Cave Science

The Transactions of the British Cave Research Association

BCRA

Volume 15 Number 3 December 1988

Cave Studies in Norway

Early Cave Photographs in Wales

Cave Science

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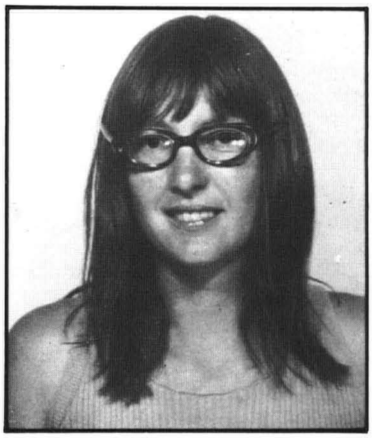
Cave Studies in Norway

In memory of Shirley St. Pierre



Following Shirley's death in June 1987, several friends felt that it would be fitting to assemble a collection of papers about those Norwegian caving subjects which were of particular interest to her. This would enable people to write something new in memory of Shirley's friendship, and hopefully contribute to an important publication which could not have occured without the personality and dedication of Shirley herself.

A letter was therefore sent to potential contributors and several themes suggested including geomorphology, particular caves and areas, and reviews of our present state of knowledge. The following papers have arisen from this invitation and bear witness to the desire of many of Shirley's friends and acquaintances to remember her in this way.

One of the most fundamental questions in speleology is the age of a cave, or at least the age of cavern initiation and major development. In *Cave Studies in Nordland, Norway* Shirley reviewed theories prevailing in 1967 for some caves in the Rana district. These can be categorised as post glacial, glacial or interglacial, subglacial and preglacial models.

The paper herein by Arne Grønlie and Erik Haugane firmly supports the preglacial theory and postulates that Hammernesgrotta and therefore probably other caves in Rana, were formed during the Early to Middle Miocene epoch of the Tertiary period. A significant element of the discussion concerns Tertiary uplift processes and the formation of the known part of the cave 300 m below the water table.

A preglacial formation for the huge seaward facing caves along the Norwegian coastline is also postulated by Rabbe Sjøberg. He discusses the chronology of the Scandinavian Tertiary uplift and the effects of glacio-isostatic depressions and varying sea-levels, concluding that these caves were formed in the late Pliocene epoch, around 1.5 million years ago.

The age theme continues in the paper by Reidar Løvlie, Helge Gilje-Nilsen and Stein-Erik Lauritzen, but covers sediment deposition rather than cave initiation. Shirley and Mark Noel had previously investigated the age of cave clays from Grønligrotta using magnetic remanence techniques. This later paper re-examines the same sediment site using denser sampling and correlation to a different secular variation record, giving a revision to the proposed age and length of time for deposition

The next paper is an abridged version of the unpublished study by Shirley herself which investigated the characteristics of the sediments in the Grønli-Seter cave system with the aim of understanding the genesis of the cave and surface palaeoenviroments.

Cave Studies in Nordland, Norway had little to say on the subject of cave fauna due to the absence of systematic studies and the presumed effects of low temperature. The paper by Heiki Hippa and Seppo Koponen is therefore of special interest in describing 60 species of invertebrates, again from Grønligrotta.

For most cavers the prime interest in Norway will probably be the 2000 or more caves recorded in the marble outcrops. However the country also has large numbers of non-carbonate caves. Wilf Theakstone's paper comprehensively discusses the development of hydrological systems inside glaciers, and relationships to subglacial limestone cave formation.

Returning to a karst theme Stein-Erik Lauritzen presents a short paper on Paleokarst and Simon Bottrell shows how the development of the caves of Lower Glomdal is influenced by both the purity and the structural features of the various marble bands. This analysis is likely to extend to many other Noregian cave areas where different marble lithologies occur together.

None of the work and ideas described in the above papers would be possible without the previous discovery, exploration and survey of Norway's caves. The final papers by David St. Pierre and David Heap review the development in our knowledge of Norwegian caves from personal perspectives.

Norway provides an ideal environment for combining the sporting enthusiasms of original cave exploration with the ensuing scientific analysis, without too great a risk of damage arising from over use or wanton negligence.

We would like to thank all those who helped in the production of this Tribute, and hope that, through BCRA, we have succeeded in constructing a whole which is even greater than the sum of its component parts.

Trevor Faulkner and David St. Pierre.

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* Joint author with D. St. Pierre

Subject Classification (After *Current Titles in Speleology*)

I. Accident & Rescue. II. Archaeology. III. Bibliography & Catalogue. IV. Biospeleology. V. Cave Descriptions. VI. Physics & Chemistry. VII. Conservation & Access. VIII. Diving. IX. Geology & Geomorphology. X. History. XI. Hydrology & Water Tracing. XII. Mines & Mining. XIII. Miscellaneous. XIV. Practical & Technical. XV. Societies & Institutions.

Not included are a number of articles (reports of trips, meetings, poems, and letters etc.) published in *Speleo* the Newsletter of SWETC Caving Club 1963-1986 and *Norwegian Caving News* published in *Caves and Caving*, British Cave Research Assoc. Bulletin 1981-1986.

Compiled by D. St. Pierre, 1988.

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Tertiary Caves in Nordland, Norway

Erik HAUGANE & Arne GRØNLIE

Abstract: Hammernesgrotta is one of several caves in Nordland, Norway, which are situated far from any drainage system which could possibly have generated the caves. By considering both the altitude of the deepest parts of Hammernesgrotta and the reconstructed entrance level in the context of the Teriary uplift of Scandinavia, we conclude that Hammernesgrotta was formed in Early Miocene time.

Until now, a Late Pleistocene age of formation for the Norwegian phreatic limestone caves has generally been taken for granted, and various theories on Quaternary cave formation have been put forward. Oxaal (1914) suggested proglacial cave formation while Horn (1947) advocated a subglacial origin. Subsequently, numerous Nordland caves have been explored, particularly by English cavers, but also since the mid sixties by Norwegian cavers. Various hypotheses on the origin of different caves have been reviewed by St. Pierre (1967).

In this paper we discuss the combined effect of the Tertiary uplift of Fennoscandia, and Tertiary erosion and climate which are factors believed to be of paramount importance when the age of formation of some of the relict phreatic limestone caves of Nordland is considered. The discussion on cave formation has hitherto been restricted to the Pleistocene but this limitation has never been documented and is a result of the lack of geological knowledge and perspective in the early part of this century. In Nordland, several existing cave systems could have originated in Tertiary times. Two obvious candidates are Hammernesgrotta and Gronligrotta both located in Rana commune, Nordland. These caves are relatively extensive systems (2-2.5 km) with voluminous, circular to elliptical phreatic tubes (Horn 1947). At present they occupy topographical positions remote from any major drainage systems. The caves presently contain small invading streams which are far too small to account for the development of the caves.

Description of Hammernesgrotta

Hammernesgrotta is situated near Langvatnet, 10 km north of Mo i Rana, Nordland (Figure 1). The north-south trending valley, Glomdal, has formed along the strike of the thrust-fault zone separating the Straumbotn and Tjørnrast Nappes

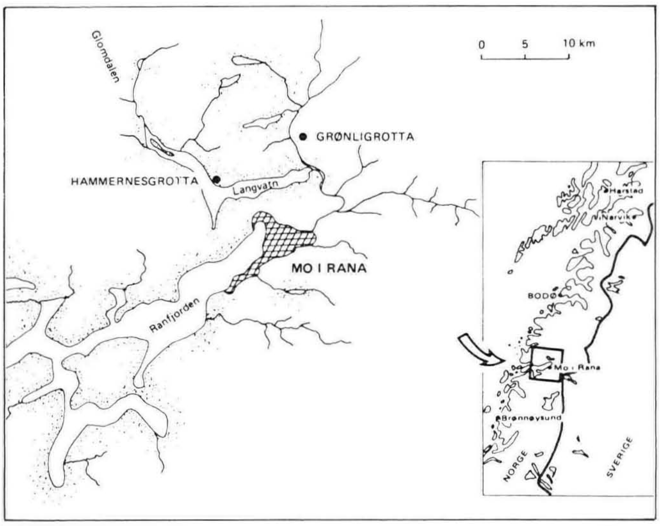


figure 1: Map showing the position of Hammernesgrotta and Grønligrotta in Rana commune, Nordland.

(Søvegjarto et al. 1981). This valley formed a tributary to the major east-west trending valley in which Ranfjorden later developed during the Quaternary, (Fig. 1).

The present day altitude of the entrances to the cave are 210-220 m asl or 163-173 m above the lake Langvatnet. They are located at the base of the cliff Hammernesflåget, just above a major talus fan. The entrances, as well as the cave itself, are located close to the base of a limestone formation at a distinct inter-formational boundary. The limestone is bounded by micaschists. An east-west profile (Figure 2), shows the geometry of the limestone formation and the position of Hammernesgrotta.

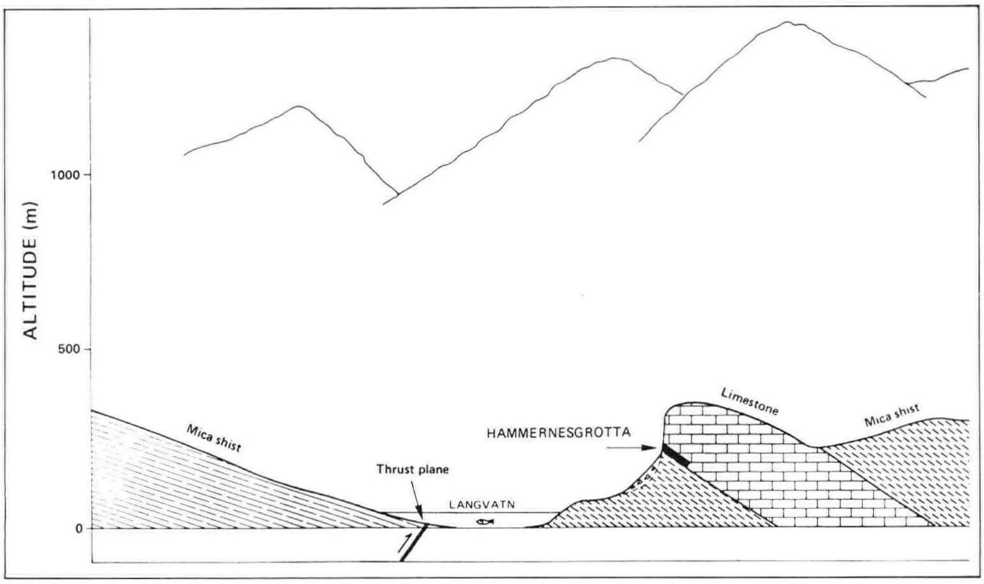


figure 2: Profile across Glomdal showing the present position of Hammernesgrotta, well above the main drainage system represented by the river Glomåga and Langvatnet.

Three other smaller caves, presumably once forming a part of the same system (Fig. 3), occur in the same stratigraphic position. The surveyed length of Hammernesgrotta (Fig. 3) is 2200 m (Horn 1947) and the cave consists of a fairly complicated network of large phreatic tubes, 2-4 m in diameter, plunging eastward at an angle of 25-30°, parallel to the dip of the limestone. The cave has seven entrances situated in a hanging position in the eastern valley side high above Langvatnet. The entrances are truncated cave passages formed by the generation of the limestone cliff. The original cave was significantly larger and the separate passages were interconnected upstream. Thus the original horizontal projection may have appeared as illustrated in Figure 4.

Horn's (1947) detailed drawings of the passage cross-sections (Figure 5) illustrate the cylindrical tubes typical of a phreatic origin. Not only did the cave lie below the water table in its juvenile period but the prevailing cylindrical cross-sections now preserved in the cave argues for a phreatic situation throughout most of the cave's development.

The passages are now mainly dry but a small stream has invaded the eastern, lowest lying passages. The stream drains the limestone plateau on top of Hammernesflåget. The invading stream has not altered the phreatic geometry of the passages.

Passage terminations are generally silted up rather than being blocked by rockfall. This is due to long-term weathering and possible sediment transportation into the cave during the glacials. The lowest portions of the cave lie at 140 metres a.s.l.

The extent and volume of Hammernesgrotta, and the passage form and size, show that only a major water supply in a system where Hammernesgrotta was situated below the water-table could have generated this cave. Thus, the cave formed when its drainage system was part of the catchment area of the main valley. Hammernesgrotta's hanging position well above the present water table excludes a Late Quaternary origin, and its relationship to a significantly higher valley floor is evident. Hammernesgrotta has not only been separated from its original drainage system, but has also remained fossil during the entire post-phreatic period. Furthermore, the cave enlargement must have been significantly reduced when the ancient fluvial system eroded the valley floor below the limestone-schist contact (Figure 6).

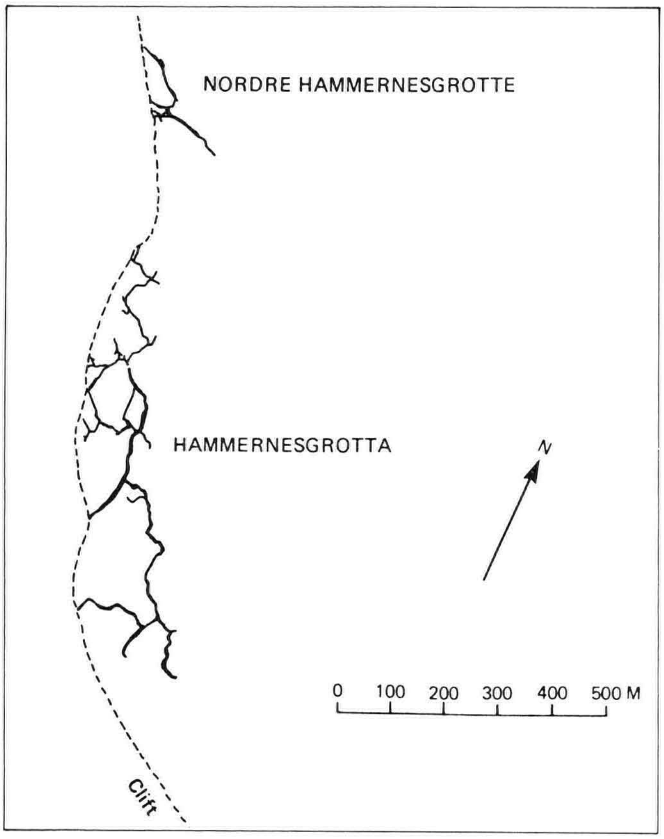


figure 3: Map of the existing caves along Hammernesflåget

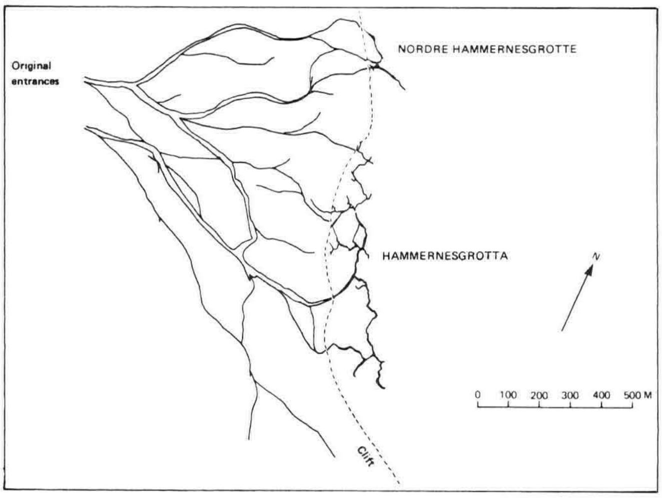


figure 4: A possible reconstruction of a former major cave-system. The present caves situated along the cliff Hammernesflåget represent the inner portion of this large, presumably Tertiary cave-system.

Effects of climate on cave formation

Although glacial meltwater and the glaciers themselves have had a considerable influence in modifying and in some cases generating caves, the limestone dissolution capacity of glacial meltwater is very limited.

The rate of passage enlargement is a function of CO_2 content and acidity of the water as well as the rate of flow. High CO_2 concentrations in the water originate from biological activity in the soil. High calcite solution rates are therefore related to temperate humid climates. In summarizing various works on karst denudation Bögli (1980) concluded that the dominant factor in dissolution of limestone is biogenic CO_2. Field investigations (Bögli 1980, p. 49) also support the view that karst denudation is most favourable in warm humid climatic zones.

The original, low CO_2 content in arctic snow is even more reduced by the process of ice-metamorphism, and deep subglacial ice is depleted in CO_2, consequently having a very limited dissolving capacity (Ford 1971, Ek 1974).

In the pro-glacial environment permafrost will also inhibit speleo-genesis. Furthermore, glacial outwash can lead to large-scale sediment transport into pre-existing caves (Ford 1977), thus inhibiting further cave development.

In northern Europe a temperate and humid climate existed throughout most of the Tertiary era, with the exception of the Pleistocene glacial period which started 2-3 million years BP. A temperate Norwegian Current which governed the onshore climate was long-lived during the Tertiary. Biostratigraphical investigations from the Vøring Plateau indicate that the climatic deterioration did not start earlier than 4.5 Ma BP (Eldholm and Thiede 1986).

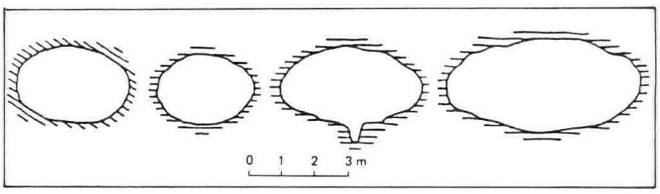


figure 5: Cross-sections of typical cave passages from Hammernesgrotta (Horn, 1947). The cylindrical cross-section originated during phreatic conditions.

figure 6: A schematic reconstruction of the Mid/Late Tertiary valley, across the position of Hammernesgrotta illustrating the situation when significant volumes of water entered the juvenile endokarst system.

