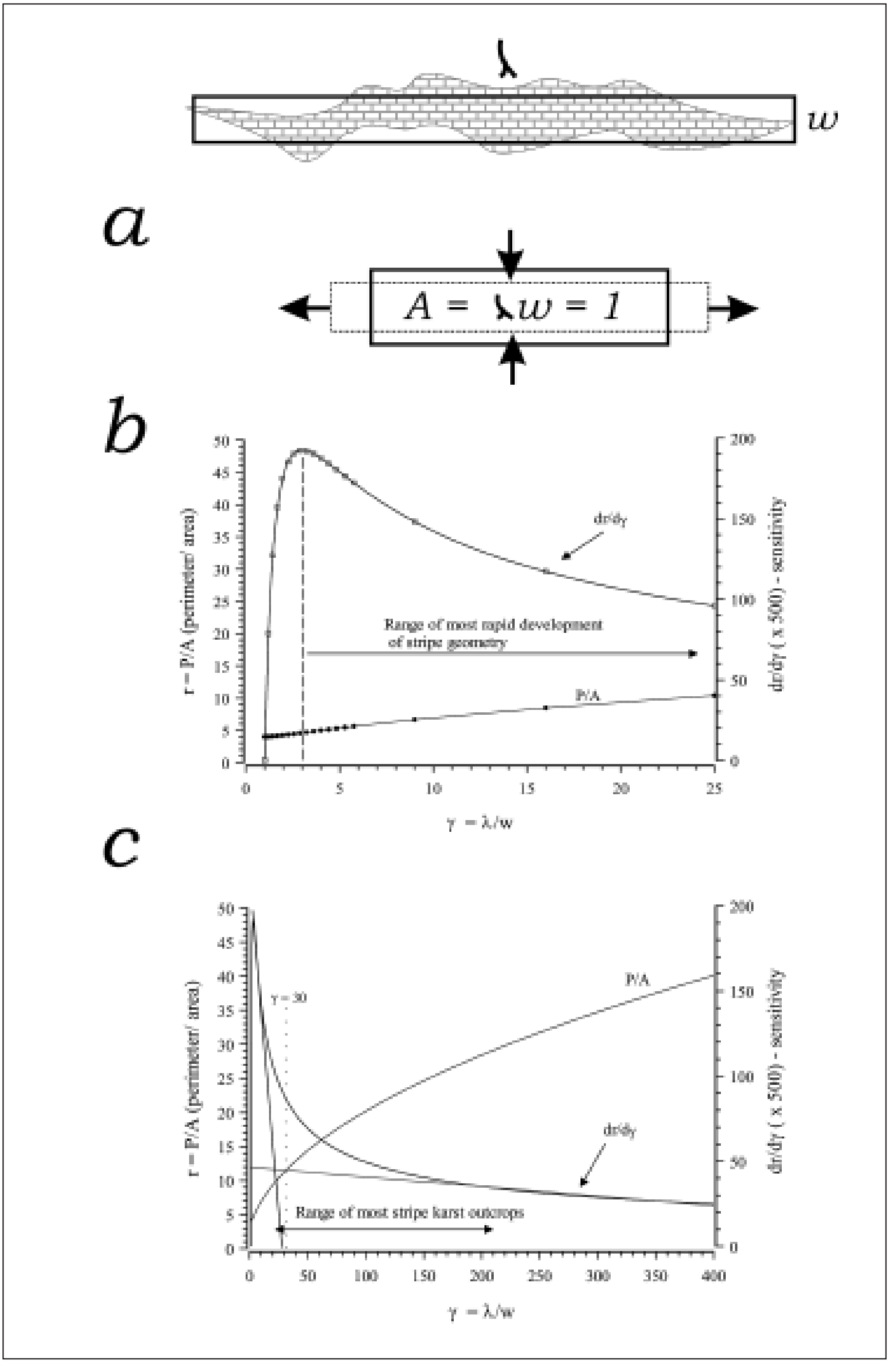



Fig. 5 - Text on page 54.

For these purely geometrical reasons, it is justified to give stripe karst a dimensionless definition as *karst outcrops with a length to (average) width ratio greater than 3, where it is fully developed at ratios greater than 30.* This makes sense from a visual point of view, as an elongated karst outcrop with $\gamma = 3$ do not 'look' like a stripe, but one at $\gamma = 30$ do. Although these apparent geometrical thresholds are mathematically appealing, and deserve further investigation, it is not clear what it would mean in terms of karstification rates or morphology. However, a karst stripe with $\gamma = 3$ would be perceived as an 'elongated patch of karst', perhaps like the *karst barré* of Corbel (1957) while a 'long outcrop' ($\gamma = 30$) is perceived as a stripe and also its allogenic effects would be optimal.

Since stripe karst is characterised by being dominated by contact effects along its allogenic perimeter, and that this contact zone do have a dimension, it is obvious that stripe karst needs an additional criterion of *absolute width*. Since the width of contact zones may vary with allogenic input, *true stripe karst* may be defined as the case where the allogenic contact zones from each side meet, Fig. 1, i.e. the stripe width ($w$) is equal or less than 2 times the penetration length of allogenic corrosion. Such penetration lengths may become rather large, depending on runoff and fracture apertures, and easily attain a few hundred meters. These widths also accord with Horn's original definition (*vide supra*), which was most probably based on morphological judgement alone. Karst stripes 100 m wide and 5 km long ($\gamma = 50$) is entirely within the ranges given by Horn. In practise, most stripe karsts display [$10 < \gamma < 200$]. Therefore, stripe karst is defined as follows:

> *Stripe Karst is an elongated outcrop of a karst rock stratum, which intersects the land surface at an angle. Its length to average width ratio ($\gamma$) is much greater than 3 and the geometry is fully developed above $\gamma = 30$. The absolute width is equal to or less than twice the penetration length of allogenic contact karstification. In most cases this width limit is some hundred meters. Impermeable and insoluble rocks, forming aquicludes, surround and isolate individual karst stripes.*

## ENDOKARST GEOMETRY IN STRIPE OUTCROPS

**Structural geology and terrain situation.** The dip of the carbonate strata themselves is unimportant for the geometry of the stripe outcrops as discussed above. Although the most common stripe karsts display steeply dipping carbonate bands in landscapes of various slopes, horizontal carbonate strata in vertical cliffs are also a type of stripe karst, Fig. 6 & 7. The critical condition is that the strata *intersect the land surface at an angle*. Stripe karst *contacts* (as other allogenic contacts) can be divided into three common types:

- Contact Type 1: Sub-vertical unconfined
- Contact Type 2: Gentle to steep dip confined
- Contact Type 3: Gentle to steep dip perched

This classification requires that the karst formation in question is uniform over some distance, i.e. at the dimensional level of individual stripe outcrops. At the dimensional level of fold struc-

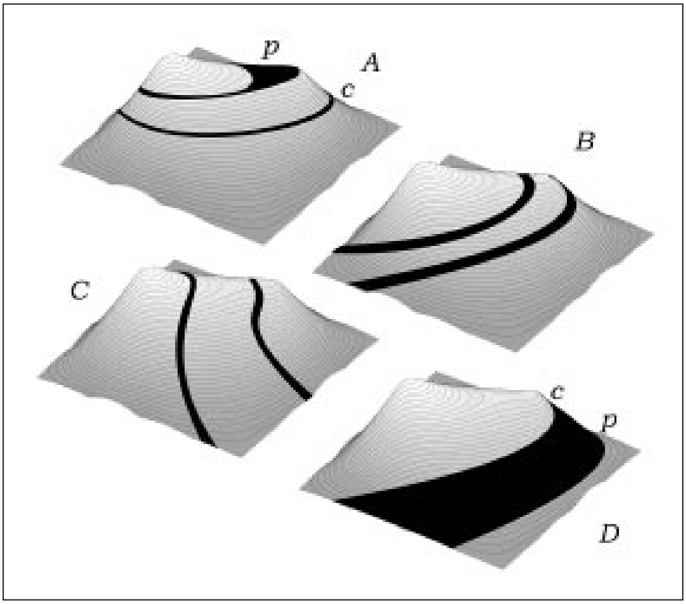
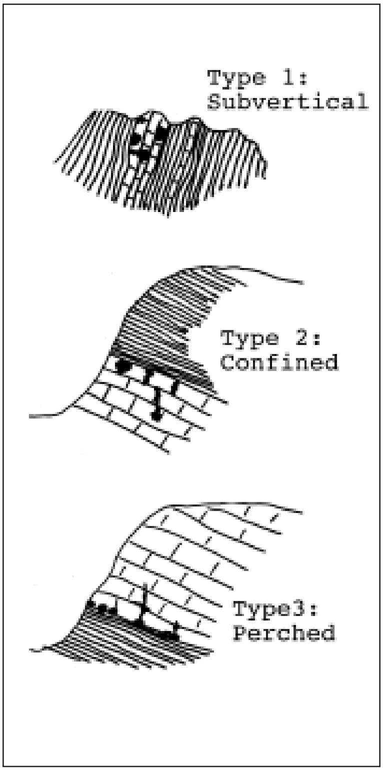



*Fig. 6: Various stripe karst settings. Karstic rocks in black. A: Sub-horizontal stripe karst, the surface outcrop of the upper band is hydrologically perched (p), if phreatic, the lower is confined (c) B: stripe karst of gentle dip; C: Sub-vertical or steeply dipping stripe karst; D: Thick 'stripe' or carbonate stratum, giving rise to either confined, phreatic karst (c) at the upper contact zone, or perched karst (p) at the lower contact.*




tures, the situation becomes much more complicated, as the confining contacts also become folded. As a consequence, caves and Endokarst will also follow these folded paths. The example of the carbonate strata in Kjøpsvik is an excellent example of multiple folding which results in complicated interference patterns, Fig.8.

**Karstification at lithologic contacts.** The lithological contact surfaces are in some cases tectonized by fractures or faults, due to shear stress and mechanical contrast between the marble and adjacent rocks. This may invoke 'bedding planes' previously sealed off in metamorphosis. Moreover, the wallrock may contain iron oxide ores or iron and base metal sulphides, which also impregnate the marble at the contacts, Fig. 9.

*Fig. 7: The three general types of stripe contact setting. Type1 is sub-vertical stripe karst where flow can be both unconfined and confined, depending on the dip of the contact. Type 2 is the low dip case with confined phreatic flow. Type 3 is the low dip, vadose case where phreatic conditions occur at the perched, lower contact interface.*

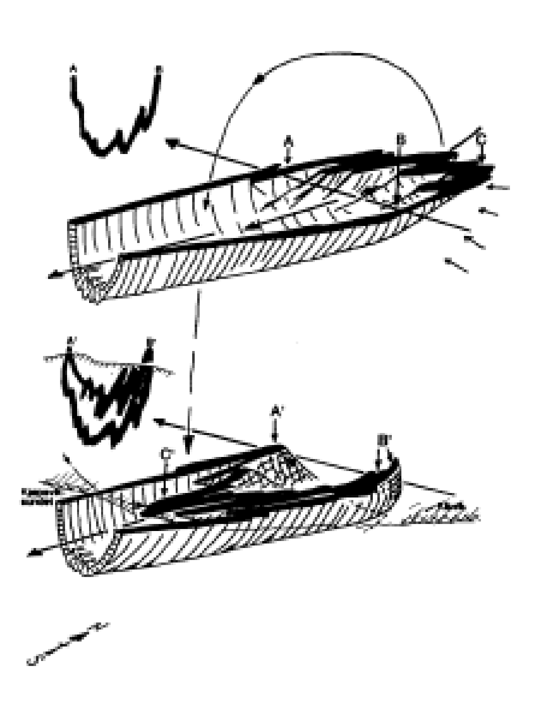


*Fig. 8: Model of the tectonic history of the marble outcrop geometry at the Kjøpsvik quarries. For location, see Fig. 3. After Larsen (1987). Storsteinshola, which is discussed in the text, is situated close to the flank at 'C'*

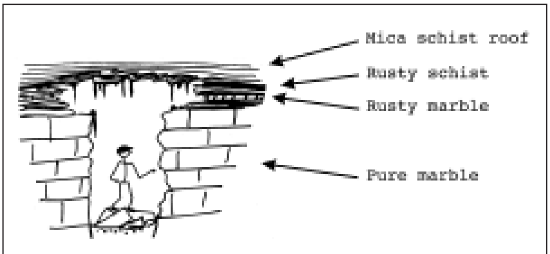
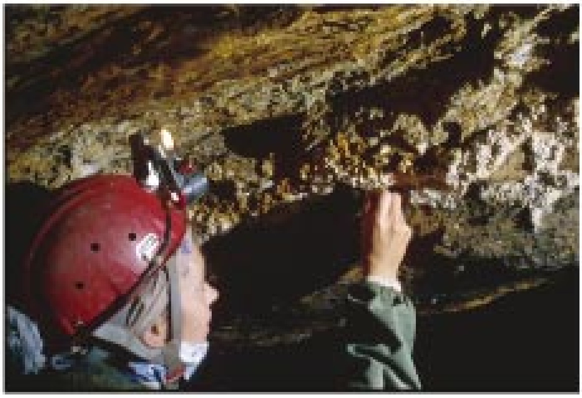



*Fig. 9: Passage developed in sulphide-impregnated contact interface between marble and mica schist wallrock. It is typical for many stripe karst caves to have non-carbonate ceilings. Profile from Okshola at Fauske.*

Such sulphide impregnation at the contacts is very common. This is revealed by a rusty coloration on weathered rock surfaces, significant increase in sulphur content towards the contacts, visible grains of pyrite in the rock and occurrence of gypsum crusts in dry cave galleries. In extreme cases, the schist wallrock of such caves may be severely weathered and destroyed by expanding gypsum, Fig. 10a, or even flake off due to gypsum expansion, Fig. 10b. Occasionally, acidic dripwater coming off mica schist ceilings corrode deep pits (30 mm diameter, tens of cm deep) into relatively recent breakdown slabs, Fig. 10c. Pyrite oxidation and sulphuric acid corrosion seem very common and is therefore an important mechanism of cave initialisation.

Finally, at the scale of caves and karst meso- and microforms, metamorphic segregation of siliciclastic material has produced zones of extremely pure calcite marble alternating with zones of high mica, quartz and Ca-silicate content. Similar zonation within the marble is also seen at trace levels for Fe, S and non-carbonate C (i.e. graphite). Magnesium content is also zoned and varies from almost nil through magnesian limestones to pure dolomite. Dolomite display very modest karst surface morphology and only a few, quite small caves are known from these outcrops. When occurring together with calcite marble, dolomitic horizons stand proud of the surface due to their lower dissolution rate, e.g. Grønlie (1980). This effect is best seen in caves, as surface exposures of the often sugary textured dolomites suffer gelifraction and in turn, grusification.

A



B

C

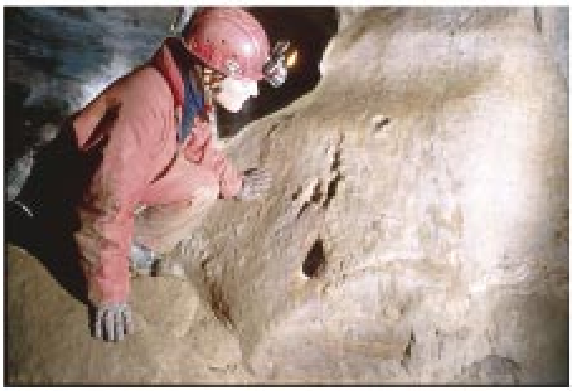


*Fig. 10: Various expressions of sulphide impregnation and pyrite oxidation processes at karst contacts.*
*a) Strongly weathered mica schist with gypsum and iron sulphates; passage roof, Grønligrotta, Rana.*
*b) Gypsum flaking in dry passage, Blåmannsisen, Sulitjelma.*
*c) Drip pits in marble formed by very acidic dripwater coming directly off the mica schist ceiling, Grønligrotta, Rana.*
*All photos: S. E. Lauritzen.*

**Structural speleology of stripe karst - morphotypes.** Since the morphological nature of caves in stripe karst (or in any karst type) is a function on how various passage elements are linked together, and how they (once) transported water, it is essential to carry out morphological analysis at the *cave system level.* Cave systems within stripe karst may, in principle, attain the same diversity of forms as found elsewhere, according to the response to hydrological conditions. However, due to the aquiclude constraints in stripe karst, cave systems are elongated and are always restricted in one of three dimensions. Caves in stripe karst may be divided into three morphological groups, which reflect both geometry and function:

- Morphotype A: Sub-vertical phreatic networks or mazes
- Morphotype B: Low dip phreatic networks or maze
- Morphotype C: Looping systems with vadose trenches
- Morphotype D: Extensive, linear drainage routes.

**Fracture constraints - geometric types of stripe settings.** Guiding fractures in stripe karst reflect the history of brittle tectonics when the formation was relatively close to the surface. Fracture sets are often orthogonal or form con-

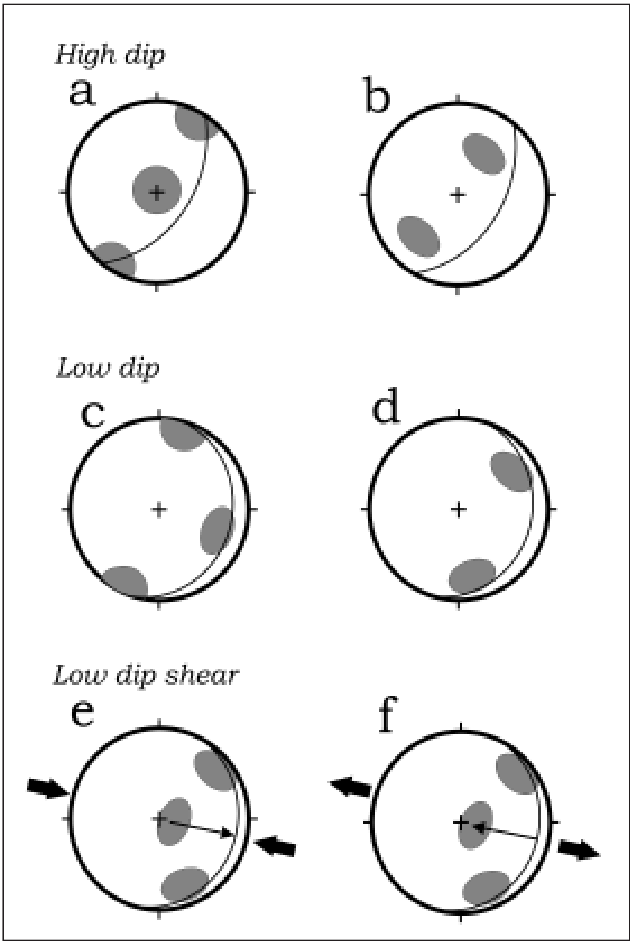



*Fig. 11: Stereonet projections of various settings between aquiclude planes (great circle traces) and poles of fractures (grey areas).*
*a) Sub-vertical to steeply dipping stripe with orthogonal joint sets, one vertical, the other sub-horizontal. b) High dip with orthogonal joint sets both at an angle, i.e. jointing oblique to the horizontal. c) Sub-horizontal or low dip with orthogonal joint sets at vertical attitudes. d) Sub-horizontal / low dip with oblique set of orthogonal joints. e) Same as d) but with sheared contact plane due to thrusting. f) Same as e) but under extension.*

jugate sets (and are therefore, by definition, brittle shearplanes). In this way, most endokarst features are developed along three sets of planes: two fracture sets which in turn may have various aspects to the surrounding aquiclude plane. Sometimes, a third fracture set is parallel with the aquiclude contact, thereby resembling 'bedding' plane partings. Various geometrical settings between fractures and 'bedding' planes is depicted in Fig. 11. In an inclined karst stripe, orthogonal fractures may either follow approximately stratal strike and dip (a and c in Fig. 11), or they may go obliquely to it (b and d, Fig. 11). In the first case. one set of fractures will have sub-horizontal strike, as well at the line of intersection between the fracture and contact plane is horizontal. Also, unloading stresses will tend to keep the sub-horizontal fractures open, which in turn enhances speleogenesis. In cases b and d, oblique fractures would expectedly force water to make phreatic loops. A third case, being a modification of either of the former, is when the contact plane itself is tectonized by faults or shear zones. Then the inclined plane itself may become the most permeable structure.