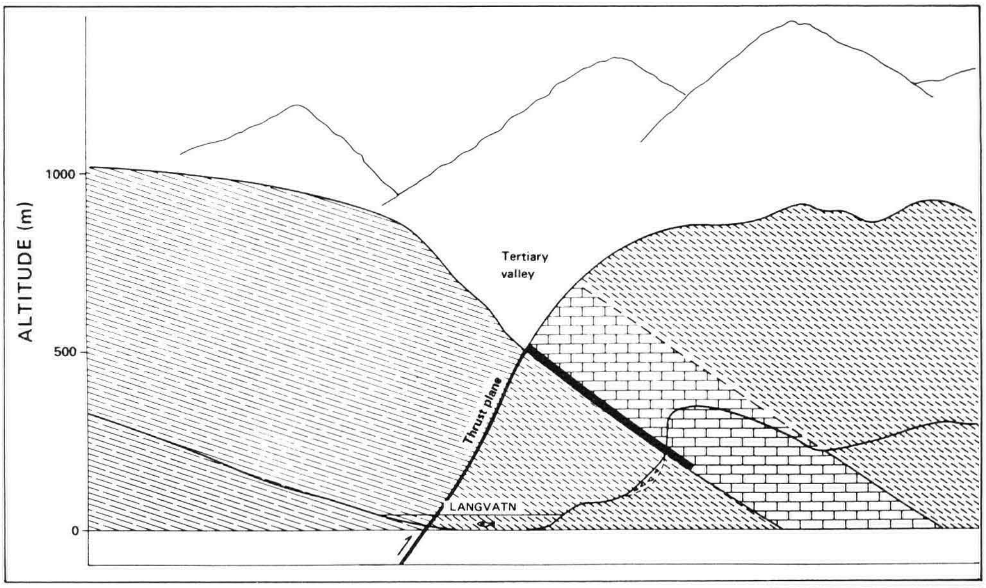
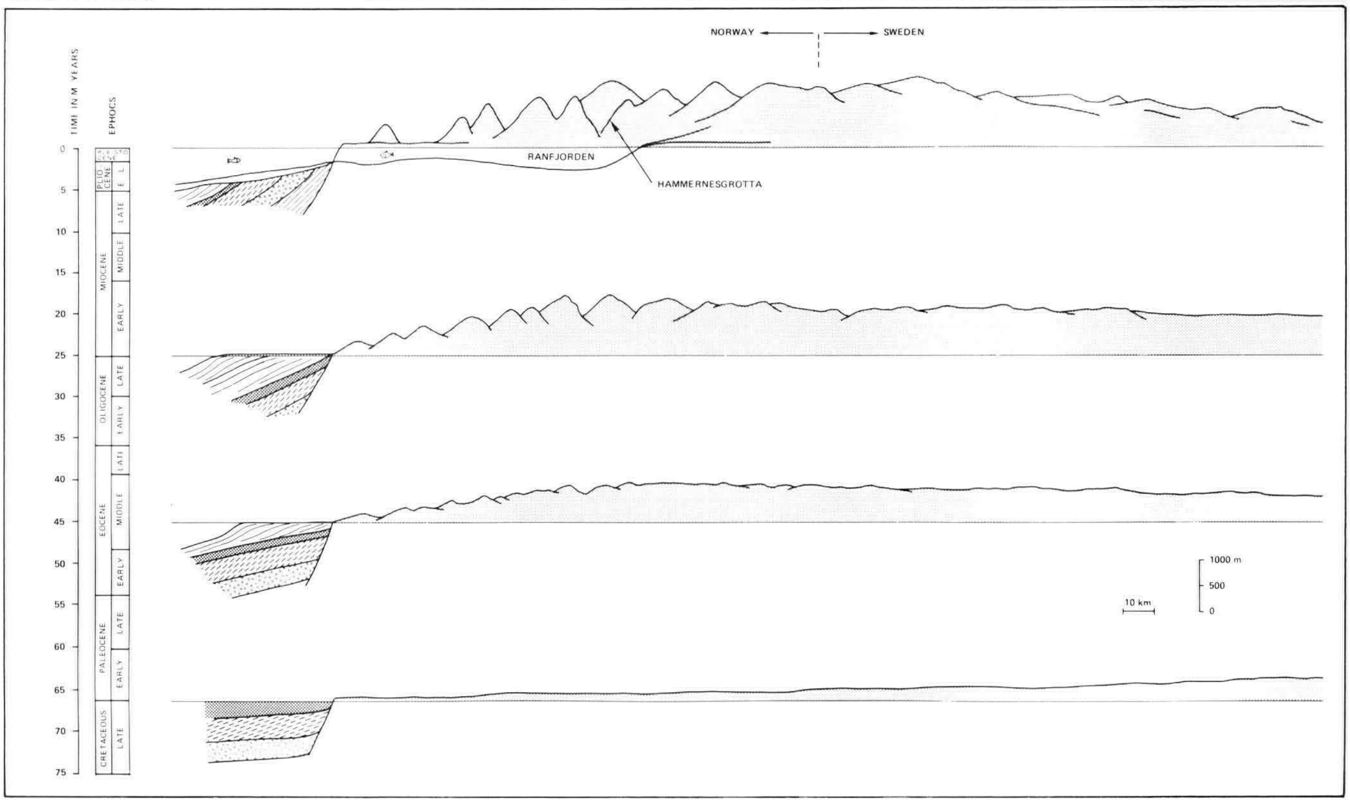


figure 7: A schematic west-east profile from offshore Nordland into the Scandinavian massif, showing the impact of the uplift during the Tertiary, assuming a mature paleo-landscape in the Early Tertiary.



The two crucial factors which had to be satisfied for karstification to occur in the Nordland limestones are exposure and a humid temperate climate. The areas where caves are found today lie far below the Early Tertiary paleosurface, and could only have been accessible to dissolution as the land was uplifted during the Mid to Late Tertiary Fennoscandian uplift. An Early Tertiary genesis of Hammernesgrotta may be excluded as the limestone beds in question were situated significantly below sea-level at that time. In the Late Pliocene, when an arctic to sub-arctic climate dominated, karstification was probably of minor importance. This points to Middle to Late Tertiary times as the most favourable period for karstification in Scandinavia during the Tertiary. Karstification was of limited extent during the Pleistocene, and Quaternary karstification was related mainly to the relatively warm interglacial periods, as indicated by speleothem dating (Lauritzen 1984). However, it seems reasonable to assume a Quaternary origin for several minor caves, and a Holocene origin for significant exokarst is evident (Haugane 1985). In rare cases, caves may form sub-glacially during a relatively short time span, Kvithola near Fauske, Nordland, being an example where high discharge rates and relatively stable ice conditions maintained a high flow rate in fractured limestones (Lauritzen 1986). The Castleguard Cave, situated directly below the Columbia Icefield, British Columbia, is another example of possible subglacial cave formation (Shroeder and Ford 1983).

Lauritzen and Gascoyne (1980) and Lauritzen (1984) dated speleothems from several Nordland caves using the uranium series method. The dating shows pronounced growth of speleothems during interglacials. Even small cave systems have been shown to be of pre-Weichselian age as they contain Eemian stalactites. Calcium denudation and precipitation takes place during the warmer and humid periods of the interglacials and the limited denudation of speleothems is consistent with the suggested limited solution capacity of glacial meltwater.

The Tertiary uplift

The Tertiary lithospheric uplift created a significant relief which was continuously eroded, and wide areas of limestones were exposed and caves were formed. This is the setting in which we postulate that Hammernesgrotta was formed.

The Fennoscandian uplift is considered to have been induced by the Eocene opening of the Norwegian-Greenland Sea (Talwani and Eldholm 1977). The oblique uplift of Fennoscandia started during the Eocene (Torske 1972). This view is supported by a significant thickness of prograding Eocene and Oligocene deposits off Helgeland (IKU 1982). The schematic profile across Nordland shown in Figure 7 illustrates the development of the Scandinavian massif throughout the Tertiary.

We assume an exponential and relatively stable uplift from the Oligocene onwards, and that this uplift has now terminated. Figure 8 illustrates the rate of uplift of the Early Tertiary paleosurface at the position of Hammernesgrotta. By extrapolating today's position of the base of the cave Hammernesgrotta back through the Late Tertiary we find that the basal part of the cave reaches sea-level in Late Oligocene - Early Miocene (Fig. 8). We suggest that a significant hydraulic gradient must have prevailed in order to account for the phreatic formation of Hammernesgrotta, and that such a gradient could not have been maintained several tens of metres below sea-level. We therefore deduce that the existing part of the cave could not have developed earlier than Early Miocene. Also, by considering a possible difference in sea-level of about 100 metres, a pre-Miocene origin for the cave is difficult to imagine.

If on the other hand, we consider the limestone exposure and related drainage system as discussed previously, we may reconstruct the entrance level by extrapolating the eastward dipping schist/limestone contact. This indicates that the pre-existing valley system would have penetrated the schist-limestone boundary at about 500 metres, or slightly less, above today's sea-level.

The glaci-isostatic rebound in the Holocene demonstrates the differential uplift on a coast-inland profile, and suggests a linear relationship between the two, as was the case concerning the Paleogene/Neogene uplift. We therefore assume that the coastal area off Ranfjorden also was uplifted during the declining phase of the Tertiary uplift. Taking into account this obliquity and the reconstructed entrance level, one finds a fluvial gradient of about 2.5 m/km to be reasonable. This rather high gradient indicates that the erosion did not keep up with the rate of uplift. There is no reason to suggest that this gradient did not persist throughout the Tertiary until the glacial erosion started.

By applying a constant erosion rate from the Middle Eocene until Late Pliocene, the valley base level can be reconstructed (Fig. 9). Our reconstructed entrance level can then be traced, and an age of Early/Mid Miocene can be deduced. This age estimate is consistent with our previous age calculations.

We suggest that most of the cave formed during the time-span when the main river had access to the limestone formation, indicating that the distal part of the cave, present-day Hammernesgrotta, formed approximately 300 m below the water-table (Fig. 7). Karstification at this depth is known to take place and may be explained by the process of mixed corrosion (Bögli, 1980).

Conclusions

We consider that Hammernesgrotta and other major caves in Nordland are remanent caves which formed mainly in Tertiary times. The exact timing of the most significant cave development is an issue for further debate. We hold the opinion that major cave systems formed during Miocene time and that remains of these caves are found today. This also explains the recognized discrepancy between the position of some major caves and today's drainage system.

In our modelling of the development of Hammernesgrotta we have considered the geometry and elevation of the cave and the geometry of the limestone formation. In our reconstruction of the lithospheric uplift through the Tertiary we assume that today's major topographic elements mimic the Tertiary fluvially eroded landscape, subsequently exposing the Glomdal limestones to the main river system.

Cave formation was limited by two crucial independent factors. We assume the maximum depth of cave formation to be limited by sea-level. The other crucial factor is the erosion of the valley floor through the limestone beds. At some time during the erosion of the valley, the limestone formation was left in a hanging position, thus preventing any major water supply to the endokarst system.

Both avenues of reasoning led to the same conclusion; Hammernesgrotta is the remaining part of a major cave system which formed during the Early to Middle Miocene. If future dating methods enable us to determine the precise timing of the actual generation of the cavities, we foresee a major progress in reconstructing the Tertiary

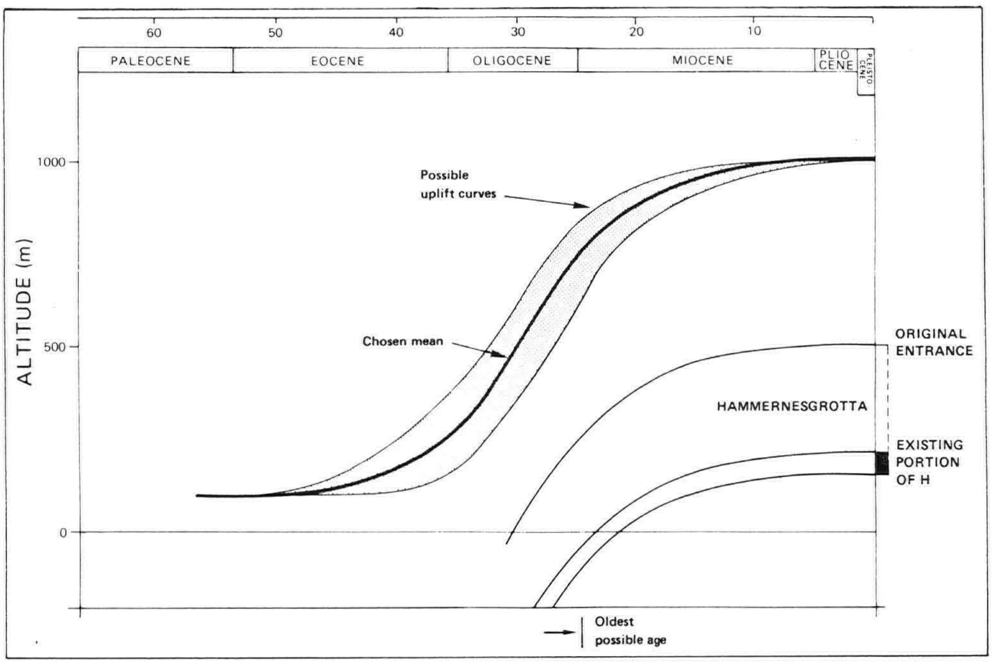
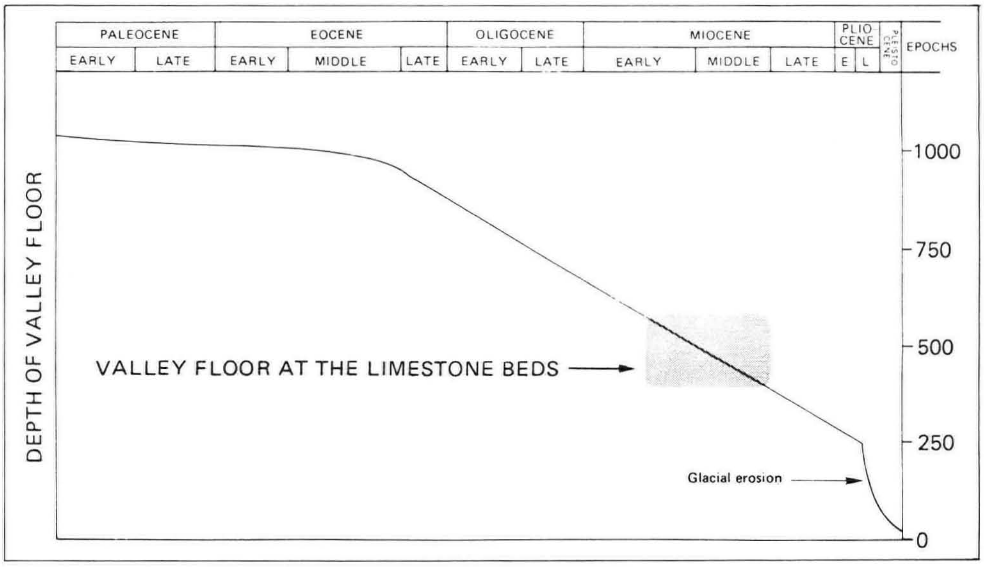


figure 8: Diagram showing the relative altitude of the lithosphere throughout the Tertiary. The altitude of Hammernesgrotta is reconstructed along the uplift curve. Considering the rather big cave passages in the lower part of Hammernesgrotta, we find it unlikely that the necessary hydraulic gradient was maintained much below sea-level implying that the cave is no older than Early Miocene.

figure 9: The diagram illustrates the assumed erosion rate by tracing the depth of the valley floor. A significant increase in erosion during the Pleistocene glaciations can account for today's elevation of the Valley floor. The valley floor passed the altitude of the extrapolated limestone formation sometime during the Middle Miocene



uplift, as the age of formation relates to the altitude of the caves which must lie above the corresponding relative sea-level. Since the assumed total uplift of the limestone areas in central and northern Norway hardly exceeds 1500 metres, no preserved cave in Scandinavia can be older than Middle Eocene.

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First we would like to thank the St. Pierre family for their encouraging love for Norway and their significant contribution to the exploration of the Norwegian caves. In connection with this paper we thank Jan Johansen for drafting the figures and David Roberts for correcting the English text.

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Coastal Caves Indicating Preglacial Morphology in Norway

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Abstract: During the last few years several caves along the Northern Atlantic coast of Norway have been studied. All these caves face the present sea, but are situated well above the highest post-glacial local shoreline. The caves are mostly of large size often more than 100 m long and around 40 m high. Four of these caves are described, herein and a 1000 km long profile from the Stadt-peninsula in More-Romsdal to Andoy in Vesteralen showing the altitudes of the caves, is shown to indicate some isostatic warping.

During the last few years several coastal caves along the Northern Atlantic coast of Norway have been researched by the author. All these caves face the present sea, but are situated well above the highest post-glacial local shoreline. The caves are mostly of large size often more than 100 m long and around 40 m high. The longest cave so far studied is the Lispingdalskyrka 325 m long, and the most voluminous is Halvikshulen with an entrance 250 m wide and 80 m high.

Four of these caves (Skjonghelleren, Halvikshulen, Lispingdalskyrka and Torghattshulet) are described herein and a 1000 km long profile (fig. 1) from the Stadt-peninsula in MÖre-Romsdal to AndÖy in Vesteralen, show the altitudes of the bottom-, roof-, and entrance levels of the caves. This profile shown an interesting linearity, in that it starts at a very low level at the Stadt peninsula proceeds with a maximum in southern Nordland and reaches another minimum at Vesteralen in Northern Norway.

Previous research

Scientists became interested in these caves long ago. In 1837 Bishop Neumann of Bergen described several caves in "Bjerg-hulerne i Bergens Stift". Among them were Skjonghelleren which he claimed to have visited on June 21st, 1827. Fifty years later, the geologist H. Reusch described many of the most prominent caves along the MÖre-Romsdal coast (1877) and showed that these caves were of marine origin. Later (1913) he argued that several of these caves were of interglacial age, as shown by deposits of clays found in Skjonghelleren, Havnsundshelleren, and Litne Byrgehilleren on VadsÖy. He argued for an excavation of the deep sediments in Skjonghelleren. This desire became true more than 100 years later (see below). Reusch was also one of the first to describe the famous cave-tunnel Torghatten outside the town of Bronnoysund (1880) which he explains as being formed by two opposed caves formed by marine abrasion along the same line of fractures.