## CAVE EXAMPLES

A large number of caves in Scandinavia are relict and truncated by glacial erosion and many of the smaller fragments can fit into any of the system morphotypes mentioned above. This may be quite misleading with respect to the morphology and function of the stripe aquifer, and we will only consider examples of large cave systems here. They are chosen because they are long (most of them are greater than 1000 m in length), so that the number of passage segments is large. In this way exploration bias is minimised, and therefore the overall system architecture can be reliably evaluated. The chosen examples are all well documented, or studied by the author so that morphological and functional aspects can be deduced with certainty. It may be argued that a selection of only a few caves would put some bias to the importance of each cave group. However, out of a total material of 1,100 registered caves longer than 30 m in Norway, only about 30 are surveyed and thereby documented to be longer than 1000 m. Statistical estimates (Zip plot) also suggest a similar number of both surveyed and still unsurveyed caves (Lauritzen, 1991a). Even if the true number of long caves may be twice as high as this estimate, a selection of 12 of them is still between 15 and 30 % of the lot. From the author's experience through the last 25 years of speleological work in Norway, this selection can also be claimed as representative of the various cave architectures encountered in the country. The location of these caves is shown in Fig. 3.

**Morphotype A: Rectilinear low dip networks.** Network caves, or mazes, are in many respects enigmatic, as their genesis require special hydrological and tectonic conditions, Fig. 12. In the classic sense (Ford and Williams, 1989a), mazes develop in rocks which are well fractured with regular spacing and where either water recharge is diffuse or where rapid and large changes in water levels occur. Since the schist wallrock in the stripe karst is practically impermeable, the first (diffuse recharge) alternative can be ruled out, and we are left with the 'floodwater maze' model. This is however quite conceivable, considering the strong diurnal and seasonal hydrological variation that dominates glaciers. In contact with Pleistocene ice-sheets and glaciers, all known maze-type caves in Norway could have received englacial and proglacial waters (Horn, 1935, 1947; Lauritzen, 1982, 1986b, 1990b). It should also be appreciated that glacial karst is also a contact karst phenomenon.

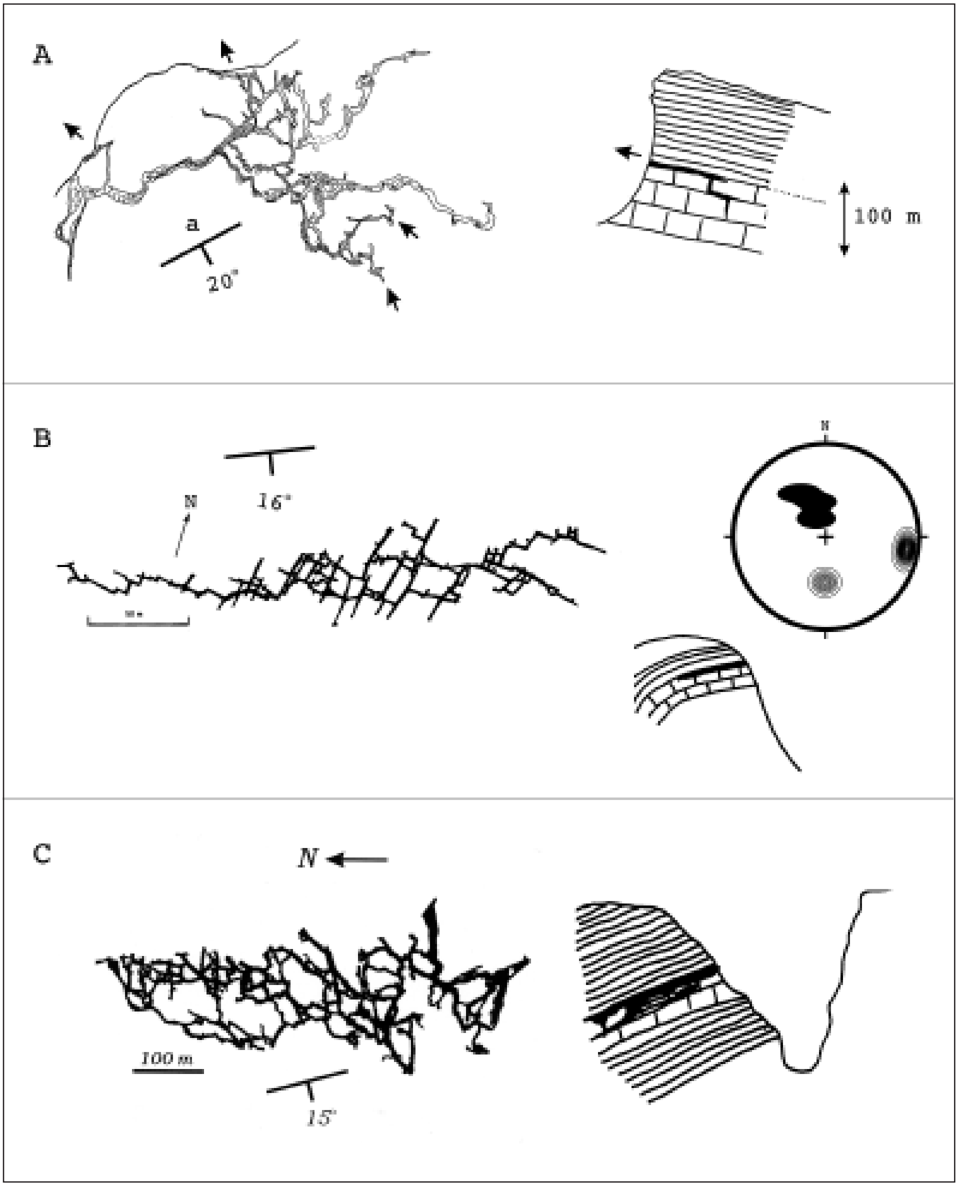



*Fig. 12: Examples of low dip network cave systems.*

*A) Grønligrotta, the classic tourist cave in Norway. The cave is a gently sloping phreatic labyrinth that was effluent when it was hydrologically active. Arrows indicate phreatic water flow. The cross-section depicts how the cave is developed at the confining schist contact, where there is also abundant sulphide impregnation. Survey after various sources (Oxaal, 1914; Horn, 1947), other data from Skutlaberg et al. (Skutlaberg et al., 2000, 2001) and work in preparation.*

B) *Nonshauggrotta, Gildeskål. Left: Plan map. The cave forms a low dip, phreatic maze along rift-shaped passages. Stratal dip is approximately 16° and guiding fractures trending NNE-SSW and E-W with steep dip. Middle: Cross-section depicting the terrain position of the cave in Nonshaugen hill. Right: Stereonet projection of the poles of guiding fractures (grey) and schist contact (black). Data from unpublished field notes and a survey of Holbye & Trones (1973).*

C) *Okshola. Left: Outline of the labyrinth section in the 12 km long system. The labyrinth is fossil, mainly phreatic, with vadose modifications. It carries an underfit stream at the downdip side. Outline made from composite surveys (Heap, 1969; Holbye, 1975). Right: Terrain position of the cave.*

- *Grønligrotta* (Oxaal, 1914; Horn, 1947; Skutlaberg *et al.*, 2000, 2001). Gentle dip phreatic maze of about 3000 m length and 115 m depth. Most of the fossil passages are well-developed phreatic tubes and phreatic mazes. The cave is confined beneath massive schists and developed at the sulphide- impregnated contact interface between marble and mica schist. Scallop morphometry demonstrate integrated, effluent network flow. Under a thick ice cover, both the cave entrances and the paleoflow direction point down-ice. It is therefore conceivable that the network morphology is in part a result of ice contact.
- *Nonshaug cave* (Holbye, 1974). This is a 2000 m long fossil phreatic network, developed in a confined situation beneath gently dipping strata. The cave is well scalloped, and therefore has potential for palaeocurrent calculations to determine whether the system was effluent or influent.
- *Okshola*. (Heap, 1969). One of Norway's two longest caves by 12 km length. Part of the system (Fig. 13) form a sloping labyrinth of passages confined beneath mica schists, Fig. 7.

**Morphotype B: Rectilinear sub-vertical networks.** Further amendment to the speleogenetic interpretation of steeply dipping or sub-vertical network caves comes in the case where one set of passages in the network happens to be horizontal and therefore may be identified as 'levels', Fig. 13. However, true 'levels' (that are linked to the external base-level concept) needs additional information, like phreatic loop segments, paragenetic/vadose elements (Lauritzen and Lauritsen, 1995), water-line corrosion forms, etc. (Lauritzen and Lundberg, 2000).

- *Rågge Javre raige - RJR* (Corbel, 1957; Heap, 1970; Lauritzen *et al.*, 1991). This is the deepest cave system in Norway at 580 m. It is a steeply dipping storied network with both vadose and phreatic features. The larger chambers in the cave occupy the full width of the karst stripe. Guiding fractures follows two orthogonal sets (type a in Fig. 6), one set horizontal, and the other vertical.
- *Salthølene*. This huge system of vertical shafts (Foslie, 1942; Corbel, 1957), or giant grikes, is situated within a narrow stripe of marble entirely isolated in mica schists. The system is 189 m deep and consists of a sub-vertical, rectilinear, storied network, with both vadose and phreatic elements (Lauritzen, unpublished fieldwork 1985).

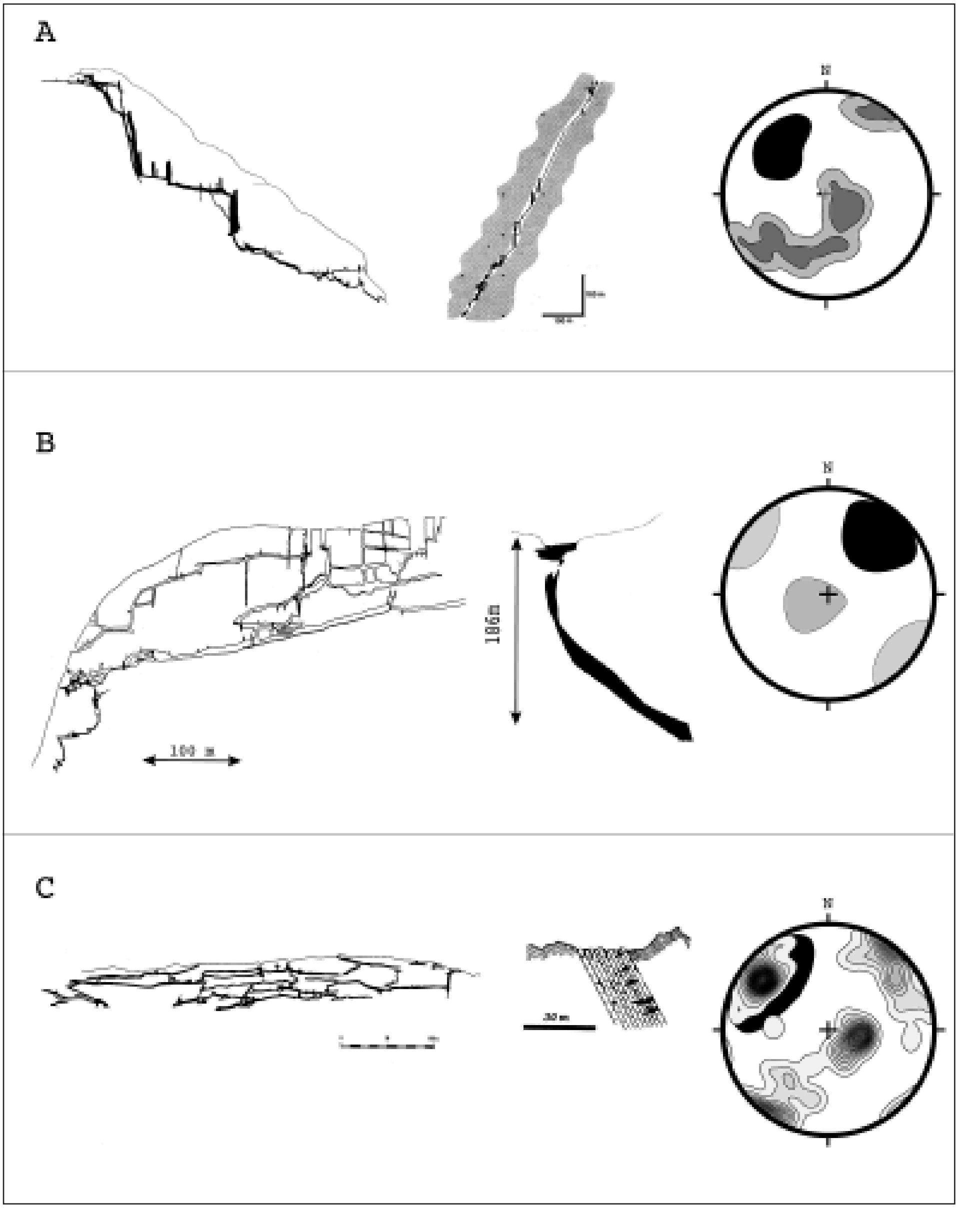



*Fig. 13: Subvertical network cave systems.*

*A) Rågge-Javre-raige cave (RJR). Left: vertical section, the cave is 580 m deep and have an aggregate length of 2,000 m. Middle: Head-on projection of the cave, looking along the strike. The larger portions of the cave occupy the whole thickness of the karst stripe. Scale is 100 m. Right: Stereonet plot of contact planes (black) and guiding fractures (grey). From Lauritzen et al. (1991) and unpublished fieldwork.*

*B) Salthølene (see location in Fig. 7). Right: Vertical section of the 186 m deep and 2,000 m long cave developed inside the stripe. Middle: Head-on view of the karst stripe as it appears from the valley side. Left: Stereonet plot of contact planes (black) and guiding fractures (grey) of the caves. Data from Lauritzen, unpublished fieldwork (1985).*

*C) The Pikhågan caves. Left: Vertical and plan projection of the cave. Middle: Head-on view of the karst stripe and cave distribution. The caves (almost exclusively phreatic tubes) tend to occupy the hanging schist contact and is therefore of the confined type. Right: Stereonet plot of contact planes (black) and guiding fractures (grey). Data from Lauritzen (1982) and unpublished field notes. Survey after Jenkins (1959).*

- *Pikhaug caves* (Horn, 1947; Jenkins, 1959; Lauritzen, 1982). This is a confined, sub-vertical maze of 2000+ m length, consisting of horizontal phreatic tubes developed within a 20 m thick stripe of pure calcite marble, Fig. 13. The stripe has a stratigraphic dip of 70 - 80° and extends as a sub-vertical stripe for more than 6 km, where it contains numerous cave systems. The fracture pattern is orthogonal, with 3 sets; one set is parallel to the stripe and also opens up the marble/mica schist interface. The other two sets are perpendicular to the stripe, one vertical and one horizontal. This corresponds to fracturing of type a) in Fig. YY. The Pikhaug caves occupy 460 m length of this stripe ($\gamma$ = 23); passages are concentrated towards the upper aquiclude contact. It is explored and mapped down to 40 m below the surface. Hence, 368,000 $m^3$ of rock contain 2000 m cave with average diameter of 2 m, yielding 1.7% explorable cave porosity. Scallop morphometry has proven that the whole cave system functioned as an integrated network of conduits when it was functional in at least the last phase of speleogenesis. The various levels did not function independently or in sequence, the whole cave was an integrated part of the phreatic aquifer.

**Morphotype C: Looping caves.** This group is rare, as only parts of the cave system in question may display classical phreatic 'loops' in the sense discussed by Ford (Ford, 1965; Ford and Williams, 1989b). This is, however, also the case for even the classical examples of looping cave systems (e.g. Swildon's Hole Mendips UK., Castleguard cave, Canada), and it is justified to claim many Norwegian caves equally well developed (Lauritzen, 1983). The following three systems have been sufficiently well mapped and analysed to identify this kind of morphology. Two of them occur in contacts of relatively gentle dip, while Sirijordgrotta, which is also 'linear' and could as well be listed in the category below, follows vertical structures and display vertical loops, Fig. 14.

- *Hamernesgrotta*. (Horn, 1947; Lauritzen, 1990b). The cave has been re-surveyed to 2900 m (Lauritzen, unpublished) and consists of a low dip, looping phreatic system. The architecture of Hamernesgrotta is similar to the Hölloch cave in Switzerland; both caves consists of nested phreatic loops developed within a sloping plane. Seen from above, it resembles a wide, irregular network, while in vertical profile it reveals numerous phreatic loops with spillover canyons. This impressive system is perched, as it is developed close to the lower schist contact, in a sheared contact plane. The cave is almost totally relic but has a small stream appearing at the lowest edge of the system.

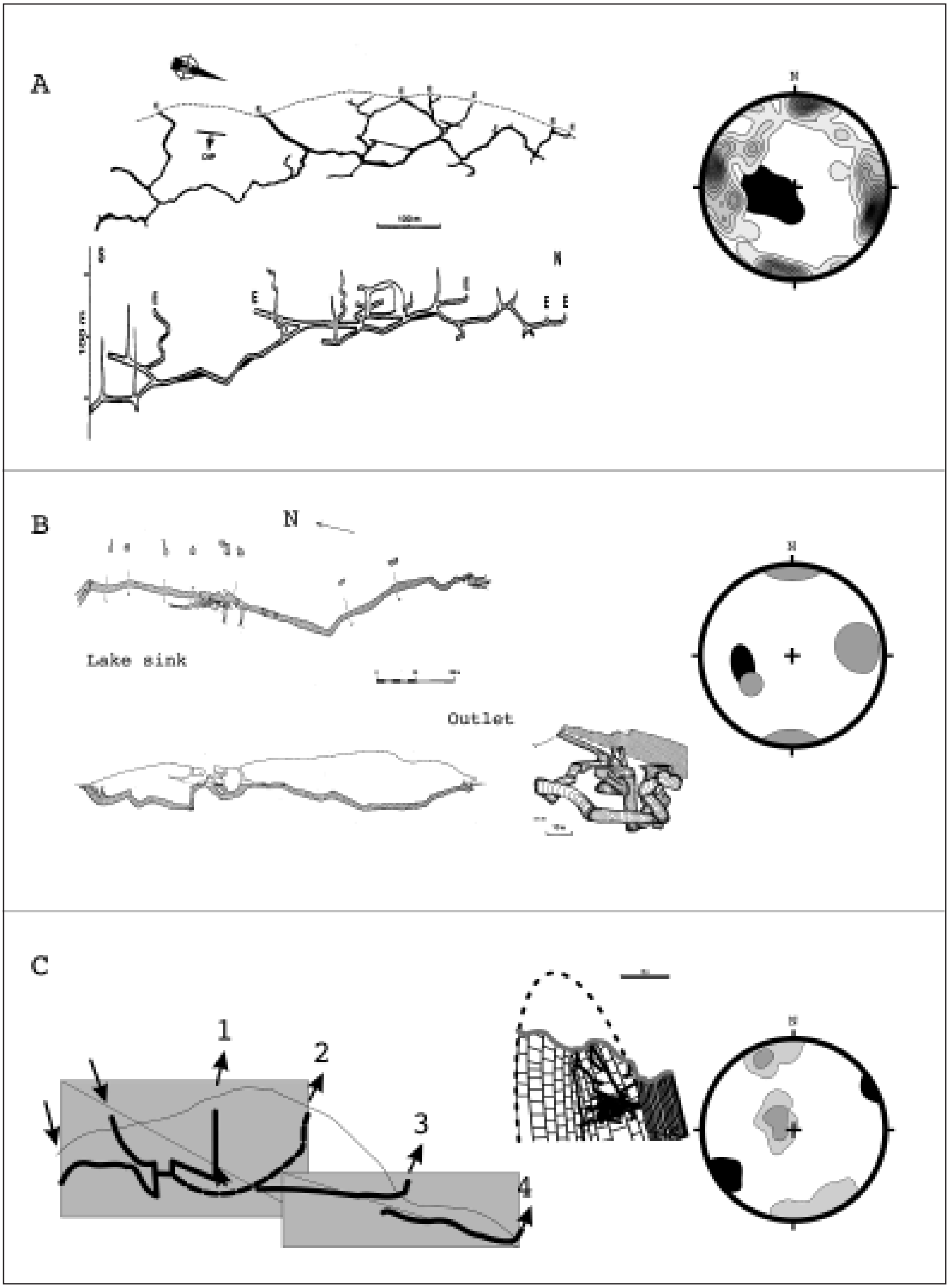



Fig. 14 - Text on page 67.