Another geologist, J. Rekstad, also discussed the origin of these caves. He argued for a postglacial formation of the caves (1900, 1917, 1922, 1925), and explained their situation high above the highest post-glacial marine limit as caused by heavy storms.

1.	Halvikshulen, Osen	340 m
2.	Lispingdalskyrka, Nordgutvik	325 m
3.	Trollhole nr. 2, Reksten	300 m
4.	Harbakkshulen, Stocksund	200 m
5.	Rephelleren, VarÖ	188 m
6.	Dolsteinshulen, SandÖn	180 m
7.	Tonneshulen, Melfjord	170 m
8.	Torghattshullet, BrÖnnÖy	160 m
9.	Gaupehulen, Bjugn	150 m
10.	Rosvik hule, Solstad	150 m
11.	Skjonghelleren, ValderÖy	140 m

Table 1. Norway's longest marine-caves.

H. Kaldhol discussed the formation of the strandflat (1932, 1946). He argued that the situation of the marine caves in the almost vertical cliffs in the inner parts of the strandflat, above the marine limits demonstrated that the strandflat was formed before the formation of the caves and that the caves were formed during an interglacial period. As a proof of this he mentioned the clays in Skjonghelleren.

Undas (1942) studied several caves during his research of the Quaternary history of Möre and Tröndelag he argued for a formation of the caves before the last glaciation. He wrote "It seems proved that these caves were eroded before the last ice-epoch. As they belong to the greatest and longest caves which have been found on the coast, the last icecap has not destroyed them. The high situated caves and the cliffs into which they have been eroded must have been preserved practically unaltered during the last ice epoch" (Undas 1942, p. 43). Undas also discussed the altitudes of the marine limits. He Stated that at Stadt, the highest postglacial marine shore level (ML) is very low, northwards from Hitra, along the coast of Nord-Tröndelag and Nordland the altitude of the ML is high. Further north in Lofoten and Vesteralen the ML again is very low. This

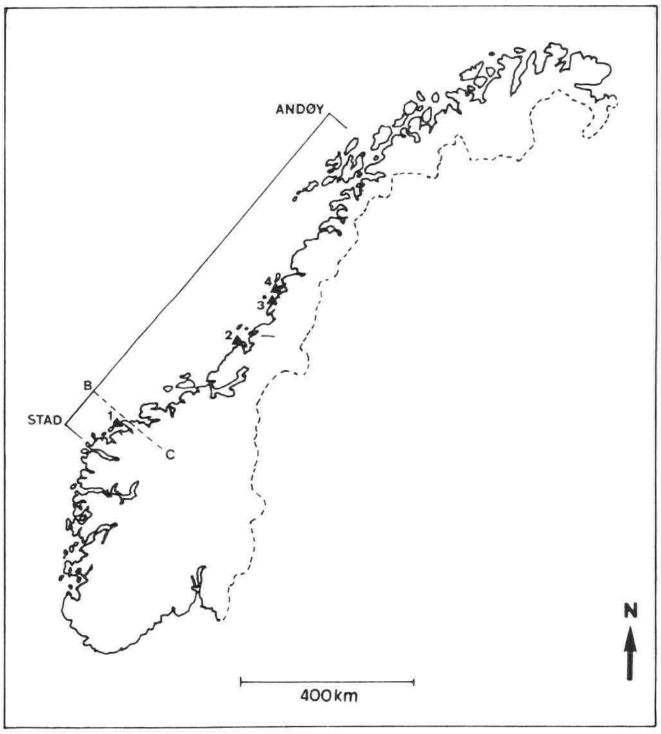


Figure 1. Map of Norway with the 1000 km long profile between the Stadt peninsula and Andoy, described in the text. 1. Skjonghelleren, 2. Helvikshulen, 3. Lispingdalskyrka, 4. Torghatten. B-C see Fig. 2.

coincides with the height of the strandflat (Undas, 1942, p. 80). He concluded "Caves eroded by the sea, raised cliff and strandflats which were certainly formed during the Quaternary period, are situated all over the coast in such heights that they indicate isostacy or movements of equilibrium during the whole Quaternary period" (Undas, 1942, p. 89).

From this early period also A. Helland must be mentioned. He himself did not do any research concerning the caves, but the many volumes of his "Norges land och folk, topografisk-statistisk beskrevet" (1898-1921), are invaluable sources of where to find descriptions of known and unknown caves.

In the postwar period the interest in these caves was very low until the beginning of the 1980's when J.J. Moller started his research on marine caves along the Lofoten and Vesteralen coast in northern Norway (Moller, 1985). He found moraines in the entrances of several of the caves and stated that it was difficult to determine whether they were really influenced by postglacial wave erosion.

A new era of marine cave research started with the excavations of the cave Skjonghelleren on Valderoy outside Alesund, by Quaternary geologists led by E. Larsen in 1983 (see below).

Inspired by the preliminary results, H. Holtedahl (1984) summarised his and other geologists' research on marine caves on the More-Romsdal coast. In an interesting diagram formed normal to the Younger Dryas Chronozone isobases, he projected maximum and minimum levels of the caves, levels of other signs of sea-abrasion, as rock-cut strand-terraces and Late Weichselian marine limits (fig. 2). which shows that the late Weichselian marine limits increase in height along the coast from southwest to northeast, due to coastline cutting of the isobases. It should be noted that the highest pre-Late Weichselian sea levels, estimated from signs of marine abrasion in caves and otherwise, do not have the same trend along the coast, but are as high , or higher, in the southern part than in the northern part.

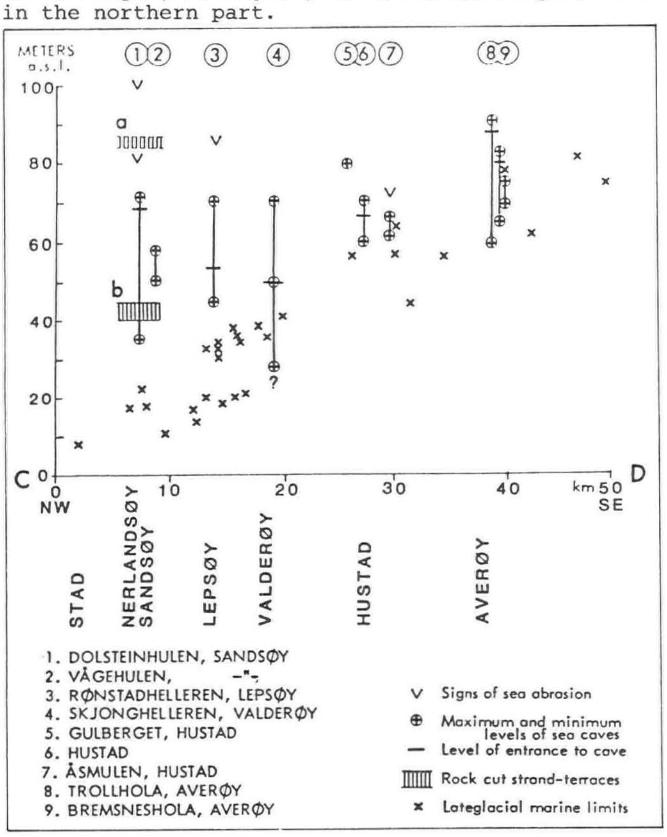


Figure 2. Maximum and minimum levels of sea-formed caves, levels of other signs of sea-abrasion, rock-cut terraces and Late Weichselian marine limits on the More-coast projected on a plane normal to the Younger Dryas isobases. (after Holtedahl, 1984).

This means according to Holtedahl, that while the Late Weichselian strandlines were formed during the deglaciation, at the time when the crust was depressed isostatically due to the ice load, the pre-Late Weichselian strand features, including the caves, were formed partly when the crust was not influenced by the load of glaciers, i.e. during an interstadial or interglacial. The fact that the cave roofs are between 70 and 80 m a.s.l., and the floors in some cases 40 m lower, leads to the assumption that the caves were eroded during varying sea-levels, and at very different times (Holtedahl 1984, p.84). These high levels of the caves are explained as a result of isostatic compensation for glacial erosion, but mainly as a result of long term neotectonic uplift. Holtedahl (1984, p.85) thus concluded that the caves are at least Eemian in age, probably much older.

The excavations in Skjonghelleren on Valderoy which started in 1983, very soon gave interesting results in the form of three layers of laminated clays and silts and a couple of diamicton layers containing amounts of animal-bones. Early results were, that these clays and silts were deposited subglacially in a small pond inside the cave, when the ice covered the area. These layers were interbedded by coarser material formed when the cave was open. In July the same year the present author visited the excavations (Sjoberg, 1983) and, supporting Reusch (1913), noted the possibility of very deep layers of sediment, so far not uncovered by the excavators. This initiated seismic investigations and corings in the cave, which proved the suggested 20 m depth of the sediments.

In the final report (Larsen et al. 1987), E. Larsen and J. Mangerud described the stratigraphy of the sediments; S. Gulligsen and S-E Lauritzen described the dating of speleothems and biogentic elements, and R. Lovlie the paleomagnetic properties in the cave. The results show at least three glaciations, and three interglacial periods since the cave was formed. The oldest interglacial period started about 80 Ka ago according to U/Th datings of speleothems clasts. The authors believe that the cave itself was formed at a high relative sea-level, sometime during the Early Weichselian.

THE CAVES

In this section, some of the caves are described (fig. 1). All caves used in the profile (Fig. 4) have been formed on steep cliffs which rise more or less abruptly from the strandflat. They are all exposed to an open sea, where wave energy, due to a considerable fetch and depth of water, has been at a maximum.

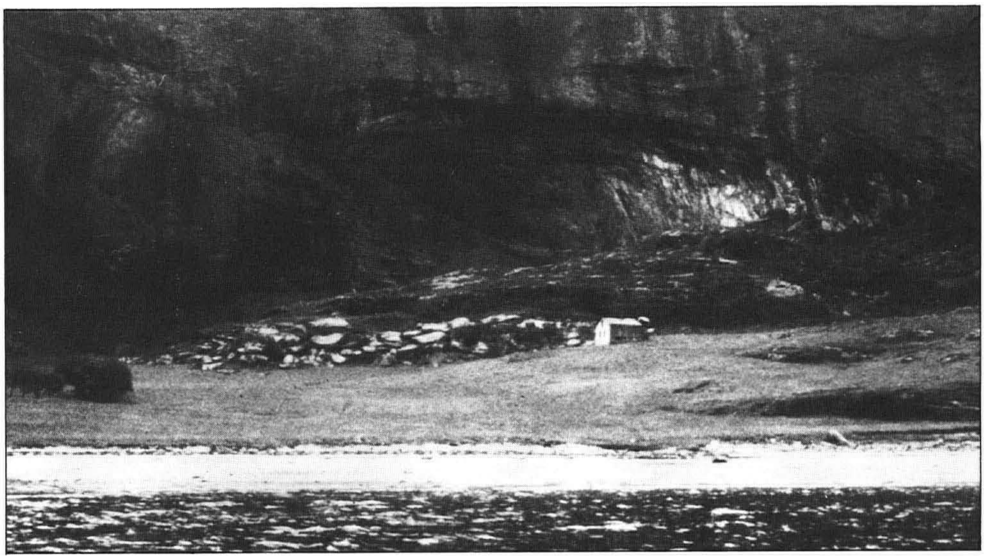
The position and form of the caves are strongly related to rock structures which have acted as areas of weakness. The rocks around the coast up to southern Nordland in which the biggest caves are formed, are mainly gneisses, partly calc-silicate gneisses. The main process of cave-formation is wave-abrasion, but different types of weathering cannot be neglected from minor features close to the cave entrances. The caves are mainly in positions which are protected against erosions by glaciers (Holtedahl 1984).

1. Skjonghelleren. Valderoy.

Skjonghelleren, 140m long, is situated on the steep western slope of Valderoy, outside Alesund, facing the ocean. Outside the cave is a well developed strandflat which rises up to 20 m a.s.l. outside the cave. It is developed in granodioritic gneisses with basic inclusions. The entrance of the cave is located on the top of a talus cone where the floor is at c. 46 m a.s.l. In the inner parts about 100 m from the entrance the level of the floor rises to 61 m a.s.l. As described above the cave contains about 20 m thick layers of sediments (Plate 1).

All the way from the entrance to the inner parts of the cave, the roof is situated around 70 m a.s.l. This means that from the bottom of the

Halvikshulen.



sediments the cave has a height of around 50 m.

As the sediments are trapped by the talus cone, and the sediments have been dated to an age of 80 Ka, it is obvious that this cone is of pre-Late Weichselian age and that the cave is formed before the talus cone. The present level of the entrance is situated above the Late Weichselian maximum shore-level which is 41-45 m at this locality.

2. Halvikshulen. Osen.

This cave has not been described in any scientific paper, but is mentioned by Helland (1898). Halvikshulen is situated on a peninsula between the Svefjord and the Vingefjord in the northern part of Osen, above the deserted farm Halvik. The entrance which opens above a talus-slope, about 117 m a.s.l., is gigantic, measuring 250 m in width, and 80 m in height (Plate 2 and 3). The outer parts which reaches 200 m inside the cave slowly diminishes in breadth and height. The inner parts consists of crawlways which give the cave a total length of c. 350 m. The cave seems to have been excavated by marined abrasion along afault dipping to the east.

The huge outer cavern is filled with very deep layers of sediments which most probably might be as interesting as those in Skjonghelleren. Furthermore, the top layers of the sediments ought to be of archaeological interest. No measurements of the highest post Late-Weichselian marine limits in the area are known by the author, but it is around 100 m a.s.l.

3. Lispingdalskyrka. Nordgutvik.

So far as is known, this is the longest of all Norwegian marine-caves (Plate 4). It is situated on the north-western part of the island of Austra, close to the village of Nordgutvik. The entrance of cave is on top of a huge talus-cone 146 m a.s.l. This cone slopes down to the cave floor 114 m a.s.l. Contrary to the other caves very little sediments cover the cave floor except for an almost 100 m long and 10 m high wall of terraced beach cobble-stones in the inner parts of the cave (Fig. 3). The up to 40 m high walls of the cave are polished by marine abrasion and in part covered by a layer of calcite flow-stone which indicates that the gneissic bedrock has a calcite matrix. On one of the vertical walls of the cave, close to the entrance, is a field of horizontal pothole-like features which according to Holtedahl (1984, p. 78) points to an origin by sea abrasion and possibly corrosion. As these forms are very much like tafonis, I do not fully agree with Holtedahl's explanation. They can just as well be the result of selected weathering or wind-erosion. Similar forms are also found inside the caves Dolsteinshulen, Ronstadhelleren and Halvikshulen further south.

The Late Weichselian maximum sea-level in the

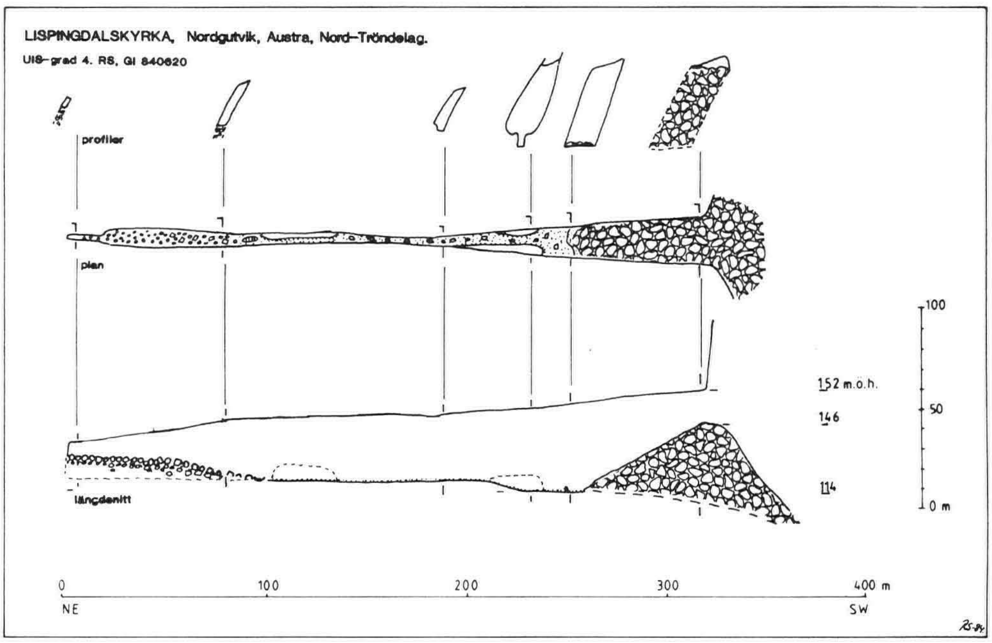


Figure 3. Survey of Lispingdalskyrka in Nord-Trondelag.

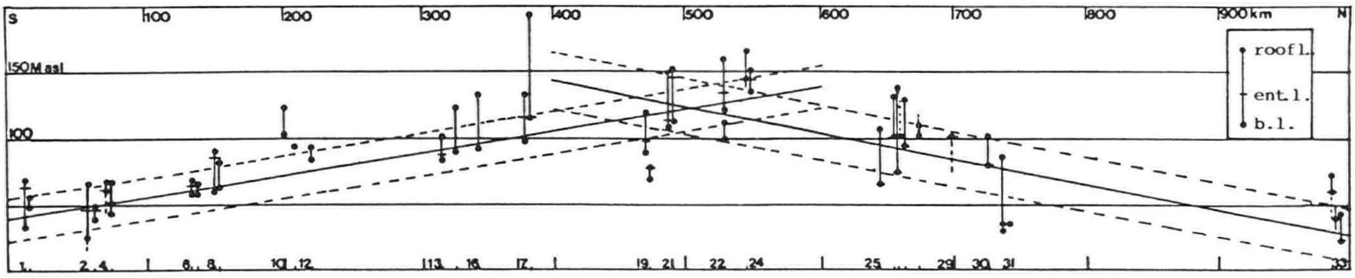


Figure 4. Maximum and minimum levels of sea-caves along a 1000 km long profile (Fig. 1). 1-33 caves according to table 2. The regressions-equation lines for the bottom-levels of the caves in table 2. The regressions-equation lines for the bottom-levels of the caves is drawn with a straight line, hatched lines show the standard deviation for the regressions lines.

area is about 75 m a.s.l., which is 40 m below the bottom of the cave, and 70 m below the top of the talus-cone. The rectangular form of the cave-passage indicates that it has been excavated by marine abrasion along a dyke of weaker bed-rock, or between fractures or schistosity planes.

4. Torghatt-hulet.

This famous cave totally penetrating the mountain Torghatten outside Bronnoysund was first described by Mohn (1870), Reusch (1881) and Vogt (in Rekstad & Vogt, 1900). The cave-tunnel, with a huge southwestern entrance (plate 5.), and a somewhat smaller northeastern entrance has a length under roof of 160 m. The whole cleft in which the cave is formed has a total length of more than 400 m. In the lowest part, in the middle of the cave, the height of the roof is around 35 m. The southern entrance is situated on top of a talus-cone 120 m a.s.l., whilst the talus-cone at the northern entrance reaches up to 138 m a.s.l. The bottom of the cave, which except for huge boulders, is free of sediments, is situated 109 m a.s.l. The cave has all the way through, a rectangular profile which shows that it is excavated by marine abrasion between parallel, vertical fractures. According to Reusch (1880), the cave was formed by the excavation by marine abrasion of two opposed caves in the same system of fractures.

As the highest postglacial marine level at Torghatten was interpolated to 120 m by Vogt, he meant that the cave was of postglacial age. The volume of the cave, and the fact that presently geomorphological features normally seems to be older than proposed earlier, are arguments for a pre Late-Weichselian dating of this cave as well.

CONCLUSIONS

Available data on the altitude of the entrance-, bottom- and floor levels of these and 35 other marine caves (Table 2) where projected on a vertical plane, constructed on a 1000 km long profile from the Stadt-peninsula to Andoy in northern Norway (Fig. 4). This profile was constructed almost parallel to the isobases for isostatic post-glacial uplift in Norway (Fig.1). As seen from the diagram (Fig. 4), it seems quite clear that the altitudes of the caves increase from south to north, until around 500 km, northwards and the levels decrease. To check the truth of this observation, the data in Tab. 2 were treated statistically so that (1) the altitudes of the bottoms of the caves were correlated against km on the profile, and the regression equation for this relation was calculated. The same was done with the entrance levels of the caves (2), the roof levels (3), and finally for the combined data (4). For these calculations the data were separated in two groups: 0 - 600 km and 400-1000 km (table 3).

As can be seen by the correlation coefficients, the values for the southern part of the diagram are higher than those for the northern part, and the standard deviations are normally lower. But as the values for the correlation coefficient are quite high, it seems to be very probable that the highest elevated caves really follow a linear increasing trend from south to north about 500 kms, and that this trend further northwards changes to a decreasing one. The regression line for the bottoms of the caves and the standard deviation for this line is drawn on Fig. 4.

The data from table 2 was also treated to find the polynominal correlations for the bottom and the roof levels of the caves studied. As can be seen from Fig. 5, both these levels show almost perfect regression lines, with a correlation coefficient R=0.86 for the bottom levels, and R=0.83 for the roof levels.

How to explain this linearity? The reason for this can only be postglacial isostatic adjustment combined with a neotectonic uplift, and this south-northern linearity is just another way of showing the same facts as on fig. 2. We can further note that the linearity most probably more

Nr.	km	Cave	Alt. in m a.s.l. bot.	ent.	roof	reference
	0	Stadt peninsula				
1.	12	Dolsteinshulen, Sandøy	33	67	70	Holtedahl, 1984
2.	58	Skjonghelleren, Valderøy	30	45	69	Larsen et. all,
3.	61	Molnåshulen, Valderøy	40	48	50	Reusch, 1877
4.	70	Havnsundshelleren, Søvik	43	66	69	Kaldhol, 1932
5.	72	Rønstadshelleren, Lepsøy	44	52	70	Holtedahl, 1984
6.	132	Cave, Hustad	59	67	69	---
7.	132	Cave 2, Hustad	60	60	67	---
8.	150	Bremsnåshulen, Averøy	67	80	92	---
9.	150	Trollhola, Averøy	76	88	90	---
10.	200	Jutulholet, Skarsøy	105	105	125	Kaldhol, 1932
11.	208	Jutulstua,	98	--	--	Undas, 1934
12.	220	Hule at Munkedahl	86.	86	95	---
13.	315	Duehelleren, Bjugn	86	86	104	Schrøder, 1984
14.	326	Høvikshelleren, Høvik	90	90	124	Undas, 1942
15.	340	Høvikshulen, Stokksund	140	140	156	Helland, 1898
16.	342	Harbakkshulen, Stokksund	92	97	134	---
17.	379	Cave at Strand, Vingsand	100	115	134	Sjøberg, 1983
18.	381	Halvikshula, Vingsand	117	117	195	Sjøberg, 1984
19.	470	Fingalshula, Skottnes	90	99	120	---
20.	488	Lispingdalskyrka, Nordgutvik	114	146	152	Sjøberg, 1984
21.	488	Lispingdalshula, Nordgutvik	110	113	150	---
22.	530	Torghatten, Brønnøysund	109	138	160	Vogt, 1900
23.	548	Monshulet, Brønnøysund	135	147	160	Sognnes, 1981
24.	550	Havlarshulet, Brønnøysund	125	144	150	Oyen, 1896
25.	644	Caves on Traena	68	68	108	Oxaal, 1913-14
26.	656	Tonneshula, Melfjord	100	100	120	Rekstad, 1925
27.	660	Cave on Hestmanøy, Hestmona	92	92	120	---
28.	663	Cave on Nesøya	88	--	--	---
29.	700	Meløyhatten, Meløy	100	150	160	St. Pierre,
30.	725	Cave on Landegode	80	80	100	Rekstad, 1916
31.	738	Kollhelleren, Moskenøy	32	25	60	Møller, 1982
32.	988	Rekvik, Andøy	40	20	50	---
33.	989	Bleiksøy, Andøy	35	58	70	---

Table 2. High elevated Norwegian coastal caves from south to north.

	0-600 km		400-1000 km	
1.	0.872	Y = 39.7 + 0.163X + -16.38 m	-0.843	Y = 215 - 0.188X + -19.05 m
2.	0.893	Y = 49.2 + 0.165X + -14.96 m	-0.743	Y = 249 - 0.244X + -31.97 m
3.	0.875	Y = 58.5 + 0.196X + -19.56 m	-0.816	Y = 262 - 0.213X + -23.89 m
4.	0.832	Y = 48.7 + 0.176X + -20.41 m	-0.749	Y = 241 - 0.208X + -27.33 m

Table 3. Correlation coefficients, regression equations and standard deviation

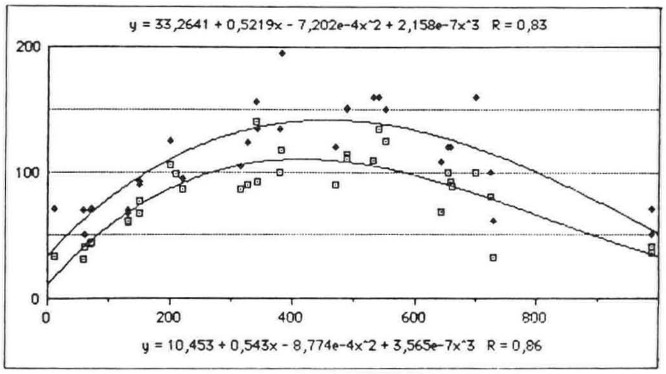


Figure 5. Graph showing the polynominal regression-lines for the bottom- and the roof levels of caves in table 2. Above the graph the equation for the roof levels is presented, below the equation for the bottom levels.

shows the effects of the early postglacial uplift, than the present rate of uplift, as on the Swedish side the highest postglacial limits are found in the High Coast area and the present maximum rate of uplift 500 km further to the north. Another explanation is that this linearity shows the of the present isobases from cutting west to east, which means that the highest elevated caves are situated further east than the caves on lower altitudes showing that the rate of isostatic uplift was higher towards the centre of the inland ise, and these that isobases in early postglacial times might not have been the same as the contemporary ones. In any case, the profile clearly shows that the caves were formed before, or in the beginning of the latest glaciation, and after or at the same time as the formation of the strandflat.

The age of the strandflat has recently been discussed in a paper by E. Larsen and H. Holtedahl (1985). These authors concluded that the age of the strandflat is younger than the cessation of the Tertiary uplift of Scandinavia which provides a maximum age of its formation, and that at least most of this uplift had come to an end by Late Pliocene time. Hence the strandflat is younger than the Middle Pliocene (Larsen & Holtedahl 1985). This is thus the earliest limit for the formation of the caves.

Larsen & Holtedahl found a connection between the glacio-isostatic depression of the crust and the elevation of the strandflat at least in the area investigated, the More-area. They suggested from this that the Strandflat was formed during glacial rather than interglacial stages. They thus concluded that the strandflat was younger than 2.5 Ma and that sea-ice erosion and frost shattering most probably are the main processes for its formation. This is in line with a model already proposed by Nansen (1904). Based on isotope studies on deep-sea cores west of Ireland, Jansen & Sejrup (1984) concluded that global ice volumes were smaller between 0.9 and 2 Ma with a corresponding higher eustatic sea-level than before, and after this interval. This could have been suitable for strandflat and sea-cave formation, and explain the high elevations of the caves.

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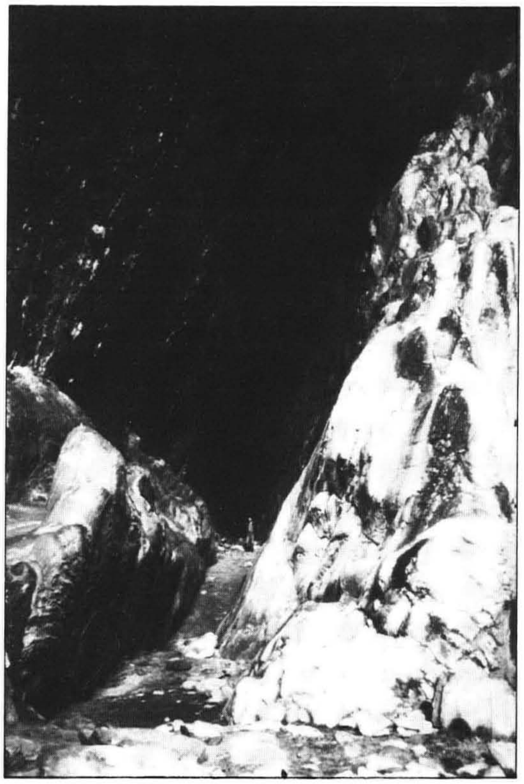

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Revised Magnetostratigraphic Age Estimate of Cave Sediments from Grönligrotta, Norway

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Abstract: A revised age is proposed for a previously dated cave sediment section in Gronligrotta, Norway, obtained by correlation of a palaeo-magnetic record (35 samples) with the British geomagnetic secular variation record for the Holocene (Turner and Thompson 1982). The c. 80 cm laminated clay section accumulated between 9500 and 8900 yr. B.P., implying that sedimentation occurred under ice contact conditions, as opposed to the previous age estimate which extended to a period during which vadose speleogenesis had commenced in the general area. Significant variations in susceptibility foliation planes are not reflected by changes in remanence directions, suggesting that magnetic fabric parameters are not unique indicators for assessing the reliability of palaeomagnetic records.

Cave sediments deposited beyond the entrance zone are difficult to date owing to the absence of syn-depositional organic material required for C14 determination of pollen-stratigraphy, although U/Th series dating of speleothems below or above a sedimentary bed may give maximum or minimum age estimates for that bed. Sediments in fossil cave passages may remain physically unchanged for long periods due to fairly constant conditions (high humidity, low temperature, general absence of bioturbation) and numerous palaeomagnetic investigations from widely different regions in Spain and Lebanon (Creer & Kopper, 1976), USA (Schmidt 1982), South Africa (McFadden et. al. 1979), Britain (Noel, 1983, 1986a, 1986b, 1987) and Norway (Noel & St. Pierre, 1984), have established that cave sediments retain stable palaeomagnetic records of the geomagnetic field at the time of deposition.

An age estimate of presumably Holocene cave sediments from Grønligrotta, Norway has been deduced by correlating characteristic patterns of palaeomagnetic directions of c. 80 cm thick clay passage fill with secular variation records from Lac de Joux, Switzerland (Noel & St. Pierre, 1984). Pronounced directional features were thought to correlate with secular variations occurring between 9600-6800 yr B.P. However, accumulation of laminated, fine-grained sediments in Grønligrotta was almost certainly restricted to ice marginal to sub-glacial conditions which ceased prior to 8000 yr B.P. (Lauritzen & Gascoyne, 1980), invalidating the proposed palaeomagnetic correlation.

A revised chronostratigraphic correlation, based on palaeomagnetic results from the same section as that reported by Noel & St. Pierre (1984), is presented here.

Geology and Sampling

Grønligrotta is developed in folded marble bands in the Rena area of northern Norway, and consists of a network of fossil phreatic passages formed under conditions of complete water-filling. Subsequent modifications have taken place by vadose stream action. Boulders, sands, silt and clay sediments suggest an ice marginal or sub-glacial origin. The youngest moraine stage of the area, associated with Weichselian ice recessions, is found some 30 km from the cave and dated to 9.300+200 yr B.P. (Andersen et. al. 1981). At around 8000 yr B.P. the ice had retreated to the highest mountains, and by that time sediment accumulation had certainly ceased in the phreatic sections of Grønligrotta. Palaeomagnetic samples were collected along the section of clay fill blocking the Klippetunnel, which was excavated and sampled by St. Pierre (Fig. 2 of Noel and St. Pierre, 1984). The c 80 cm thick sequence consists of laminated clay containing six different coloured zones.

A total of 35 oriented (magnetic compass) samples (multiple samples from three horizons) were collected along the section. The samples were obtained by pushing or hammering a brass tube, reinforced with a stainless-steel tip, into the cleaned sediment surface. Each sample was collected with slightly different orientation in order to detect and average out any directional errors caused by the "push-effect" (Gravenor et. al. 1984; Lovlie et. al. 1986). The sediment was subsequently pushed into plastic cylinders (21-22 mm) and closed with tight lids. Orientation errors in sampling are of the order of ±2°.

MAGNETIC PROPERTIES

Natural remanent magnetization

The direction and intensity of the natural remanent magnetization (NRM) were measured on a Digico magnetometer. NRM intensities range between 20-150 mA/m showing no systematic changes in relation to visible lithology or stratigraphy (Fig. 1). Bulk susceptibilities, determined on an induction bridge (KLY-1) range between $2.1\text{-}3.0 \times 10^{-4}$ SI, indicating a fairly uniform concentration of magnetic grains along the section (Fig. 1). The significantly larger range of intensity variations is thus likely to reflect variations in the degree of magnetic grain alignment contributing to the NRM.

All samples were subjected to progressive alternating field demagnetization (af) to 90 mT. A small secondary component, removed below 6 mT, is superimposed on a stable single component magnetization (Fig. 2). High median destructive fields (MDF) (mean: 65.2±6 mT) are indicative of very fine-grained remanence-carrying grains.

Characteristic remanent magnetizations (ChRM) show consistent stratigraphic variations in delination and inclination (Fig. 1). Small amplitude scatter is partly attributed to orientation inaccuracies. Although there is broad agreement between the directional patterns defined by the present results and those derived from the work of Noel and St. Pierre (1984), the latter reported on significantly steeper inclinations in the lower section (Fig. 1). The present samples were collected less than 20 cm to either side of the section sampled by St. Pierre, implying that the observed directional discrepancies may reflect either small scale lateral variations in the fidelity of the depositional related remanent magnetization, or effects due to the different sampling procedures. The close directional agreement between multiple samples (Fig. 1) favours the latter interpretation.

The most pronounced directional feature is the easterly swing in declination between 29-40 cm which is defined by two samples from the same level. This feature is absent in the previous report from this section (Noel and St. Pierre, 1984) evidently due to the low sampling density employed (Fig. 1).

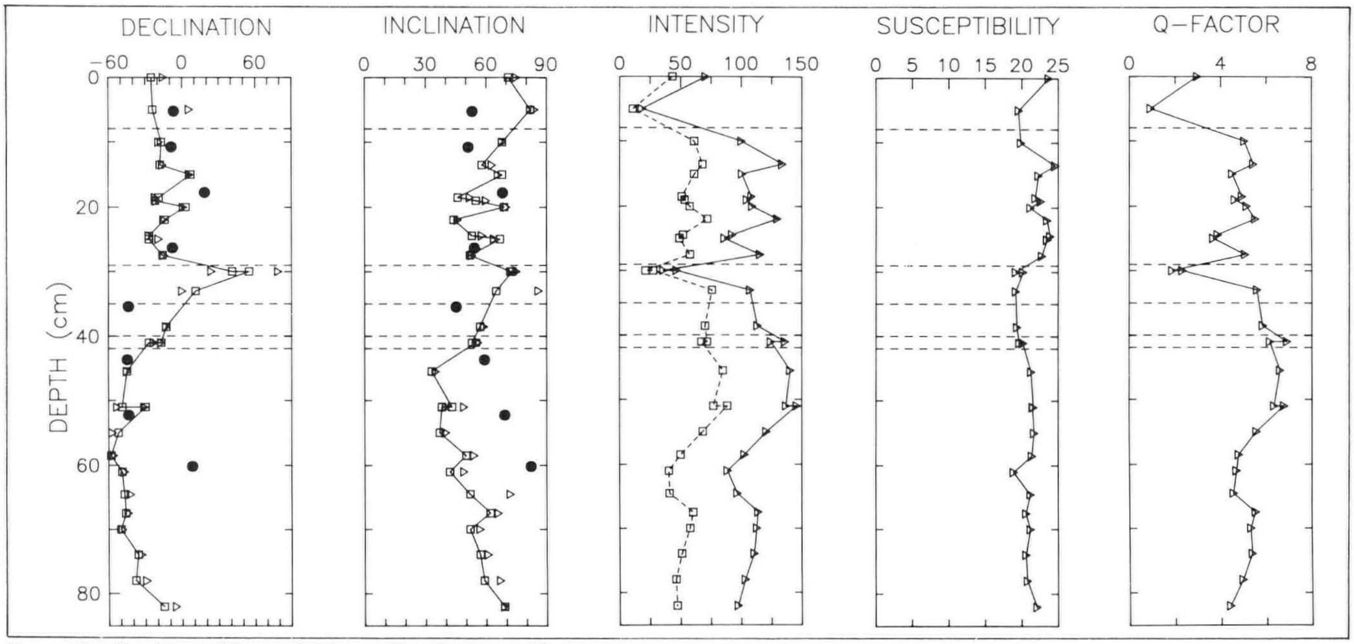

Figure 1. Stratigraphic variations of palaeomagnetic directions and bulk magnetic properties along the clay fill section in the Klippetunnel, Grønligrotta. Directional precision indicated by multiple samples at three levels. Distinct colour-boundaries indicated by horizontal dashed lines. Note apparent absence of significant changes in magnetic properties across most colour-boundaries. Symbols: triangles/squares: NRM/Characteristic remanent directions. Filled circles: palaeomagnetic results redrawn from Noel and St. Pierre (1984). Intensity in mA/m, susceptibility in 10^{-6} cgs. Q-factor: NRM intensity/susceptibility.