*Fig. 14 (on page 66): Cave systems with phreatic loops.*

*A) Hamarnesgrotta, Rana. Right: Plan and vertical projection (vertical scale exaggerated) of the cave. The passages are mainly circular and elliptical phreatic tubes with vadose modifications. The cave is developed close to the sloping contact plane which is tectonized. In plan view, the cave resembles an open, relatively irregular network. In vertical projection (below,) it reveals multiple phreatic loops with spillover canyons (hatched). The cave occupies a perched situation at the lower aquiclude contact. Right: Stereonet projection of contact planes (black) and guiding fractures (grey).*

*B) Jordtulla, the underground outlet of lake Glomdal, Svartisen. Left: Plan survey and vertical section of the cave. Middle: Head-on view of the cave and the schist contact. The cave occupies a confined situation underneath the hanging aquiclude wall. Right: Stereonet plot of contact planes (black) and guiding fractures (grey) in the caves. Surveys from Lauritzen et al. (1985), other data from unpublished field notes.*

*C) Sirijordgrotta, as surveyed by Valen et al. (1997). Left: Vertical section of the cave. From morphology and paleocurrent analysis, the speleogenetic sequences are interpreted as a series of phreatic loops developed in pace with a lowering base-level (1..4) controlled by the river valley and aquiclude contact. From Lauritzen et al. in prep. Middle: Head-on view along the fold axis in the surrounding rock mass. Thick black lines are the centreline survey rotated to obtain maximum overlap. Left: Stereonet projection of aquiclude contacts of the stripe (black) and guiding fractures (black).*

- *Jordtulla.* (Lauritzen *et al.*, 1983, 1985). This is an active phreatic system, forming the only outlet of a lake. It was explored and mapped by cave diving to a length of 580 m and 25 m depth. It is a moderate to low dip, looping phreatic system, confined beneath the hanging schist wall. The architecture is similar to Hamernesgrotta, but less complicated.
- *Sirijordgrotta.* (Faulkner, 1980, 1987; StPierre and StPierre, 1980; Valen *et al.*, 1997). The cave is relict with an underfit invasion stream and is essentially a sub-vertical, storied network with looping elements. Stratigraphically, the cave is guided by contact against almost vertical amphibolite dykes, with sulphide impregnation at the contacts. The karst stripe is also the flank of a tight anticline, formed between mica schist wallrock and amphibolite / schist in the core of the fold. When the cave centreline survey is rotated to obtain maximum passage overlap, the view axis (317°/6°), is parallel with the fold axis. Shafts and lifting chimneys basically follow E-W vertical fractures, while gently plunging elements of the cave follow the subhorizontal or low dip fractures, often in contact with the aquiclude or aquiclude-parallel silicate bands.

**Morphotype D: Linear systems.** With linear systems we here mean a set of cave passages that drain more or less directly between two points in the aquifer, preferably from a physical input (sink) to a physical output (spring). This is rarely observed, and by presenting the following examples one runs the risk of considering a fragment of a larger-scale feature, Fig. 15. For example, Horn’s No1 (*vide infra*) may also be regarded as the rising segment of a much larger phreatic loop, and Sirijordgrotta in plan projection, is also a ’linear’ feature, guided by intrusions at the core of a fold. The point is however to demonstrate that ’linear’ systems are in fact controlled by

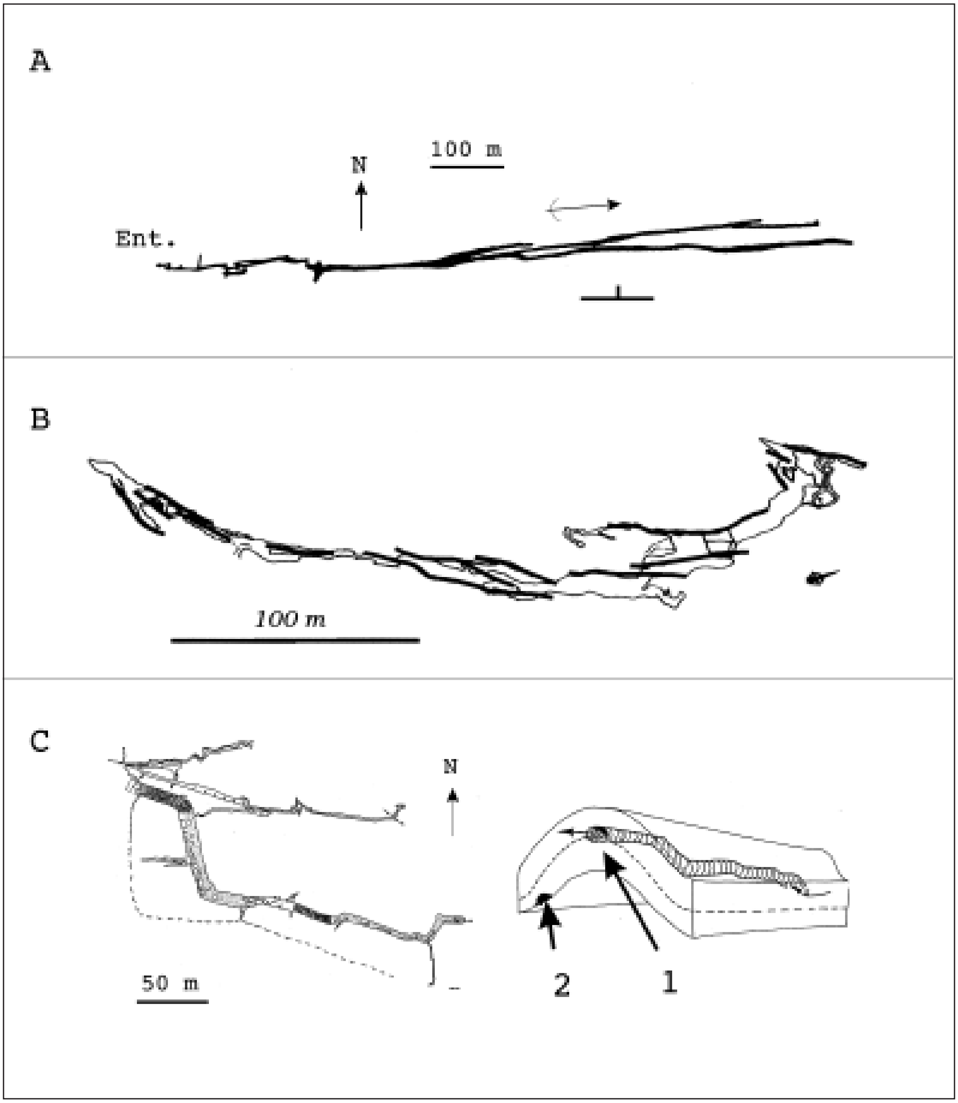



*Fig. 15: Linear cave systems.*

*A) Plan of Larshullet, Rana (Horn, 1947). 2,500 m of almost straight, phreatic passages. The galleries are controlled by the fold axis (dipping 12° E), and vertical fractures (NNE-SSW) in the rock mass.*

*B) Plan of Storsteinshola, Kjøpsvik. The cave consists of paragenetic galleries and is developed in marble stripes between amphibolite and schist layers depicted with black thick lines. These inliers are bodinaged and permit the cave to penetrate through them. Survey by Lauritsen et al. 1997, geology after Lauritsen 1977.*

*C) Horn's No 1. Glomfjell. This cave is developed at the contact zone between upper, impure marble ('yellow marble') and a purer 'grey' calcite marble. a) Plan map. b) Geologic position of the fossil, phreatic (and effluent) tube, (1) and later vadose invasion.*

some other 'linear' structure, in these cases, it is either silicate intrusions or a contact interface, and the caves tend to be parallel to local fold axes. At least in the case of Horn's No1, the cave occupy the hingeline of the fold.

- *Larshullet* (Horn, 1947; Railton, 1954). This remarkable phreatic system of 2,500 m aggregate length consists of almost straight, phreatic passages, following the trend and plunge of fold axes (-12°) for a horizontal distance of more than 1,300 m (Horn, 1947). Vertical jumps are guided by steeply dipping cross-joints, Fig. 15.
- *Storsteinshula.* (Holbye, 1969; Lauritzen and Lauritsen, 1995; Lauritsen, 1996; Lauritsen and Lauritzen, 1996). The cave is situated in the quarries for a cement factory in Kjøpsvik, and was originally opened by the quarry operations, which also display the surrounding geologic structures very well. The main passage is a paragenetic canyon incised between sub-vertical amphibolite and schist inliers in marble. The passage breaks through these barriers where they are bodinaged. The passages can be followed for about 400 m along a slightly curved path, Fig. 15. The marble stripes are parts of the complicated interference pattern depicted in Fig. 15.
- *Horn's No1.* (Horn, 1947; Lauritzen, 1990a). This is an interesting example of stripe karst within other carbonates. The Glomfjell karst (Corbel, 1953, 1957; Bogen, 1976; Lauritzen and Bogen, 1985) consists of some 200 km$^2$ metacarbonates containing bands of relatively pure calcite marble ('grey marble') interbedded with mica schist and less purer, micaeous marble ('yellow marble'). The 650 m long 'Horn's No 1 cave' is mainly an effluent phreatic trunk passage developed at the confining contact between grey and yellow marble. The old phreatic conduit follows the crest of an anticline in the contact, while later vadose invasion occupy a stratigraphically lower position in the grey marble.

## KARSTIFICATION DEPTH

On a large and general scale, karstification may be compared to a weathering front that develop in phase or out of phase with land surface lowering, depending on the karst penetration rate relative to the erosion rate. If erosion rate is high, karst will tend to become immature and shallow, if erosion rate is low, karst will develop to maturity and penetration will die out more slowly. For the Scandinavian Caledonides, it can be argued, that since the land block has been uplifted since mid- Tertiary, it may be argued that karstification depth and surface denudation may have developed in pace, while enhanced mechanical denudation during glacial periods might have been high enough to rejuvenate karstification. Pleistocene glacial erosion have indeed left stripe karst aquifers hanging high up in the sides of overdeepened throughs. This contrasts many other karst areas, which have either been tectonically stable, or have experienced both uplift and subsidence during the timespans available for karst development. The apparent lack of palaeokarst younger than the Caledonian in Norway (Lauritzen, 1988, 1989, 1996) may be taken as supporting evidence for this view.

The depth, or penetration distance of meteoric karstification is an important parameter for the evaluation of its maturity relative to the landmass surface it developed from. This is interesting from a theoretical as well as a practical point of view. In particular, engineering and water extraction from (stripe) karst is dependent on whether the karst is permeable or not at a given depth. In the following, we will discuss various ways karstification depth and age have been estimated in stripe karst of the Scandinavian Caledonides.