Magnetomineralogy

The magnetomineralogical composition has been investigated in order to assess the magnetic fabric results. Thermomagnetic curves (heating the air to 700°C, 20°C/min, 480 mT) reveal inversion temperatures around 350°C associated with a reversible Curie temperature (T_c) around 580°C indicative of partly maghemitized magnetite.

Progressive acquisition of isothermal remanent magnetization (IRM) experiments of eight samples show that saturation occur above 430 ± 70 mT, associated with remanent acquisition coercive forces (RACF) of 122 ± 5 mT and remanent coercive forces (RCF) of 96 ± 8 mT. These quite high values are consistent with very fine-grained magnetite.

Using the diagnostic methods of Dankers (1981), the Grønligrotta samples yield a mean RACF/RCF ratio of 1.3 ± 0.1, which is not significantly different from the empirically derived ratio 1.6 ± 0.2 indicative of pure magnetite (Dankers, 1981).

Similarly, established grain size dependent relationships between RACF and RCF for pure magnetite (Dankers, 1981) yield grain size estimates of <2.5u and <3.0u respectively.

The magnetic domain state, investigated by the Lowrie-Fuller test (Lowrie & Fuller, 1971), af demagnetization curves of NRM and saturation IRM (SIRM) suggest single to pseudo-single domain states (Dunlop, 1983).

The NRM of Grønligrotta clay section is deduced to be carried by small grains of almost pure magnetite.

Anisotropy of magnetic susceptibility

Sediments acquire a detrital remanent magnetization (DRM) more or less contemporaneously with deposition by physical alignment of the magnetic field direction. Deposition in flowing water may cause significant, systematic deviations of DRM directions (Rees, 1961, 1964), and it is thus crucial to assess any effects due to currents.

The anistropy of magnetic susceptibility (AMS) in magnetite-carrying sediments effectively reflects the statistical orientation of grain axes, and may reflect systematic grain orientation due to current (Rees, 1961). AMS properties define the magnetic fabric and are represented by the magnitude and direct of three principal susceptibility axes; k-max, k-int, k-min. Lengths ratios define foliation (P1=k-max/k-int), lineation ($P3=k_{int}$/k-min), anistropy factor (P2=k-max/k-min), ellipticity (E=P3/P1).

All Gronligrotta samples have significant anistropies (>7%, Table 1) defining foliation dominated (oblate) magnetic fabric (E>1, Table 1). Sub-horizontal foliation planes (Fig. 3) are a typical feature of gravity-dominated deposition (Rees and Woodall, 1975). The distribution of k-max axes is perpendicular to the passage direction (N-S), indicating some systematic relationship between grain orientation and phreatic water flow. However, while distributions of k-min above 46 cm depth are closely grouped, defining a north-dipping foliation plane, k-min in the lowermost section define foliation planes tilting both towards north and south which is not associated with any systematic directional changes of NRM (Fig. 3).

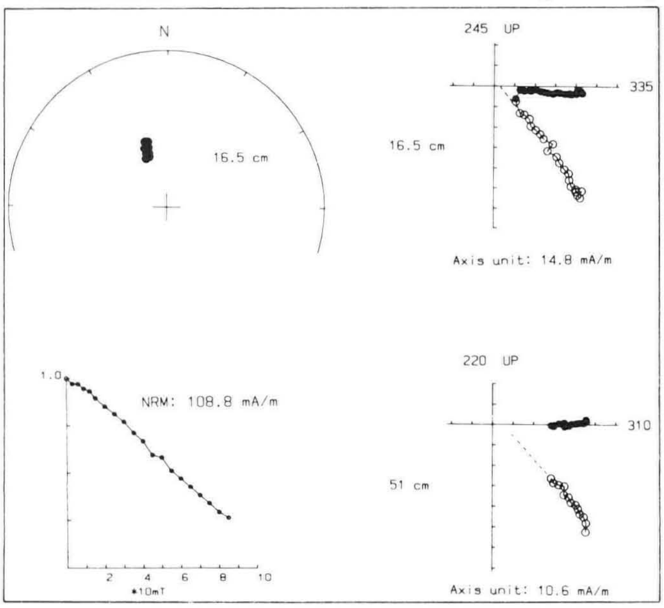

Figure 2. Alternating field demagnetization results in stereographic and optimum orthogonal vector projections. Slightly deviating low coercivity components, removed below 6mT, are superimposed on stable, high coercivity components. The sample from 16.5 cm depth represents the magnetically softest magnetization.

Thus, although AMS properties apparently reflect some effects due to currents, the latter has evidently not modified DRM directions in any systematic manner. These observations suggest that the remanent magnetization and magnetic fabric are not directly coupled, reflecting spatial distributions of two populations of magnetic grains.

DISCUSSION

The high stability, single component magnetizations define regular changes in direction (Fig. 3). Variations in k_{min} directions, probably reflecting changing regimes, are not related to changes in magnetic directions, and it is thus reasonable to assume that the palaeomagnetic directions are a record of geomagnetic secular variation at the time of deposition. The sediment age can hence be estimated by correlating with a dates secular variation master curve.

A correlation between the British geomagnetic secular variation record (Turner & Thompson, 1982) and the Grønligrotta profile (univectorial 5-point running mean) is suggested in Fig. 4. The particular variations in declination and inclination of the Gronligrotta profile are not evident in the large amplitude pattern on the British geomagnetic secular variation record master curve. However, on a much smaller scale, a remarkably similar pattern, appears on the British master curve between c. 9600-9000 yr. B.P. (Fig. 4). The larger amplitudes observed on the Grønligrotta record may be attributed to the latitudinal differences between Britain (=55°N) and the Grønligrotta site (=66°N). Since the longitudinal difference between the two sites (≈14°) represents a phase lag of some 100 years due to the westward drifting sources of secular variation (0.2°/yr, Creer and Tucholka, 1982), the Gronligrotta section covers a time interval between 9500 to 8900 yr. B.P.

The proposed correlation is based on some small scale features on the British secular variation record, which is constructed by averaging 10 dated cores of lake sediments (Turner and Thompson, 1982). The reality of these features can still be questioned, however, but inspection of dated palaeomagnetic lake records from other European sites reveals that a similar pattern consistently appears within the same time interval (Thompson and Turner, 1979; Creer et. al. 1980, 1986), justifying the proposed correlation.

Depth (cm)	P1	P2	P3	E
0	1.023	1.076	1.052	1.028
5	1.018	1.077	1.058	1.039
10	1.014	1.113	1.098	1.083
13.5	1.060	1.135	1.071	1.010
15	1.024	1.123	1.096	1.069
18.5	1.054	1.139	1.080	1.025
19	1.032	1.120	1.085	1.051
20	1.015	1.100	1.083	1.067
22	1.017	1.108	1.088	1.070
24.5	1.021	1.134	1.110	1.087
25	1.022	1.126	1.101	1.077
27.5	1.015	1.130	1.113	1.097
30	1.014	1.086	1.071	1.056
33	1.021	1.075	1.052	1.030
38.5	1.010	1.101	1.089	1.078
41	1.042	1.100	1.055	1.012
45.5	1.041	1.107	1.063	1.021
51	1.014	1.124	1.108	1.093
55	1.053	1.108	1.051	0.998
58	1.043	1.121	1.074	1.030
61	1.029	1.115	1.083	1.052
64.5	1.046	1.104	1.054	1.008
67.5	1.015	1.109	1.092	1.076
70	1.024	1.101	1.075	1.050
74	1.041	1.088	1.045	1.004
78	1.031	1.102	1.069	1.037
82	1.013	1.074	1.060	1.046
Mean values:	1.027	1.106	1.077	1.049
St. dev.:	±0.015	±0.019	±0.019	±0.029

P1: Lineation (k_{max}/k_{int})
P2: Anisotropy factor (k_{max}/k_{min})
P3: Foliation (k_{int}/k_{min})
E: Ellipticity (P3/P1)

Table 1 Grønligrotta:
Anisotropy of magnetic susceptibility results

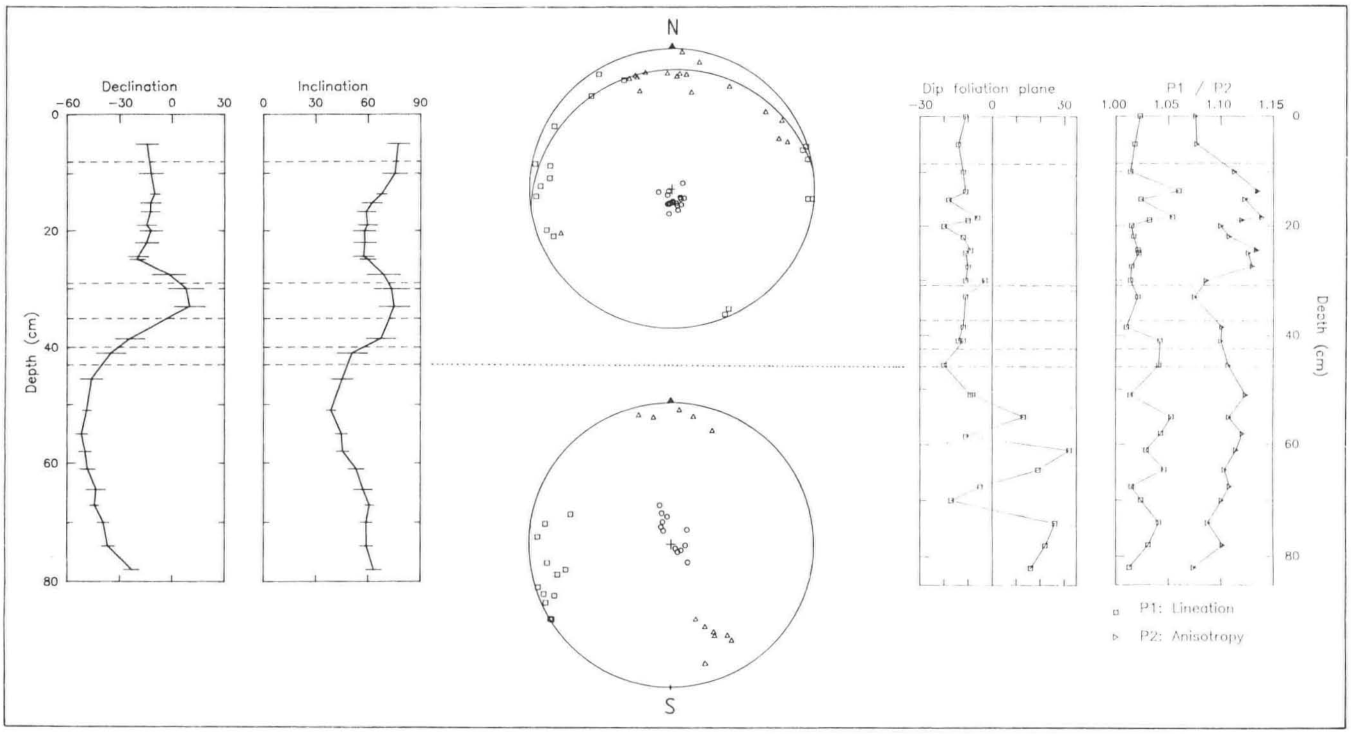

Figure 3. Composite plot of palaeomagnetic and magnetic fabric results. Stratigraphic plot of 5-points running mean (univectorial) of palaeomagnetic directions with α_{95} error bars (left). Stereographic distribution of principal susceptibility axes (middle); k-max (squares), k-int (triangles), k-min (circles), all lower hemisphere projection. Stratigraphic plots of the dip of magnetic foliation planes and variations of lineation (P1) and anisotropy factor (P2) to the right. Note that below 46 cm (long horizontal dotted line), foliation planes tilts both towards North and South with no significant correlation with either magnetic fabric parameters or palaeomagnetic directions. Direction of cave passage ≈N-S. Horizontal dotted lines represent colour boundaries.

CONCLUSIONS

The proposed palaeomagnetic age of the Grønligrotta clay section between 9500-8900 yr. B.P., implies that deposition commenced more or less contemporaneously with the formation of moraine stage D (9500 yr. B.P.) and terminated shortly after moraine stage E was deposited (9300 yr. B.P.). Theoretical ice profiles (Paterson, 1981) extrapolated from these stages are compatible with ice-contact conditions at the location of Grønligrotta (Gilje-Nilsen, 1988). The c. 80 cm section thus represents a time interval of some 600 years, which is significantly less than the almost 3000 years proposed by Noel and St. Pierre (1984). According to the present age estimate, the clay section was deposited under ice-contact conditions during a glacial recession. The previous suggested age estimate extends to 6800 yr. B.P., more than 1000 years after vadose speleogenesis had commenced in the general area (Lauritzen and Gascoyne, 1980), which appears to be incompatible with the known glacial history of the region considering that the present cave entrance is situated some 236 metres above sea level.

It is emphasized that the precision of the age estimate presented herein relies on the averaging procedures employed for construction of the British master curve (Turner and Thompson, 1982).

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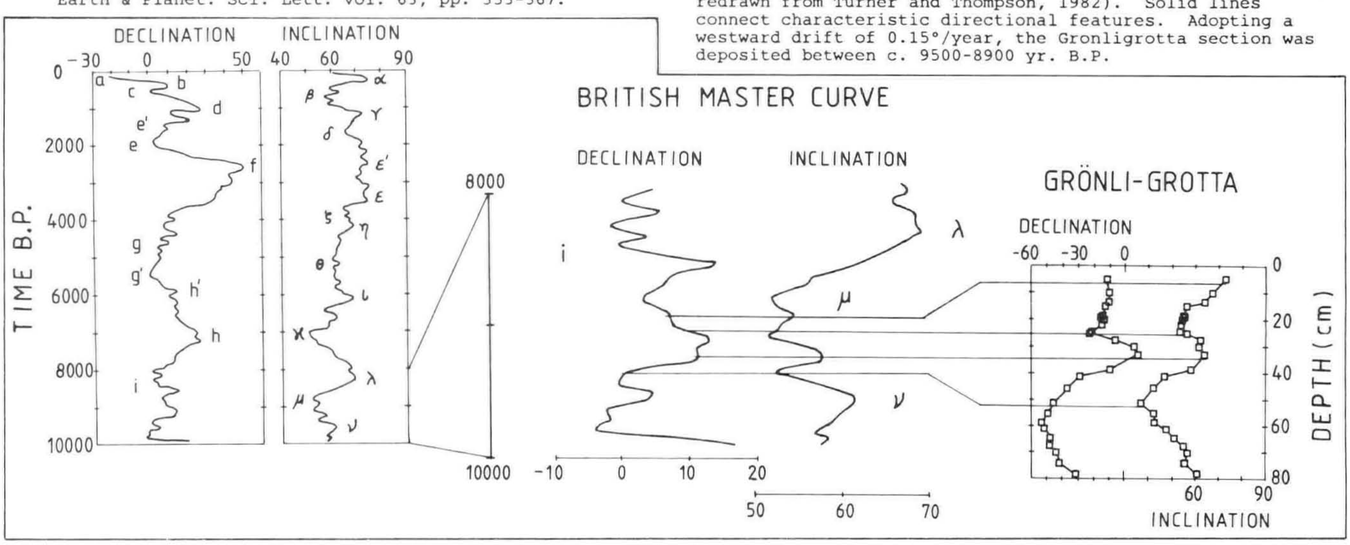

Figure 4. Proposed correlation between the Grønligrotta palaeomagnetic profile (5-points running mean, to the right), and the British geomagnetic secular variation master curve for Holocene (to the left and expanded in the middle, redrawn from Turner and Thompson, 1982). Solid lines connect characteristic directional features. Adopting a westward drift of 0.15°/year, the Gronligrotta section was deposited between c. 9500-8900 yr. B.P.

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Morphology and Sediments of the Grönli-Seter Caves, Norway

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Abstract: The morphology and sediments of the Grønli-Seter Cave system in the Rana district of Nordland, Norway are described and analysed. S.E.M. examination shows that the quártz grain samples exhibit features diagnostic of a glacial environment and a short period of transport from the glacier or ice sheet into the cave.

The Grønli-Seter cave system is situated 20 km NW of Mo i Rana, Nordland, Norway close to Grønlien and Saeterås farms, a few miles south of the Arctic Circle .

Grønligrotta must have been known since before 1750 when Grønlien was first settled. Kaptein Hvoslef reached the deepest part of the cave, -107 m, in 1906. The cave was studied by John Oxaal (1914) who mapped about 1210 m of the cave, and in the 1930's by Gunnar Horn (1947). Jean Corbel (1957) and Lewis Railton (1954) visited the cave in 1951. The streamway extended 300 m by SWETC (St. Pierre, 1965) was surveyed with other extensions by Grønlie, Haugane et al. 1969/70 (1980) giving a total length of 2000 m.