**Exploration depth.** Direct exploration in sub-vertical stripes yield maximum depths perpendicular to the land surface between 40 and 180 m, Table I. RJR is an extreme end-member in this context, it is also penetrating below the present sea level, which is known to have fluctuated greatly during the quaternary. In stripes of lower slope, down-dip penetration amount up to some 300 m; the lower the dip, the deeper is the interstratal penetration. Faulkner (2001) states 50 m as the limit of exploration depth in south Nordland.

*Table I: Morphological and geological properties of stripe karst caves.*

| **Cave** | **Stripe karst properties** | | | **Cave properties** | | **Penetration from surface (m)** | | **Karst and cave types** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Dip ( )** | **W[1] (m)** | **$(m^{-1})$** | **L[2] (km)** | **D[3] (m)** | Vert[4]. | Dip[5] | Contact type | Morphotype | Fracture geometry |
| Grønli | 20 | 50+ ? | 5 | 3 | 115 | 200 | 250 | 2 | Network (A) | c |
| Nonshaug | 16 | 10 + ? | - | 2 | 20 | 40 | 50 | 2 | Network (A) | d |
| Okshola | 15 | ? | - | 11 | - | - | 300 | 2 | Network (A) | d |
| RJR | 63 | 25 | 40 | 2 | 580 | 185 | 185 | 1 | Storey network (B) | a |
| Saltholene | 60-90 | 20 | 25 | | 187 | 90 | 90 | 1 | Storey network (B) | a |
| Pikhaug | 75-80 | 20 | 23 | 2 | 40 | 40 | 40 | 1 | Storey network (B) | a |
| Hamarnes | 18-25 | 100 | 5 | 3 | | 120 | 150 | 3 | Loop (C) | e |
| Jordtulla | 20-30 | 30 | 17 | 0.6 | 35 | 35 | 60 | 2 | Loop (C) | c |
| Sirijord | 80-90 | 25 | 19 | 1.25 | 75 | 55 | 55 | 1 | Loop & storey (C&D) | a (b) |
| Larshullet | 12 | 50 | - | 2.5 | 334 | 265 | 1330 | 2, 3 | Linear (D) | c |
| Storstein | 90 | 200 | - | 2 | 30 | 50 | 50 | 1 | Linear (D) | a |
| Horn 1 | 12 | 10 | - | 0.6 | 36 | 60 | 185 | 2 | Linear (D) (C) | e |

*[1] Width of the host karst stripe. [2] Total surveyed length.[3] Total surveyed depth. [4] Maximum vertical depth below surface directly above the gallery in question. [5] Down-dip penetration of the cave measured from the surface.*

Only drained karst aquifers in 'hanging' positions elevated above the local water table, may be subject to significant vertical exploration. Any cave survey based on human exploration is necessarily a *minimum* estimate of both the amount and depth of caves. In fact, many of the 'deep' caves in Norway do end in either sumps or sediment chokes, often without any signs of termination of the passages themselves. This has been demonstrated by digging sediment chokes and by diving. Cave diving has demonstrated that sumps in gentle dip cave systems may bell out to huge water-filled passages and quickly become deeper than the limit of normal diving. Explorational depth is therefore by no means a reliable measure of the limit of karstification depth, and we have to find other means of estimating this.

**The Milanovich equation.** One way to estimate karstification as a function of depth is to evaluate the vertical distribution of voids with depth. Often, this is found to change systematically. Milanovich (1981, 2000) evaluated 146 borehole logs from the Dinaric karst and found that the frequency of karst voids beneath the epikarst zone decreased approximately exponentially with depth. Converted to 'half-depth' units ($D_{1/2}$), Milanovich's data suggests that karstification (excluding the upper, extremely porous, epikarst zone which did not fit the model) is halved for every 58 m depth. The assumption is that borehole logs in fact record a proportional picture of the real amount of voids at any depth. This assumption can also be applied to certain caves. In long and well-explored cave systems one may assume that the bias of *lateral exploration* is independent of depth, i.e. that cavers (in long and well documented caves) are able to find approximately the same fraction of the existing total voids at various depths. In narrow, vertical stripes, like Pikhaugene and Salthølene, lateral exploration has been pushed to near completeness, and this assumption should hold for the vertical range of known caves. Total passage volume was integrated at each depth interval and plotted against depth, yielding coefficients of the Milanovich equation, which in turn convert to $D_{1/2} = 51$ m, Fig. 16a and Table II. This is surprisingly close to the half-depth found by Milanovich for the Dinaric karst, but it must be kept in mind that the two data sets are normalised to a karst index of 10 at 10 m depth. In the Dinaric karst, the absolute porosity may be higher at 10 m depth than in the Salthølene karst stripe.

Another, and in some ways much more complete data set became available when engineers performed seismic tomography across a sub-vertical karst stripe at a damsite in northern Norway (By *et al.*, 1988). The site is close to the cave *Horn's No 1* as discussed above. The tomogram traverse covers a total area of 20,000 m$^2$ (400 × 50 m) and have a pixel resolution of 2.5 × 2.5 m. Low-velocity zones, which was interpreted as karst voids, displayed a patchy distribution all over the explored depth interval and numerous occurrences at the lower limit of the tomogram clearly

*Table II: Parameters of karstification depth.*

| Data set | Decay constant (m$^{-1}$) | Half-depth ($D_{1/2}$) m |
|---|---|---|
| Tomography, epikarst | -0.087 | 8.0 |
| Tomography, deep karst | -0.028 | 24.7 |
| Saltholene | -0.014 | 50.7 |
| Milanovich equation | -0.012 | 57.8 |

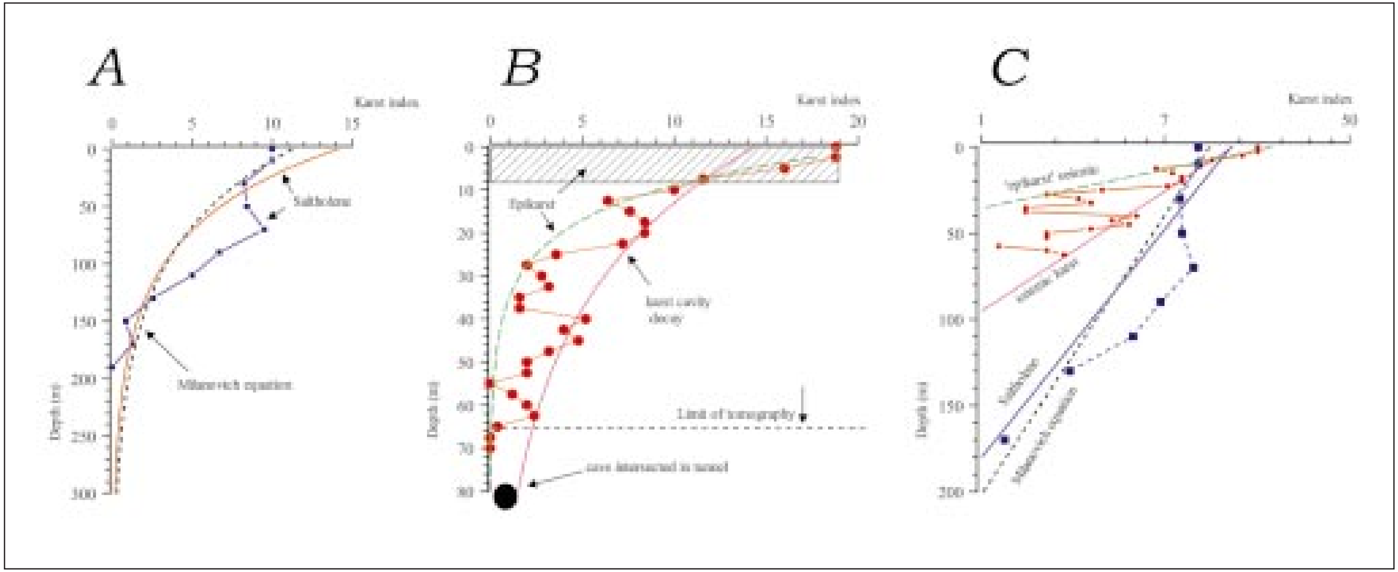



*Fig. 16: Estimating the depth of karstification by means of the Milanovich equation.*

*A) Total surveyed cave volume for Saltholene integrated in 20-m depth intervals and normalised so that the 'karst index' is 10 at 10 m depth. (squares with line). Solid line is exponential decay equation fitted to the data. The thick, dashed line is the Milanovich equation, based on 146 borehole logs in the Dinaric karst. The two curves have very similar decay constants and the half-depth is about 50 m for both. From Lauritzen (1986a).*

*B) The seismic survey of By et al. (1988) digitised and integrated in depth intervals of 2.5 m (red dots). An upper, intensively corroded epikarst zone is evident in the data, depicted with the hatched rectangle. The two curves are exponential decay functions fitted to the upper 'epikarst' zone (green dashed line) and the deeper karst zone (red line), respectively. From Lauritzen (1990a).*

*C) All data plotted in a semilogaritmic scale, so that each decay function appear as a straight line. Epikarst (grikes) die out quickly, whilst both the seismic data and the cave survey suggests that the maximum depth of karstification in these stripe karsts do penetrate deeper than 50 m, probably beyond 100 m.*

indicated that these voids penetrate deeper than the 50 m depth limit of exploration. Later, the tomogram was analysed in a different way, by integrating the area of void zones as a function of depth (Lauritzen, 1990a). The depth-distribution of voids show three maxima: 0-15 m, ≈ 20 m and ≈ 40 m. Although the pixels close to the surface are affected by interference at the rock- air contact, the high density zone is six pixels deep and cannot be explained by interference only. Hence, the upper 5-10 m may be interpreted as an epikarst zone which quickly die out ($D_{1/2}$= 8m). This is entirely consistent with observed grike depth in the area, which go down beyond 10 m. The remaining karst display a decreasing frequency with depth; $D_{1/2}$= 25 m, i.e. about twice the rate of Milanovich's data and the cave voids in Salthølene, Fig. 16b. Therefore, the amount of karst voids at 50 m depth would only be reduced to ≈ 30 % of the amount at 10 m depth, and significant voids may occur down to at least 4-5 half-lengths, i.e. 100 - 125 m below the surface. This prediction was indeed confirmed when dam constructions commenced. First, a 20 m deep surface shaft caved in under a machine; second, a sand-filled cave of substantial size was intersected at 80 m depth.