1500 m of Setergrotta was surveyed in 1939 by Horn (1947). Two extensions (Mitchell, 1966; St.Pierre, 1965) increased the length to 2400 m.

The late author visited Grønligrotta and Setergrotta many times during the period 1963-86. This paper is part of the previously unpublished results of a sedimentology project undertaken in 1978 whilst a student at Birkbeck College, London University, 1975-1980.

Geological Setting

Geologically the Rana district is part of the Caledonian complex of Nordland. The area was mapped by the Norges Geologiske Undersøkelse and the Rana sheet compiled by Holmsen (1932). There was no division into structural and stratigraphic units except at Sulitjelma where in the eastern part of the area fossils were found, and on this evidence the rocks were considered to be Cambro-Silurian in age. More recently absolute dating by Neuman (1960) has given an age of 565 $\pm$ 57 Ma for the Bjellatind granitic gneiss, i.e. very late Precambrian to early Cambrian.

The rocks in Nordland are chiefly metasediments and consist of granitic gneisses found mainly in two belts, along the Norwegian border with Sweden and in the coastal region. Between these two belts mica schists predominate and are thinly interbedded with marbles which comprise some 15% of the outcrops as narrow zones varying considerably in extent, lithology, dip and thickness , probably as a result of folding during the Caledonian orogeny. In general, the marbles are impure containing varying quantities of magnesite, tremolite, actinolite, wollastonite, quartz and mica and are collectively known as the North Norwegian Mica Schist Series.

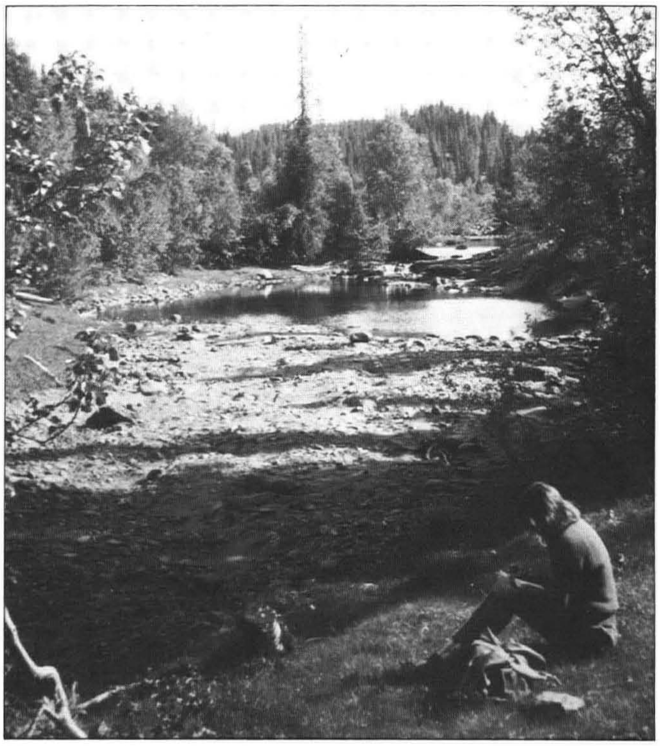
Pleistocene and Recent deposits occurin the valleys as glacial debris, moraines and marine, lacustrine and fluvatile terraces.

The area has been greatly affected by the Pleistocene glaciations. The land was depressed by the weight of the ice which probably attained a thickness of some 1500-2000 m and the topography much modified by glacial erosion. Nansen (1932) calculated that a layer 1200 m thick was removed.

When the ice melted the sea level rose inundating the land. The highest known marine terrace is located in Dunderlandsdal, 130 m above present sea level. The height of this terrace as a eustatic marker cannot be directly extrapolated to Røvassdal, as isostatic and subsequent rebound may have been differential. The highest marine terrace found in Røvassdal is only 108 m a.s.l.

Bearing in mind that sea level could have been much higher Setergrotta was examined for evidence of marine deposits. However nothing was found in the form of shells or shell fragments of Mytilus edulis, Macoma baltica, Saxicava pholadis, mya truncata, Buccinum undatum and Balanus common in the marine terraces.

Striations indicate that during the major glaciations the ice moved in a westerly direction (Grønlie, 1939), contrary to the ice movement in many of the valleys, so presumably the valley glaciation only took place at the onsets and ends of the major glaciations, while the westward moving icesheets were responsible for scouring and



The Strokbekk sink - the source of the stream in the Grønli-Seter cave system.

rounding the upland masses.

Topographically the Rana district is an uplifted land mass, average elevation of 1000 m, deeply dissected by major valleys. Mostly it lies within the drainage basin of the Ranenelv and both this and its tributaries, including the Røvasståga tend to follow the north-east to south-west direction of the Caledonian trend and cross the country at very moderate elevations.

In the north western part of Rana and extending into Salta are the Svartisen Ice Caps covering an area of some 400 km^2 they are rapidly retreating. Their perimeters are estimated to have receeded about a kilometre since the beginning of the century (Theakstone, 1965). Meltwater from the east and south-eastern edges of Østisen feeds some of the tributaries of the Røvassaga.

In the vicinity of the Grønli-Seter cave system the Røvasståga flows in a deep glacial trough and the cave system lies in the east side of this valley. Grønligrotta has two entrances at the base of steep cliffs 236 m and 223 m and Setergrotta two entrances about a kilometre to the north at about 100 m. The stream seen in various parts of the cave system comes from the Strokbekk, a tributary of the Røvassaga.

The Strokbekk rises on an undulating plateau with a maximum elevation of some 500 m. It flows in a north-westerly direction to the farm at Grønlien. It has a very shallow valley and is evidently a postglacial stream that has arisen on the plateau at the end of the last glaciation. For most of its course it flows over mica schist bedrock, but it has also cut through a terrace in

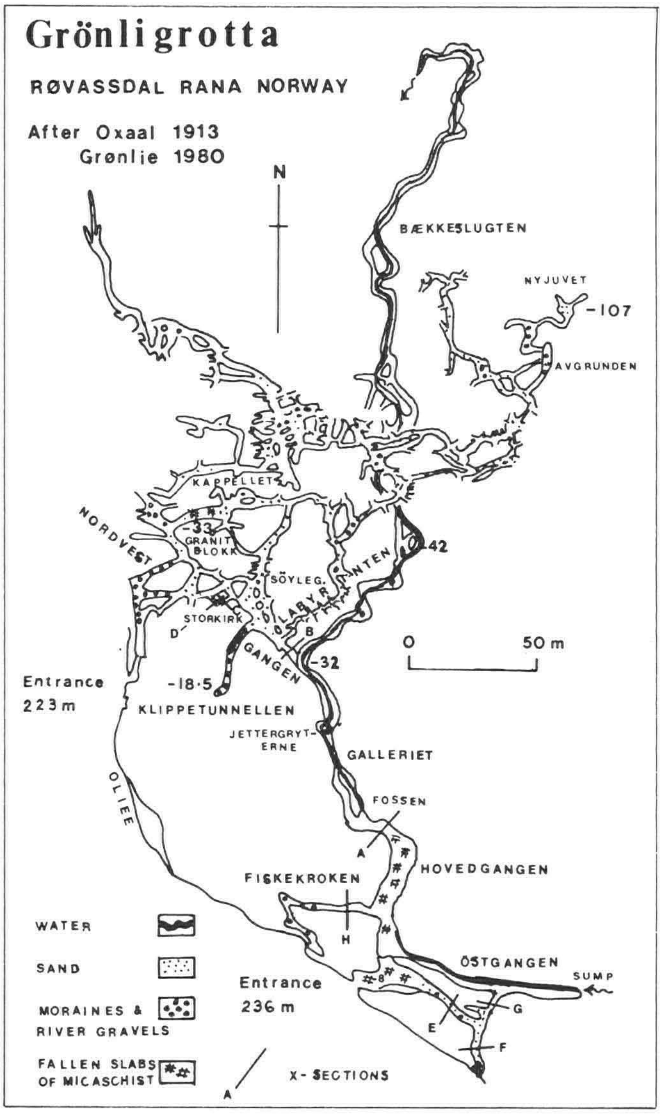


Figure 1. Grønligrotta survey after Oxall 1913

Baekkeslugten, Grønligrotta (Photo by A. Grønlie).

the vicinity of Grønlien. Just above Grønlien the Strokbekk crosses a marble outcrop which extends down to the Røvassaga. There are several sinks both in the river bed and in the right bank where the river meets the marble outcrop. In conditions of moderate flow all the water sinks here and the river bed below is dry, but under high water condtions the Strokbekk has a surface course all the way down to the Røvasståga.

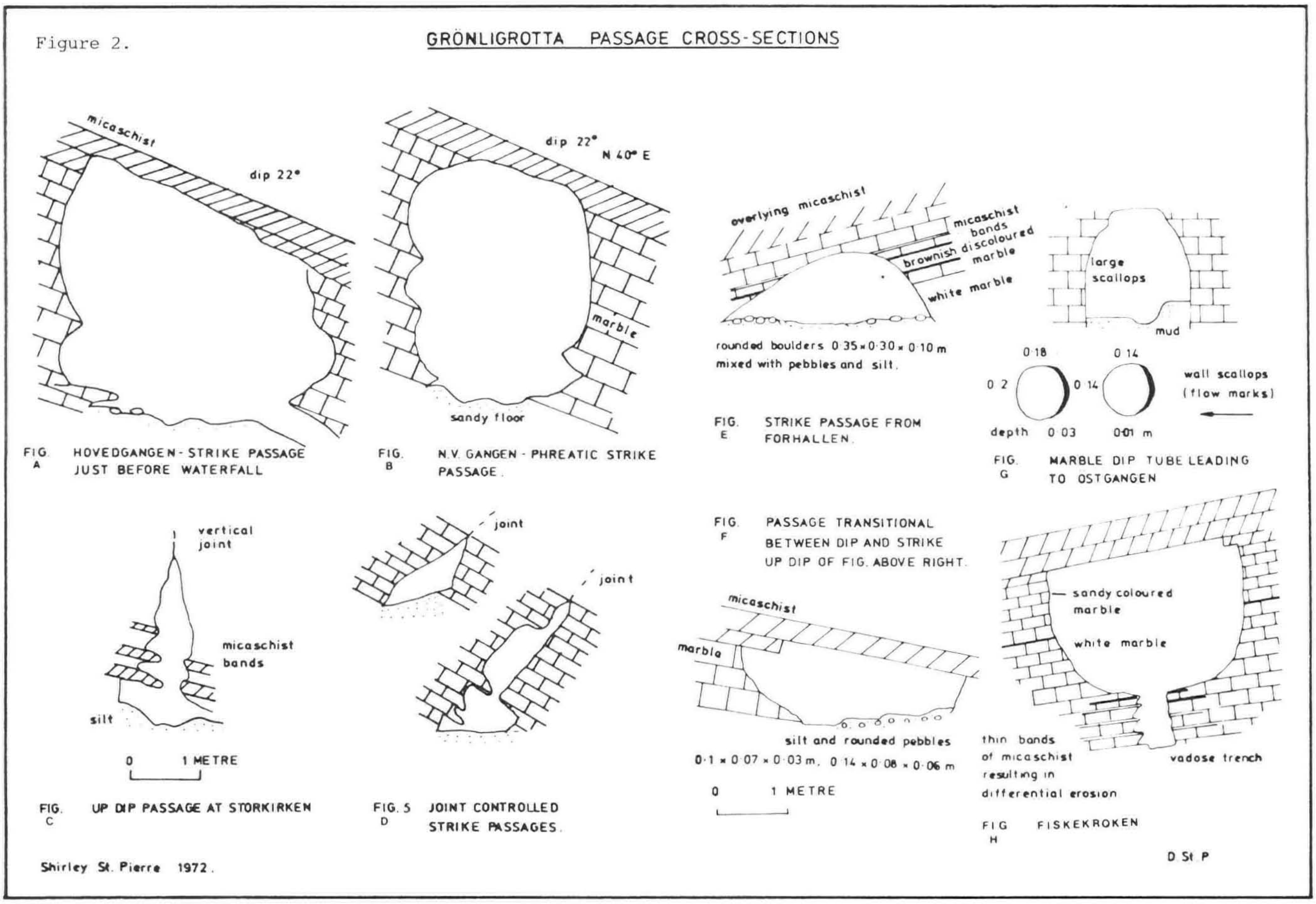
The water sinking in the stream bed flows through Grønligrotta where it finally disappears in impenetrable joints to reappear in Setergrotta which has a series of sumps. The water eventually emerges at a pool at the base of the cliff further north.

The morphological features of the caves suggest that there have been at least two main phases of development.

The morphology & sediments of Grønligrotta

Grønligrotta can be divided into two main morphological units: an abandoned network and an active streamway.

The dry passages have circular to elliptical cross sections comprising of dip tubes in the upper part coming in from the cliff face linked by an undulating strike passage - the Nordvestgang. Below the Nordvestgang is a joint



controlled labyrinth terminating in a vertical drop of 9 m into a pit - Avgrunden. At the bottom is a short section of horizontal passage before a second drop of 12 m - Nyjuvet, leading to a descending passage which becomes choked with sediment. This is the lowest surveyed point in Grønligrotta (- 107 m).

The rounded passage profiles and the undulating Nordvestgang can only have developed under conditions of complete waterfilling. The general lack of scallop markings on the walls, a common feature in other major caves in the area of the same morphological type, indicates very slow flow. The second major phase occurred with the drainage of these passages: a relatively rapid process as only very minor vadose modification is seen.

The cave became occupied by a vadose stream. This now enters at the Østgang sump follows at first a route along the old network passages which it has partly modified, but eventually leaves them and flows through a vadose passage - Baekkeslugten where it has cut through very impure marble which extends below the Nordvestgang and Labyrinten. Large fossil potholes above the streamway indicate that formerly the stream was much larger.

The cave sediment distribution is indicated on the plan of the cave. There is very little sediment being deposited in the Grønligrotta streamway at the present time although a sediment bank occurs where the stream first enters the cave just beyond the Østgang sump. Occasional slabs of bedrock collapsed from the roof and walls are found. In the Hovedgang the stream flows along the extreme edge of this wide chamber beneath collapsed blocks of micaschist.

In the wholly vadose section of the streamway the marble is very impure containing quantities of a crystalline silicate probably wollastonite or tremolite resulting in differential erosion. The silicate boulders are very distinctive, decomposition in the streamway gives them a black slimy surface.

In contrast the dry series contains much sediment: roof collapse has resulted in occasional blocks of mica schist but most of the labyrinth is is floored by extensive silt and sand deposits.

At two locations in the cave there are clay deposits and near the Østgang sump is a bank of banded silt/clay. Samples of which were collected together with samples from the undisturbed grey banded clays at the top of the steeply ascending Klippetunnell. These sediments have been the subject of palaeomagnetic investigation (Noel & St. Pierre, 1984; Løvlie et al., 1988, this issue).

Large boulders of granitic gneiss are found blocking some of the passages leading in from the direction of the cliff and on the floors of some of the entrance passages. These are particularly interesting since the passages to the surface all terminate in a near vertical cliff. The best example is the 'Granite Block'. Moraines and river gravels have also been washed deep into the cave. The nearest outcrop from which the granitic gneiss could have come if brought by the valley glacier is 7 km up the valley.

The morphology & sediments of Setergrotta

The main passages in Setergrotta are much larger than those in Grønligrotta. Resakjelen the much collapsed and frost-shattered entrance is one example. Although the large abandoned passages in Setergrotta do not have the characteristic elliptical profiles of Grønligrotta, the existence of a passage network and the lack of vadose features indicate that they also have been formed under conditions of complete water-filling. These large passages can be followed down to a fragmented vadose streamway - the water from Grønligrotta.

There are two periodically active passages: the Slamgang and the Marmorgang. The Slamgang leads to an upstream section of the streamway, whilst the Marmorgang ends at a static sump.

The distributions of the main types of sediment in Setergrotta are shown on the plan. In most of the network section the floors are covered in collapsed mica schist blocks except in the northern part where there are gravelly silt and sands. Some of the collapse is fresh and there are numerous fragments of blocks that have broken off on impact, varying in size from large fragments several metres in length to dust. Although water has not flowed in these passages since the most recent collapse, the presence of ice in places suggest that some of the breakdown is due to the freeze/thaw action of infiltrating surface water.

In the Slamgang the floor is covered by gravelly silt and sand. Railton (1954) described a stream flowing here which entered the main cave from a rift in the roof above the sump during his visit. The deposits on the floor of the Slamgang have been partially eroded leaving silt banks along the sides.

At the inner end of the Slamgang a series of drops lead down to the stream. In periods of wet weather the passage fills completely at this point, but in dry weather it is possible to descend, wade through the pool at the bottom and reach the stream which disappears into an impenetrable sink just before the pool. Only a little rain is required (2 mm, St. Pierre, 1965) to cause the stream to overflow into the pool and rise to seal off the passage. The water then backs up the streamway and if there is sufficient hydrostatic head, overflows down the Slamgang. At periods of high water-flow, milling of the sediments has resulted in almost spherical cobbles and pebbles. The cobbles are found in the bottom of the incline, the small pebbles part way up between the streamway and the Slamgang, while at the top in the Slamgang itself only particles below 4 mm in diameter have been deposited.

The Marmorgang (marble passage) which leads off from above the main sump has always been dry when visited, but is evident from its clean-washed, white marble walls that it periodically carries a stream. There are considerable granitic intrusions in the marble and ptygmatic quartz veins, which in places have formed a barrier to solutional cave development. Where they have been broken through fragments remain, but elsewhere the passage is entirely devoid of sediment except in the vicinity of the static sump where piles of sand form banks.

Much of the upper part of the active streamway is covered by collapse and there are several large breakdown chambers but lower down at the main sump the stream has a bed of pebbles. Upstream of this it has partially eroded banks of stratified fill which have coarser and finer layers of predominantly sand and pebble size.