The two data sets display an irregular, but systematic decrease of karst voids with depth. Both analyses indicate that karstification depth in vertical stripe karst is site-dependent and variable, but goes beyond 100 m and may penetrate beyond 150 m. In low dip stripes, dip-aligned penetration as well as vertical depth beneath land surface may go much deeper, 200 to 300 m.

## AGE AND DEVELOPMENT OF THE STRIPE KARST

The karst landforms of Norway can be given a formal classification according to their terrain position in a glacial and pre-glacial landscape, which reflects their age-potential (Lauritzen, 1981):

- valley floor caves
- valley wall caves (hanging caves)
- valley shoulder caves (hanging caves)
- paleic surface caves

The 'paleic surface' is the name given to the pre-glacial land surface in Scandinavia (Gjessing, 1967; Lidmar-Bergström, 1996). The potential age for a given karst form (i.e. relict cave) increase with its distance above baselevel. The dominant action of glacial erosion rates imply that caves located within valley profiles cannot be much older than the valley itself, but many relict caves are associated with the paleic surface. They should therefore have a correspondingly high age. However, by critically reviewing this problem, it was found that the essential age criterion for a cave is the conduit diameter and its distance above the nearest valley floor. Very few caves in Norway satisfy these conditions to the extent that they, beyond doubt, would have survived the Pleistocene glaciations (Lauritzen, 1990b).

Direct, radiometric dating or discovery of *in situ* Tertiary deposits in a cave would provide a final answer to the question. No such deposits have yet been found in Scandinavia. Uranium-series dating of speleothems have, by means of the TIMS technique, yielded ages up to 750 ka, which is the limit of the method. The potential of long-lived cosmogenic nuclides ($^{10}Be$, $^{26}Al$) is important for dating clastic cave deposits as well as the surface of surrounding landforms (Gosse and Phillips, 2001).

## CONCLUSIONS

Stripe Karst is an elongated outcrop of a karst rock stratum, which intersects the land surface at an angle. Its length to average width ratio ($\gamma$) is much greater than 3 and the stripe geometry is fully developed above $\gamma = 30$. The absolute width is equal to or less than twice the penetration length of allogenic contact karstification. In most cases this width limit is some hundred meters. Impermeable and insoluble rocks, forming aquicludes, surround and isolate individual karst stripes.

Stripe karst thus provides an extreme kind of allogenic contact karstification, particularly when the contact effects from each side merge. Stripe karst develops characteristically in metamorphic carbonates from orogenic cores, and multiple folding and nappe thrusts result in complex interference patterns in the outcrops. It is the dominating karst type in the Scandinavian Caledonides and is named the *Norwegian karst type*.

Karstification is intensive at lithological contacts; between marble and mica schists, but also between different marble lithologies. Mica schist contacts often contain iron oxides and sulphides, giving rise to sulphuric acid speleogenesis; many caves are indeed developed along such contacts.

Stripe karst contacts is classified into three main types: sub-vertical, moderate dip confined and moderate dip perched. In many cases, speleogenesis may start under phreatic conditions at the upper, confining contacts (which may also carry sulphide impregnation), but under vadose conditions, caves may cut down towards the lower contact and become perched.

Due to the metamorphic processes, all primary voids are absent, and speleogenesis is entirely dependent on fractures formed in the brittle deformational regime. Often, two orthogonal sets of fracture are found, which, together with the allogenic contact plane, form a 'box' unit which may display various attitudes depending on stratal dip and the orientation of the two fracture sets. From this, we may deduce three different settings of fractures, which split up into six cases when high and low stratal dip is introduced.

Stripe karst cave systems form four main morphotypes: subvertical phreatic networks or mazes, low dip phreatic networks or mazes, looping systems with vadose trenches, and linear drainage

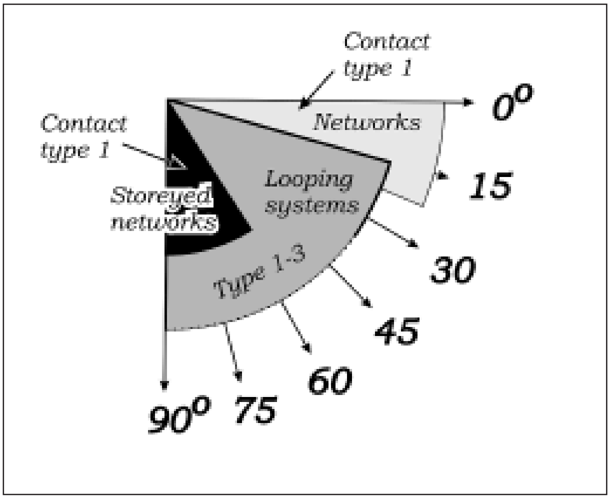



*Fig. 17: Cave architecture as a function of stripe karst dip. 'Random' networks are only found in low dip situations, layered, or storied networks tend to occupy the steep dip members, and systems with well-developed phreatic looping can be found in moderate to steep dip. Borders are approximate.*

systems. Three examples of each morphotype is presented and discussed. The various morphotypes do show systematic dependence on stratal dip of the allogenic stripe contacts, of the type of contacts, and to a lesser extent, the fracture patterns.

Low dip Phreatic networks is found exclusively in confined contacts where fracturing may be both vertical and horizontal, or oblique. Storied phreatic networks are generally guided by horizontal and vertical fracture sets. Looping caves occur both in gentle dip and almost vertical stripes, and fracturing tend to be oblique as well as horizontal-vertical. Linear systems tend to be aligned to some other linear structure in the rock mass, like a fold axis, or linear intrusive veins. The dip-dependence of the various cave morphotypes and contact types is summarised in Fig. 17.

Finally, karstification depth in stripes can penetrate beyond 100 - 150 m below the land surface. Some areas display high density of grikes at the surface, which may be taken as a kind of epikarst. Such grikes may penetrate beyond 10 m depth. Due to the high erosion rates prevailing during the Quaternary, stripe karsts in Scandinavia are relatively young: although many caves are several glacial cycles old, no unequivocal evidence of pre-glacial, or Tertiary caves have yet been presented.

## ACKNOWLEDGEMENTS

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## REFERENCES

Bögli, A. 1978: *Karsthydrographie und physische Speläologie* Springer-Verlag, Heidelberg. 292 pp.

Bogen, J. 1976: *Geomorfologisk befaring i Sundsfjordvassdraget* Universitetet i Oslo, Oslo. 18 pp.

Bryhni, I. & Andréasson, P.G. 1985: Metamorphism in the Scandinavian Caledonides. pp. 763-781 *In:* Gee, D.G. & Sturt, B.A., (Eds.) *The Caledonide Orogen - Scandinavia and Related Areas*. John Wiley & Sons Ltd., London.

By, T.L., Lund, C. & Korhonen, R. 1988: Karst cavity detection by means of seismic tomography to help assess possible dam site in limestone terrain. pp. 25-31 *In:* Romana, (Ed.) *Rock Mechanics and Power Plants*. Balkema, Rotterdam.

Corbel, J. 1953: Une région karstique de Haute Laponie. Navnlosfjell (La Montagne-qui-a-perdu-son-nom). *Revue de Geographie de Lyon 28[4]*, 329-344.

Corbel, J. 1957: Les karts du Nord-ouest de l'Europe et de quelques régions de comparison. *Institute des Etudes Rhodanniennes. Mémoires 12*, 1-541.

Faulkner, T. 1980: Sirijordgrotten and other caves in Eiteraadal, Vefsn, Norway. *Cave Science 7*, 53-69.

Faulkner, T. 1987: Caves of the Jordbruelv and Jordhulefjell, South Nordland, Norway. *Cave Science 14*, 31-45.

Faulkner, T. 2001: Cave development in Central Scandinavia. *Proceedings of the 13th International Congress of Speleology 1*, 155-S1 (1-5).

Ford, D.C. 1965: The origin of limestone caverns: a model from the central Mendip. *National Speleological Society, Bulletin 27*, 109-132.

Ford, D.C. & Williams, P.W. 1989a: *Karst geomorphology and Hydrology* Unwin Hyman, London. 601 pp.

Ford, D.C. & Williams, P.W. 1989b: *Karst geomorphology and Hydrology* Unwin Hyman, London. 601 pp.

Foslie, S. 1942: Hellemobotn og Linnavarre. *Norges Geologiske Undersøkelse 150*, 1-119.

Gjessing, J. 1967: Norway's Paleic Surface. *21*, 69-132.

Gosse, J.C. & Phillips, F.M. 2001: Terrestrial in situ cosmogenic nuclides: theory and application. *Quaternary Science Reviews 20*, 1475-1560.

Grønlie, A. 1980: Grotter i Grønliflåget. *Norsk Grotteblad 5*, 22-30.

Heap, D. 1969: *Report of the British Speleological Expedition to Arctic Norway 1969, including the work of 1968 Hulme School's Expedition* Kendal Caving Club, 37 pp.

Heap, D. 1970: *William Hulme's Grammar School's Expedition to Arctic Nordland 1970*, Manchester. 21 pp.

Holbye, U. 1969: The caves of Kjøpsvik, North Norway. *Cave Research Group of Great Britain. Newsletter 115*, 2-11.

Holbye, U. 1974: *Om vern av kalksteinsgrotter og grotteområder i Norge* Norges Naturvernforbund, Oslo. 59 pp.

Holbye, U., 1975: *Øvre Okshola. Plan map outline*. Unpublished.

Holbye, U. & Trones, S., 1973: *Nonshauggrotta, CRG grade 3, plan outline*. Unpublished.

Horn, G. 1935: Über die Bildung von Karsthöhlen unter einem Gletcher. *Norsk Geografisk Tidsskrift 5*, 494-498.

Horn, G. 1937: Über einige Karsthöhlen in Norwegen. *Mitteilungen für Höhlen und Karstforschung*, 1-15.

Horn, G. 1947: Karsthuler i Nordland. *Norges Geologiske Undersøkelse 165*, 1-77.

Jenkins, D.A. 1959: Report on the Cambridge University Caving Club's expedition to Svartisen, Norway, 1958. *Cave Science 4*, 206-228.