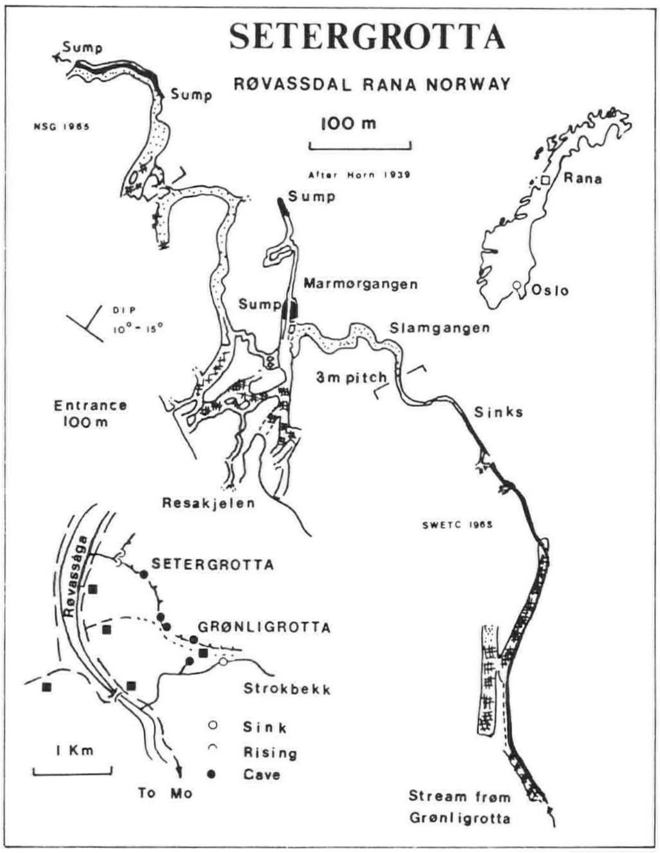


Figure 3. Settergrotta.

Sediment Sampling

24 samples of surface and underground sediments were collected from the Grønli-Seter cave system in 1977 for sedimentological and quartz grain surface feature studies (St. Pierre, 1978). The samples were lithologically described, tested with hydrochloric acid for carbonates (most samples showed a negative reaction) and the minerals identified. The grain sizes were determined by direct measurement or sieve analysis. The results of the sieve analyses were tabulated and plotted as cumulative probability curves. Phi percentiles obtained from the graphs were used to work out the Folk and Ward mean particle size, the McCannon mean, the Folk and Ward Standard Deviation, the McCannon Standard Deviation, the Inman Skew, the Folk and Ward Skew, and the Folk and Ward Kurtosis.

The terminology of Folk (1974) was used to describe the standard deviation (degree of sorting), skewness and kurtosis of the samples.

Conclusions of the sediment analyses

The presence of granitic gneiss and mica schist in the rock fragments and the considerable quantities of garnet in the finer sediment indicate derivation from a metamorphic terrain. As the mica schist is soft and easily broken down either by glacial or river erosion it seems likely that the mica schist fragments have been locally derived either exogenically from surface outcrops in the vicinity of the caves or endogenically from collapsed roof blocks. The break-down of the mica schist would also provide a source for some of the mica particles. However, as mica is a very durable mineral and muscovite particularly is likely to be stable under the prevailing climatic conditions, much of the mica could be of exogenic origin. The presence of biotite which is unstable and already beginning to break down indicates limited transport before deposition.

The rock fragments of granitic gneiss are generally fairly well-rounded. The nearest outcrops are 2 km to the south and 7 km to the north. However, as the last ice sheet moved in a westerly direction in this area they could have a more distant source. Under the S.E.M. quite a number of quartz grains are seen to be well rounded implying a long transport history. However it is possible that grinding within or at the base of a glacier or ice sheet could provide a mechanism for rounding quartz grains in a relatively shorter period. The presence of hornblende which is moderately unstable seems to indicate a local source probably from breakdown of glacial sediments.

The statistical analysis of grain size distribution shows that the sediments are, with one exception, moderately sorted, poorly sorted or very poorly sorted, They are generally platykurtic, but there is a variation in skewness between the samples from the dry series and the streamway. Two of the streamway samples are nearly symmetrical and one is completely symmetrical. The dry series samples however vary from strongly coarse-skewed to fine skewed. Some of the sediments showed bimodal and polymodal characteristics which are considered in the discussion. A few of the samples from Grønligrotta contained calcareous concretions.

Samples of the banded clays from the top of Klippetunnelen were identified by R. Merriman who found from x-ray diffraction that the clay is composed mostly of illite. Lesser amounts of chlorite are present and anhydrite and pyrite are suspected of being present.

The varied provenances described and the variety and nature of the sediments indicate that the majority are probably glacial sediments which have been washed into the caves after a very limited fluvial transportation.

Concretions

The calcareous concretions found in some of the Grønligrotta sediments - near the Granite Block, above the Østgang and near the Avgrund have also been found in other Nordland caves and on the surface (Jenkins, 1959; Drakes, 1965; St. Pierre, 1967; Theakstone, 1981). The concretions generally occur as ellipsoidal simple or compound forms with their long axes parallel to the bedding. Several samples contained laminated sediment of silt to pebble size and X-ray diffraction and chemical analysis showed that calcite is a major constituent of their cement.

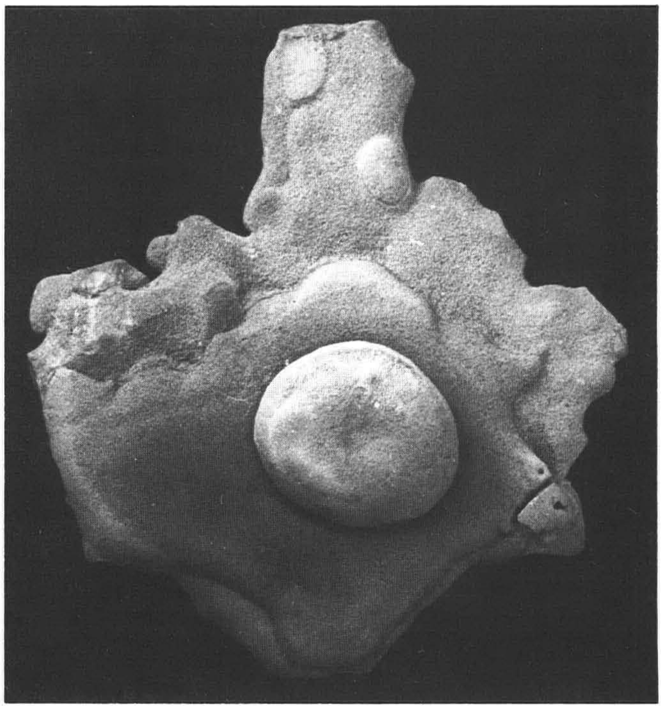
Concretions of this type do not appear to have been recorded from British cave sediments and it seems likely that cold climate is the dominant factor in their formation. They probably form as a result of snow meltwater from a limestone outcrop containing dissolved calcium carbonate flowing over or into a warmer environment resulting in carbon dioxide degassing and rapid deposition of calcium carbonate.

S.E.M. Analysis of quartz grain surface features

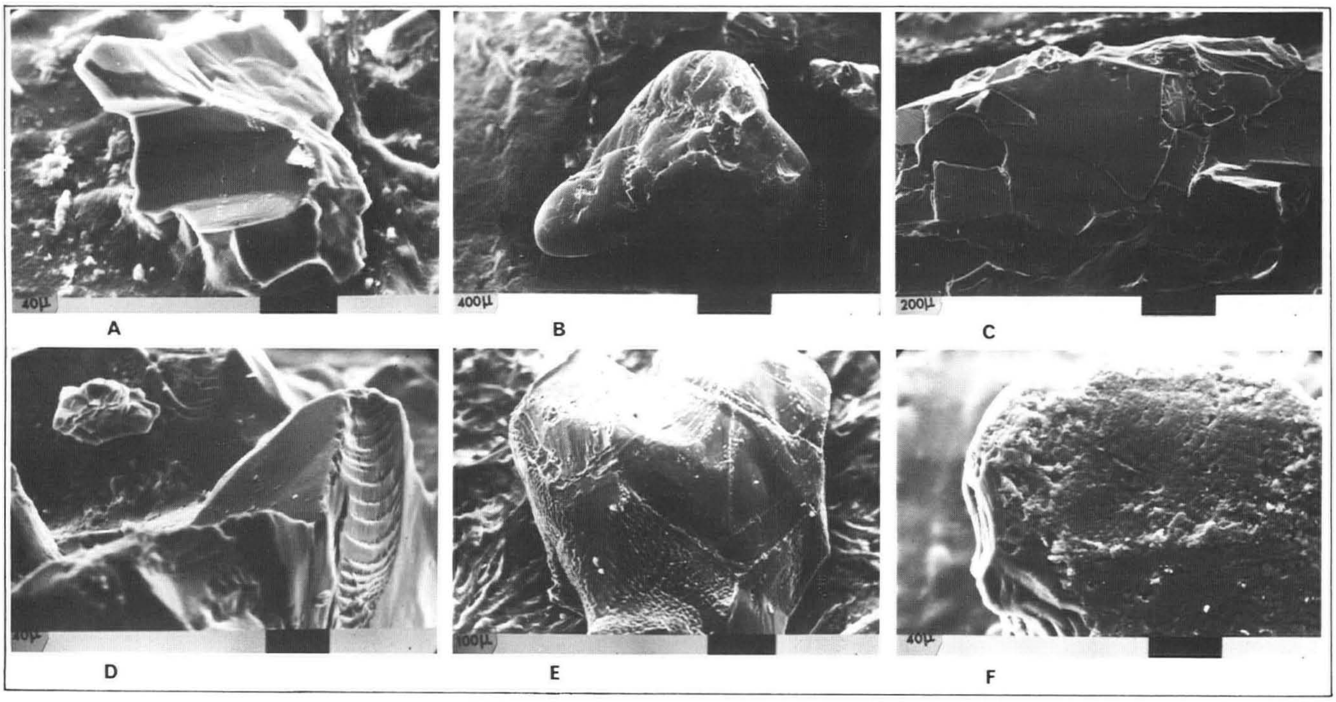
A few quartz grains from all the samples of suitable size were mounted for scanning electron microscope analysis. These were compared with photographs in the *Atlas of Quartz and Sand Surface Textures*, (Krinsley and Doornkamp, 1973) and photographs in Bull (1976).

Quartz grains from glacial environments are thought to exhibit surface features characteristic of grinding, the lack of water action and the extreme variability of the size content of the sediment transported. Krinsley and Margolis (1969) and Bull (1976) consider that the resultant features diagnostic of glacial action are conchoidal fractures , very high relief (related to the particle size and the large amount of energy available), semi-parallel steps, arc-shaped steps, parallel striations and breakage blocks. They believe that the presence of four or more textures over large areas of a single grain are adequate evidence of a glacial origin.

The majority of the quartz grains showed at least four of these features, the remainder showed



Concretions in the silt in Grønligrotta.



Scanning Electron Micrographs of sediments
a) Highly angular grain with conchoidal and cleavage fractures; Nordvestgang, Grønligrotta.
b) Quartz grain rounded by silica precipitation; irregular areas are due to conchoidal fractures and stepping. Slamgang, Grønligrotta.
c) Grain with marked conchoidal fractures and strong stepping; from near Marmorgang Sump in Setxergrotta.
d) Grain with conchoidal fractures, arc-shaped steps and breakage blocks; by main stream sump in Setergrotta.
e) Quartz grain with silica overgrowth; Fiskekroken, Grønligrotta.
f) Grain partly covered by silica precipitation; left-hand end shows sharp unmodified cleavage plates; near Avgrunden, Grønligrotta.

one, two or three characteristics, with the exception of a very few grains which had silica overgrowths. One grain showed the development of euhedral faces. However usually the overgrowths could be seen to rest on cleaved surfaces indicating again a probable glacial origin for the grains.

The smoothing of grain surfaces and pitting characteristics of river action were absent. The freshness of the glacial features and the lack of fluvial characteristics seems to indicate a relatively short transport from the glacier or ice-sheet into the cave, a conjecture supported by the other evidence above.

Discussion

In order to try to reconstruct the history of sedimentation, in the absence of absolute dating, it is necessary to consider when the caves were formed.

When attempting to establish the age of the old dry sections of the Grønli-Seter cave system and of other caves of similar morphological type in the area, with relation to the Pleistocene glaciations, the Norwegian geologist Horn (1947) considered preglacial, interglacial, subglacial and postglacial origins. For the first possibility Horn pointed out that the mountain peaks mark the pre-glacial land surface which was thought to have a peneplaned topography. The caves would then have been about 500 m below the surface and far beneath the existent water-table and cave formation at this depth was hardly likely. If the caves had been this old, Horn would have expected them to be much larger. This argument was also used against an interglacial age. A post glacial-origin was also considered unlikely as most of the caves visited were morphologically dead and he thought that they must have been so since the development of the present topography.

He believed that the caves had sub-glacial origins. Based on the work of Werenskiold and the findings of Sverdrop and Ahlmann in 1934 in Spitzbergen, Horn pointed out that the ground beneath a glacier was not necessarily frozen and that circulating sub-glacial meltwater could result in the formation of caves.

Oxaal (1914) who studied and surveyed Grønligrotta had concluded that this cave was formed during the last glaciation, but suggested that cave formation took place at glacial margins. Later work, particularly Kirkland (1958) and Jenkins (1959), though proposing a Tertiary origin, supports major cave formation subglacially or at glacial margins. Thus with the exception of Corbel (1957), there is general agreement that the caves largely developed during or at the end of the last glaciation. Most subsequent workers, particularly Kirkland (1958), have found that Corbel's hypothesis of post-glacial formation for these caves is in conflict with the evidence.

Having established that most of the cave formed near the end of the Pleistocene, the cave sediments will also probably have been deposited and reworked during this period and later through Recent times to the present day. The sediments in the caves have been divided into three main groups - collapsed blocks of mica schist from the roof, moraines and river gravels, and gravel, sand and silt. The collapsed roof blocks form a major feature in some parts of Setergrotta. The collapse may have taken place largely when the passages were drained and the roof was no longer hydrostatically supported and this process may be aided by seasonal freeze-thaw of infiltrating surface water. In Grønligrotta collapsed roof blocks rest on top of sands so it seems likely that here also the passage roofs are still unstable and subject to collapse.

The water which formed the Grønligrotta network entered from the cliff face, initially forming dip tubes which became linked by an aslant strike passage. Horn (1947) suggested that the water was derived from the Ice-sheet of the last glaciation. Oxaal (1914) thought the cave was formed by meltwater from the glacier which filled Røvassdal to a height of at least 250-300 m above the valley bottom. As the ice retreated it left behind boulders and other morainic material filling and blocking up some of the entrances - Fiskekroken, Klippetunnellen, 'Granite Block' passage and others. Some of this material was washed or slid over an ice floor deep into the cave and the smaller material was carried through into Setergrotta and deposited on the floors of passages and large chambers causing Grønligrota to become completely blocked by sediment in the lower reaches. Since analysis found that a large proportion of the cave sediments comprised grains of less than 63 microns in diameter it seems likely that the blockage caused ponding and widespread deposition of the fine grained sediment.

The bimodal and polymodal grain size characteristics of some of the samples probably reflect fluctuations in the flow of water carrying sediment into the cave, particularly as most of these samples occur in passages leading up towards the cliff. This process probably took place towards the end of the main period of deposition when the cave was largely flooded with pulses bringing in coarser morainic sediments which became mixed with the finer material settling out from suspension.

Two samples from the dry series of Grønligrotta showed a decrease in the fine fraction probably indicating some stream sorting. They were collected where moraines have blocked passages leading up to the cliff face, so possibly there has been minor vadose resorting by small streams draining in from the cliff and percolating through the fill.

The clay deposits are rather enigmatic. The banding indicates that they were laid down in slow flow conditions. Perhaps they were deposited when the network was still completely waterfilled towards the end of the first phase of cave development. Bretz (1942) suggested a similar origin for clay fills in caves in the U.S.A. although these fills were more extensive and unbanded. Some of the sediment in the caves has been resorted by the vadose stream as can be seen in part of Setergrotta where the present stream is eroding a partial fill of sand and gravel. It also seems likely that the stream in Grønligrotta has washed out the sediment from the parts of the network it occupied as it now has a floor of bedrock. The fact that the stream was once considerably larger is indicated by the large fossil potholes. Occasional rounded boulders of granite gneiss and mica schist remaining on ledges above the streamway are an indication that these passages once contained a considerable fill. The presence of a sump in the Østgang makes it unlikely that they were brought into the cave by the vadose stream.

The Jettergrytte - a fossil pothole above the Grønligrotta streamway, indicating a phase with a larger stream.

The almost spherical cobble and pebbles collected in the section between the streamway and the Slamgang in Setergrotta can be used to deduce the average velocity of the stream in high water conditions. Hjulström (1935) has prepared a chart which shows the relationship between average velocity across a transverse profile of a river and size of uniform particles. The average diameter of the cobble was 7.6 cm. This would give a mean velocity of about 200 cm s^{-1} when the stream had filled the passage and became powerful enough to move the cobble. The stream is unable to transport the cobble uphill, as it has obviously been there a considerable time to acquire its sphericity; so this figure is probably quite close to the maximum velocity of the stream in high water conditions at this point. The small pebbles, all situated at a higher level, have an average diameter of 1.35 cm. implying a mean velocity of about 100 cm s^{-1}.

At the top of this section in the Slamgang only gravel, sand and silt have been deposited. It is impossible to use Hjulström's curve to determine the velocity for sediments of varying size distribution but the decrease in sediment size deposited indicates a further decrease in velocity.

It has not been possible in this limited study to determine whether the minor climatic fluctuations since the Pleistocene are reflected in the cave sediments. However cave sediment deposition has been related to the last glaciation.

The source of the glacial sediments in the dry parts of the cave has completely disappeared. All that remains on the surface is a near vertical cliff. This shows that caves can sometimes provide an important record of past sedimentation when the surface evidence has been removed. It may in the future be possible to correlate sedimentary cycles in the caves of this area e.g. (Bull, 1977) and ultimately to work towards reconstructing the palaeoclimate of the area.