Klimchouk, A. & Ford, D.C. 2000: Lithologic and Structural Controls of Dissolutional Cave Development. pp. 54-64 *In:* Klimchouk, A., Ford, D.C., Palmer, A.N. & Dreybrodt, W., (Eds.) *Speleologenesis. Evolution of Karst Aquifers*. National Speleological Society, Huntsville Alabama, USA.

Larsen, M. 1987: *Rapport - Kjøpsvikforekomsten og ressursberegningsskjemaer (Report - evaluation of the Kjøpsvik limestone deposit)* Kjøpsvik Quarries, NORCEM Concrete Factory, Kjøpsvik. pp.

Lauritsen, Å. 1996: *Geomorfologisk utvikling av grottesystemene i Kjøpsvik, Nordland (Geomorphological development of cave systems in Kjøpsvik, Nordland)*. MSc Thesis, Department of Geology, Bergen University, Bergen.

Lauritsen, Å. & Lauritzen, S.E. 1996: Quaternary cave and landform development in the Tysfjord region, north Norway. *Karst Waters Institute Special Publication 2*, 73-77.

Lauritzen, S.E. 1981: Glaciated karst in Norway. *Proceedings, 8th. International Speleological Congress. Bowling Green 8*, 410-411.

Lauritzen, S.E. 1982: The paleocurrents and morphology of Pikhåggrottene, Svartisen, North Norway. *Norsk Geografisk Tidsskrift 36*, 183-209.

Lauritzen, S.E. 1983: *Arctic and Alpine karst symposium, august 1- 15. 1983. Program and Field guide* Department of Chemistry, University of Oslo, Oslo. 89 pp.

Lauritzen, S.E. 1986a: *Ingeniørgeologi og karstlekkasje i Glomdalen* Vassdragsforsk, Oslo University, Oslo. pp.

Lauritzen, S.E. 1986b: Kvithola at Fauske; Northern Norway: an example of ice- contact speleogenesis. *Norsk Geologisk Tidsskrift 66*, 153-161.

Lauritzen, S.E. 1988: Paleokarst in Norway. *Cave Science 15*, 129-131.

Lauritzen, S.E. 1989: Paleokarst of Norway. pp. 71-76 *In:* Bosak, P., (Ed.) *Paleokarst a systematic and regional review*. Academia, Praha.

Lauritzen, S.E. 1990a: *Storglomvatn Damsted. Lekkasjerisiko og verneverdige karstformer* Fylkesmannen i Nordland, Naturvernavdelingen, Bodø. 74 pp.

Lauritzen, S.E. 1990b: Tertiary Caves in Norway: a Matter of Relief and Size. *Cave Science 17*, 31-37.

Lauritzen, S.E. 1991a: Karst resources and their conservation in Norway. *Norsk Geografisk Tidsskrift 45*, 119-142.

Lauritzen, S.E., 1991b: *Karstformer i Norge: nord-Nordland og syd-Troms* 1:500 000. Geologisk Institutt, Universitetet i bergen & Direktoratet for naturforvaltning.

Lauritzen, S.E., 1991c: *Karstformer i Norge: nord-Troms og vest-Finnmark* 1:500 000. Geologisk Institutt, Universitetet i bergen & Direktoratet for naturforvaltning.

Lauritzen, S.E., 1991d: *Karstformer i Norge: nord-Trøndelag og syd-Nordland* 1:500 000. Geologisk Institutt, Universitetet i bergen & Direktoratet for naturforvaltning.

Lauritzen, S.E. 1996: Paleokarst and speleogenesis in Spitsbergen. pp. 30-31 *In:* Horoi, V. & Constantin, S., (Eds.) *The XIVth International Symposium on Theoretical and Applied Karstology. Baile herculane - Romania, may 26- June 1, 1996*. Institul de Spéologie "Emil Racovita", Bucarest.

Lauritzen, S.E. & Bogen, J. 1985: Glaciokarst landforms in the Glomfjell area, Svartisen. *Geolognytt 20*, 35.

Lauritzen, S.E. & Lauritsen, Å. 1995: Differential diagnosis of paragenetic and vadose canyons. *Cave and Karst Science 21*, 55-59.

Lauritzen, S.E. & Lundberg, J. 2000: Meso- and Micromorphology of Caves. pp. 408-426 *In:* Klimchouk, A., Ford, D.C. & Palmer, A.N., (Eds.) *Speleogenesis: Evolution of Karst Aquifers*. National Speleological Society, Huntsville, Ala.

Lauritzen, S.E., Ive, A. & Wilkinson, B. 1983: Mean annual runoff and the scallop flow regime in a subarctic environment. *Transactions of the British Cave Research Association 10*, 97-102.

Lauritzen, S.E., Abbott, J., Arnesen, R., Crossley, G., Grepperud, D. & Ive, A. 1985: Morphology and hydraulics of an active phreatic conduit. *Cave Science 12*, 139-146.

Lauritzen, S.E., Kyselak, J. & Løvlie, R. 1991: A New Survey of Råggejavri-Raigi and the Hellemofjord Karst, Norway. *Cave Science 18*, 131-137.

Lidmar-Bergström, K. 1996: Long term morphotectonic evolution in Sweden. *Geomorphology 16*, 33-59.

Lowe, D.J. 2000: Role of Stratigraphic Elements in Speleogenesis: The Speleoinception Concept. pp. 65-76 *In:* Klimchouk, A., Ford, D.C., Palmer, A.N. & Dreybrodt, W., (Eds.) *Speleologenesis. Evolution of Karst Aquifers*. National Speleological Society, Huntsville Alabama, USA.

Milanovich, P. 1981: *Karst Hydrogeology.* Water resources Publications, Colorado.

Milanovich, P. 2000: *Geological Engineering in Karst.* Zebra, Belgrade. 347 pp.

Mørk, M.B.E. 1985: Geology and metamorphism of the Krutfjellet mega-lens, Nordland, Norway. pp. 903-915 *In:* Gee, D.G. & Sturt, B.A., (Eds.) *The Caledonide Orogen - Scandinavia and Related Areas*. John Wiley & Sons Ltd., London.

Oxaal, J. 1914: Kalkstenshuler i Ranen. *Norges Geologiske Undersøkelse 69*, 1-46.

Railton, C.L. 1954: Caving in Norway. *Transactions of the Cave Research Group of Great Britain 3*, 17-39.

Skutlaberg, S., Øvrevik, R. & Lauritzen, S.E. 2000: Karst hydrology in the Grønli- Seter system, Mo i Rana, Norway. p. 123 *In:* Onac, B.P. & Tamas, T., (Eds.) *Karst Studies and Problems: 2000 and beyond. Proceedings of the joint meeting of Friends of karst, Theoretical and Applied Speleology and IGCP 448*. Presa Universitara Clujeana, Cluj-Napoca.

Skutlaberg, S., Øvrevik, R., Hestangen, H. & Lauritzen, S.E. 2001: The Grønli- Seter cave system, Mo i Rana, north Norway: morphology, hydrology and sedimentology. *10th Speleological School, Postojna June 2001, Abstracts*, 1.

StPierre, S. & StPierre, D. 1980: Caves of Velfjord, South Nordland, Norway with particular reference to Sirijordgrotten. *Cave Science 7*, 70-82.

Valen, V., Lauritzen, S.E. & Løvlie, R. 1997: Sedimentation in a high-latitude karst cave: Sirijordgrotta, Nordland, Norway. *Norsk Geologisk Tidsskrift 77*, 233-250.

## MARMORNAT PASASTI KRAS SKANDINAVSKIH KALEDONIDOV: SKRAJNI PRIMER KONTAKTNEGA KRASA

### Povzetek

Pasasti kras je skrajen primer kontaktnega krasa, kjer je obseg alogenega dotoka velik v primerjavi s površino kraškega izdanka. Širine pasov znašajo do nekaj sto metrov in redko presegajo dvakratni "penetracijski doseg" kontaktnega zakrasevanja. (penetracijski doseg = penetration length, dolžina, na kateri hitrost raztapljanja vode v razpoki pade za določeno razmerje, npr. 1/e). Posamezne pasovi mejijo na obeh straneh na nepropustne in netopne kamnine. Nemalokrat se v pasastem krasu stikata vpliva kontaktnega zakrasevanja dveh nasproti ležečih stikov.

Pasasti kras je značilen v metamorfnih karbonatih skandinavskih Kaledonidov, kjer je večkratno gubanje in narivanje privedlo do kompleksnega prostorskega vzorca kraških izdankov.

Zakrasevanje je intenzivno tako na stiku med marmorji in sljudnimi skrilavci, kot na stiku marmorjev z različnimi litološkimi lastnostmi. Železovi oksidi in sulfidi v sljudnih skrilavcih so lahko vzrok spleogeneze zaradi korozivnega delovanja žveplove kisline.

Pasasti kras delimo v tri glavne tipe: subvertikalni, zmerno nagnjeni omejeni in zmerno nagnjeni viseči. Speleogeneza se velikokrat začne v freatičnih pogojih na zgornjem kontaktu, nadaljuje z vadoznim vrezovanjem kanalov v pas marmorja, in konča na spodnji meji z visečim tokom.

Speleogeneza je omejena na sisteme tektonskih razpok, ki velikokrat tvorijo ortogonalne oziroma konjugirane nize. Ti skupaj z ravnino kontakta tvorijo skelet v kateri se odvija speleogeneza. Značilnosti jamskih spletov so pogojene s smerjo razpok in naklonom pasu.

Ločimo štiri morfološke tipe jamskih spletov v pasastem krasu: freatični jamski spleti z majhnim vpadom, sub-vertikalni jamski spleti, spleti freatičnih zank in linearni jamski spleti. V članku so obravnavani trije primeri vsakega morfološkega tipa. Freatične mreže najdemo izključno v omejenih kontaktih z majhnim naklonom. Razpoke so vertikalne, horizontalne ali poševne. Mreže freatičnih zank so tako v pasovih z majhnim naklonom, kot v vertikalnih pasovih. Linearni sistemi se največkrat navezujejo na kako drugo linearno strukturo, npr. os gube ali linearne intruzijske žile.

Zakrasevanje v pasovih seže 100-150m globoko pod površje. Na nekaterih območjih je na površini velika gostota škrapelj, kar lahko vzamemo za neke vrste epikras. Glede na veliko hitrost erozije v kvartarju je pasasti kras v Skandinaviji relativno mlad. Razvoj verjetno poteka že več poledenitvenih obdobij, zaenkrat še ni trdnega dokaza predglacialne oziroma terciarne speleogenetske faze.