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The Arthropod Fauna of Grönligrotta, Norway

Heikki HIPPA & Seppo KOPONEN

Abstract: About 60 arthropod species were collected in Grønligrotta, northern Norway, by pitfall traps and hand-picking. The material included 20 dipteran, 11 beetle, 10 springtail, 6 spider, 4 stonefly, 3 cryptostigmatid and 2 prostigmatid mite, 1 mayfly and 1 caddis fly species. Several species of insects which as larvae prefer cold, fast-running rivers occured in this cave, many of them in great numbers. No troglobiontic species were found, but nearly a quarter of the species collected can be regarded as troglophilous. The occurence of many species in Grønligrotta can be explained by chance.

Cavernicolous invertebrate faunas have long been actively investigated in central and southern Europe. In northern Europe, only little attention has been paid to the subject, even though caves, including very large ones, are not uncommon in many areas of Scandinavia. Only fragmentary information concerning the northern cave fauna occured until recent years (e.g. Krogerus, 1926, Wolf, 1934-38, Gislen & Brink, 1950, Drakes, 1966, St Pierre, 1967, Tell et al., 1967, Hjorthen, 1968). A project to obtain basic faunistic data from the Scandinavian caves was carried out by a Finnish team in the mid-1970s. Caves were investigated in three areas: on the Baltic island of Gotland and in Scania, Sweden, and in the Rana area, Norway. Papers on certain animal groups have been published so far: spiders, harvestmen and pseudoscorpions (Hippa et al., 1984a), earthworms (Hippa et al., 1984b), mayflies, stoneflies, caddis flies and moths (Hippa et al., 1985a), beetles (Hippa et al., 1985b), millipedes, centipedes, isopods and amphipods (Hippa et al., 1986), springtails (Hippa et al., 1988a) and certain mite groups (Hippa et al., 1988b). Some other notes on Scandinavia cave fauna have been published (Engh, 1980, Lauritzen, 1981, Fjellberg, 1985, Østbye et al., 1987).

The previous occasional collecting using unsuitable methods caused a common impression that either none or very few and infrequently occuring insects and other arthropods live in caves of northern Scandinavia. Our work in two caves near Mo i Rana, Norway, showed rather diverse cave fauna living even on the Arctic Circle. No true troglobiontic species, obligate cave-inhabitants, were found, but several troglophilous species which live permanently in caves and reproduce there occured in caves of the Rana area.

One of our study caves is Grønligrotta situated near Mo i Rana. In the present paper, we will present the arthropod fauna found in Gronligrotta and discuss the origin of these cave-dwelling animals. The paper is based on our publications mentioned above. In addition, unpublished information concerning Diptera (flies and midges) is included.

The arthropod material was collected by hand-picking and especially by pitfall traps. The traps were placed in Grønligrotta on July 25 and removed on October 8, 1975.

CAVE FAUNA

We found the following arthropod groups in Grønligrotta: mites, spiders, springtails, mayflies, stoneflies, caddis flies, beetles and dipterans (flies and midges); altogether about 60 species (Table 1).

MITES. The mite material collected from Grønligrotta included 72 species of which half belong to the Mesostigmata and are so far identified. Three cryptosigmatid and two prostigmatid species were identified. Chamodotes cuspidatus, the most abundant species in the material, and Linopodes motatorius have been earlier found rather commonly in caves of Central Europe, and the last-mentioned has been regarded as troglophilous (Dixon, 1974 Dobat, 1975, Hippa et al., 1988b).

SPIDERS. Six species of spiders were found, and all spider species, with the exception of Leptorhoptrum robustum, are known to be troglophilous species (see Hippa et al., 1984a). Especially the large-sized Meta menardi is a well-known inhabitant of caves in Scandinavia. Østbye et al. (1987) reported M. menardi, M. merianae and Porrhomma convexum from Norwegian caves.

SPRINGTAILS. Of the ten species found, the following have been reported also by Østbye et al. (1987) from Norwegian caves: Neanura muscorum, Agrenia bidenticula, Isotoma notabilis and Arrhopalites sp., Neanura muscorum, Lepidocyrtus violaceus and Isotoma notabilis have been found in Central-European caves and Arrhopalites principalis in caves in England (Dixon, 1974, Hazelton, 1975) and in the Urals (see Hippa et al., 1988a).

MAYFLIES, STONEFLIES AND CADDIS FLIES. Six species of these groups were found. The mayfly Heptagenia dalecarlica, stonefly Amphinemura borealis and caddis fly Philopotamus montanus seem all to be permanent inhabitants of Grønliggrotta, because dense larval populations live in the river. The density of P. montanus pupae/praepupae was locally 10-15 ind./sq. dm near the waterfall in Grønligrotta (Hippa et al., 1985a). Of the above species, Philopotamus montanus has also been found in caves in Germany (Dobat, 1975).

BEETLES. Eleven species were collected, and at least the following species can be regarded as troglophilous: Quedius mesomelinus, Lesteva pubescens and Catops sp. (Hippa et al., 1985b). Eight of the present eleven beetle species were also found by Østbye et al. (1987) from Norwegian caves.

DIPTERA. About twenty species of Diptera, belonging to several families were found. Except the species of Trichoceridae and Simuliidae, the dipterans were collected in low numbers and near the cave entrances only. Trichocerids were distributed even in the most distant part of the cave investigated. The Trichocera larvae were caught by pitfall traps about 40m inside the cave entrance. Trichocera maculipennis has been regarded as troglophilous species (e.g. Dobat, 1975, Hazelton 1977).

Simuliidae larvae and puparia occured in all parts of the river when only a suitable bottom was available. Their maximal density was 40-50 individuals per sq. dm. Only a few adults were caught, both by hand-picking and trapping. At least six blackfly species were observed in Grønligrotta. The most abundant species, Helodon ferrugineum, is known to develop in cold waters (Ussova, 1964), and it seems to be a permanent inhabitant of the cave.

In the material of Mycetophilidae one female

Table 1. Arthropod fauna found in Grønligrotta.

Mites (Acari)	
Cryptostigmata	
Hypodamaeus brevitibialis Bulanova-Zachvatkina	5
Belba sp.	5
Chamobates cuspidatus (Michael)	18
Prostigmata	
Linopodes motatorius (Linnaeus)	2
Thoribdella meridionalis (Thor)	4
Mesostigmata spp.	38
Spiders (Araneae)	
Nesticus cellulanus (Clerck)	4
Meta merianae (Scopoli)	1
M. menardi (Latreille)	20
Leptorhoptrum robustum (Westring)	2
Porrhomma convexum (Westring)	15
Lepthyphantes pallidus (O.P.-Cambridge)	2
Springtails (Collembola)	
Neanura muscorum (Templeton)	2
Agrenia bidenticulata (Tullberg)	1
Isotoma notabilis Schäffer	13
Pogonognathellus flavescens (Tullberg)	2
Lepidocyrtus violaceus Lubbock	57
Smithurides malmgreni (Tullberg)	1
Arrhopalites principalis Stach	1
A. secundarius Gisin	26
Smithurinus concolor (Meinert)	22
Dicyrtoma fusca (Lubbock)	108
Mayflies (Ephemeroptera)	
Heptagenia dalecarlica Bengtsson	abundant
Stoneflies (Plecoptera)	
Amphinemura borealis (Morton)	abundant
Leuctra hippopus Kempny	1
Isoperla obscura (Zetterstedt)	1
Diura nanseni (Kempny)	1
Caddis flies (Trichoptera)	
Philopotamus montanus (Donovan)	abundant
Beetles (Coleoptera)	
Patrobus atrorufus (Ström)	1
Trechus rubens (Fabricius)	4
Calathus micropterus (Duftschmid)	1
Pteroloma forsstroemi (Gyllenhal)	9
Catops sp.	1
Quedius mesomelinus (Marsham)	3
Olophrum consmile (Gyllenhal)	1
Arpedium quadrum (Gravenhorst)	14
Lesteva monticola Kiesenwetter	2
L. pubescens Mannerheim	1
Oxypoda spectabilis Märkel	1
Midges and flies (Diptera)	
Tipulidae	
Pedicia immaculata (Meigen)	1
Trichoceridae	
Trichocera maculipennis Meigen	41
T. regelationis (Linnaeus)	6
Trichocera sp. larvae	2
Simuliidae	
Helodon ferrugineum (Wahlberg)	98
Cnephia fuscipes (Fries)	29
Eusimulium bicorne Dorier & Rubzov	2
E. ?meigeni Rubzov & Carlsson	5
Eusimulium sp.	7
Simulium rostratum (Lundström)	5
S. tuberosum (Lundström)	30
Mycetophilidae	
Mycetophila strobli Lastovka	2
Mycetophila sp. (females)	3
?Speolepta leptogaster (Winnertz)	1
Sciaridae	
Bradysia spp. (females)	5
Itonidae sp. (female)	1
Chironomidae	
Macropelopia sp.	1
Diamesa sp.	1
Culicidae	
Aedes sp. (female)	1
Empididae	
Platypalpus cursitans (Fabricius)	1
Phoridae spp.	3

specimen in bad condition has been determined to be Speolepta leptogaster which we have found also in several Swedish caves. The species is a well-known troglophile (Dobat, 1975) and it was recently reported from southern Norwegian caves by Østbye et al. (1987). They mentioned that S. leptogaster may be a troglobite under the Norwegian climatic conditions.

The chironomids caught are in such a bad condition that they can be identified to the genus level only. The species of Diamesa are known to be inhabitants of cold and Arctic waters (Serra-Tosio, 1972) and so very probably live in cave rivers.

The six individuals of Bradysia are all female and they could not be identified to species level, but there are at least two species. Some Bradysia species as well as certain Phoridae species are regarded as troglophilous (e.g. Dixon, 1974, Hazelton, 1975, Dobat, 1975).

Except Speolepta leptogaster there are no species of Diptera in common with the material of Østbye et al., (1987).

Table 2. Comparison of arthropod fauna (species found) in Grønligrotta and in Lummelundagrotta, Gotland, southern Sweden; Diptera excluded. The trapping periods were same and also other collecting activity comparable. There are also rivers in both caves.

	Grønligrotta	Lummelundagrotta
Opiliones (Harvestmen)	0	5
Pseudoscorpionida (Pseudoscorpions)	0	2
Araneae (Spiders)	6	17
Cryptostigmata (Cryptosigmatid mites)	3	6
Prostigmata (Prostigmatid mites)	2	3
Diplopoda (Millipedes)	0	3
Chilopoda (Centipedes)	0	1
Isopoda (Woodlice & freshwater isopods)	0	7
Amphipoda (Amphipods)	0	1
Collembola (Springtails)	10	14
Ephemeroptera (Mayflies)	1	0
Plecoptera (Stoneflies)	4	0
Trichoptera (Caddis flies)	1	5
Lepidoptera (Moths)	0	2
Coleoptera (Beetles)	11	39
Total species found	38	105
Total groups found	8	13

DISCUSSION

Markedly few arthropod individuals were caught in cave interiors, especially in the dry cave tunnels of Grønligrotta. The species found at the innermost collecting site (nearly 200m from cave entrance) was the midge Trichocera maculipennis. Also two beetles, Pteroloma forsstroemi and Quedius mesomelinus, were trapped far from the cave entrance (120-150m).

A special group in Grønligrotta includes species living as larvae in cold, fast running river, many in great numbers. These insects included mayfly, stonefly and caddis fly species and, among dipterans, blackflies, especially Helodon ferrugineum, and the chironomid genus Diamesa. The total number of these water-dwelling insect species was about fifteen. The permanence of these populations in caves and the role of possible drift of larvae or eggs by rivers from the surroundings is open to discussion.

Clear difference in diversity of cave fauna between Grønligrotta and Lummelundagrotta, southern Scandinavia, was found (Table 2). Several animal groups were found in Lummelundagrotta but not in the more northern Grønligrotta. Also the species number observed was markedly higher in Lummelundagrotta than in Grønligrotta. On the other hand, species of cold running water occured in Grønligrotta, not in Lummelundagrotta. In a recent paper Østbye et al. (1987) reported some groups, based on a small amount of material, from Norwegian caves. For comparison, their material from eight caves in northern Norway included 37 arthropod species.

No true troglobiontic arthropod species was found in Grønligrotta. Troglophilous species were found especially among spiders but also in beetles, mites and dipterans, perhaps also in springtails. Nearly 25% of the species found in Grønligrotta can be regarded as troglophilous. The occurence of the rest (about 75%) of species found in Grønligrotta is probably dependant only on chance and they originate from the surrounding habitats.

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Glacier Caves and Subglacial Water in Nordland, Norway

W THEAKSTONE

Abstract: Glacier caves, created when streams flowing down the adjacent valley side continue beneath the ice, tend to be elongated tunnels of approximately circular cross-section, sloping down towards the centre of the glacier. Caves formed as glaciers lose contact with an irregular surface over which they are sliding are particulary common where the bed gradient increases: many are found against rock steps, and their length and cross-sectional form depend on the height of the up-glacier wall, the gradient of the floor along the ice flow direction, and the rate of sliding. Water within the caves may freeze onto cold rock surfaces. Water at a glacier bed may be in the form of a film which effectively lubricates the glacier-rock interface by submerging small irregularities which impede sliding, or it can flow through a system of distinct channels. Areas of subglacial terrain exposed around the margins of glaciers which have retreated in recent years provide evidence of glacial basal drainage systems. Glaciers and their hydrological systems are unlikely to be sufficiently stable for a long enough period, both to initiate cave formation in calcareous bedrock, and also to cause extensive development or modification in relatively unchanging conditions: most caves in soluble carbonates affected by glacial processes are likely to have experienced periods of development in widely-different conditions.

INTRODUCTION

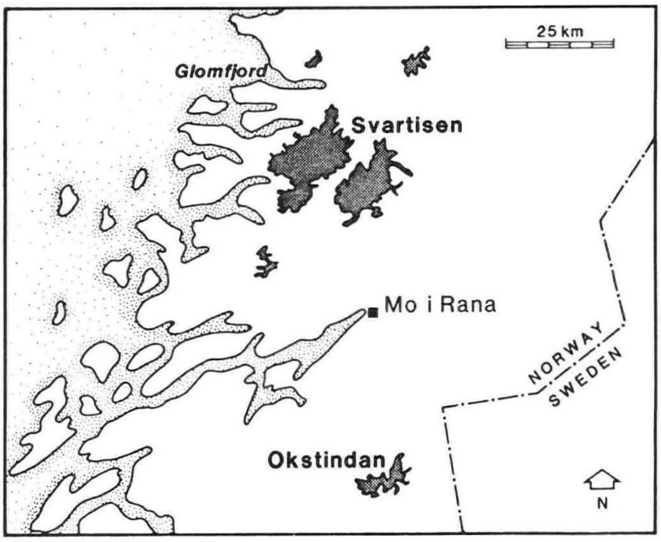
Some of Norway's most extensive cave systems have been developed in the marbles of the North Norwegian Mica-Schist Series in the Svartisen area (Corbel, 1957; St Pierre and St Pierre, 1969, 1985; Saltfjellet-Svartisen, 1982). Whilst little calcareous bedrock now is overlain by glacier ice, many caves have experienced the effects of glacier melt water in the past: in order to understand their mode of formation and development, knowledge both of the conditions which exist beneath glaciers and of glacier hydrological systems is essential. Opportunities for examination of subglacial conditions is provided by the existence of a variety of natural cavities ('glacier caves') beneath glaciers. Investigations of glacier hydrological systems, and of the processes associated with them, have been in the forefront of glaciological research in recent decades. Both glacier caves and glacier water have been studied at Svartisen and at Okstindan, some 80km further south.

The hydrological systems of glaciers have a number of similarities with those of limestone areas, but there are some striking differences. Although abundant meltwater is generated at the upper surface of a glacier during the summer, most becomes englacial within a short distance by way of crevasses or vertical shafts (moulins); some seepage also may occur. Englacial conduits tend to widen as a result of heat transfer from the water passing through them, but tend to close under the overburden pressure imposed by the overlying ice. Water pressures within them vary, depending on whether or not they are entirely filled by water. The englacial routeways followed by the water are likely to become integrated into a system which feeds a single principal river or, at most, a few separate major streams. Glacier rivers commonly issue through a portal which is only partly water-filled. In some cases, subglacial river courses are indicated by depressions at the overlying surface, surrounded by concentric crevasses, caused by partial collapse (Theakstone and Knudsen, 1986).

Exploration of the internal drainage networks in glaciers is hazardous, and rarely attempted, but some moulins have been descended and followed to the point beyond which no further travel is possible (Vallot, 1898; Carol, 1945; Pulina, 1984; Reynaud, 1987). A few active river courses have been followed up-glacier for a short distance from the portal, but exploration of abandoned courses has been more common (Battle, 1952; Pulina, 1984). More frequently, subglacial conditions have been studied in natural cavities accessible from the glacier margin (Forel, 1887; Kamb and LaChapelle, 1964; Theakstone, 1967, 1979; Anderson and others, 1982; Andreasen, 1983).

GLACIER CAVES

Some glacier caves are created where streams which flow down the adjacent valley side continue beneath the ice (Stokes, 1958; Davies, 1961). Generally, they are elongated tunnels of approximately semi-circular cross-section, sloping down towards the centre of the glacier. Their development results largely from warm air entering the caves with the stream water. The ice surface frequently is scalloped, a consequence of the flow pattern of warm air. Because it is true glacier ice, it is clear, and appears blue in colour as a result of refraction of light within the overlying ice. The cross-sectional areas of the tunnels tend to decrease with distance from the margin, partly because of the decreasing advection of heat and partly because the overburden pressure increases as the ice thickness increases towards the centre of the glacier. In the usual conditions, where the stream entering such a cave is small, the limit of access is determined by glacier thickness: it is rarely possible to penetrate far beyond the point at which the



overlying ice is 50m thick. Where the ice is thin and stagnant, tunnel cross-sections may enlarge considerably, leading to the danger of collapse.

Most glacier cave entrances are blocked by snow in winter. Water flow into them is likely to be greatest during the period of snow melt (generally between late May and early July at the Nordland glaciers), but periods of heavy rainfall in summer also may produce rapid increases of discharge, because the streams flow over extensive areas of bare rock on their way to the glacier. If the volume of water entering a cave in a given period exceeds that which can escape from it, the pressure in water-filled conduits leading away from the cave may rise. Surface levels of pools beneath glaciers have been seen to rise in such circumstances.

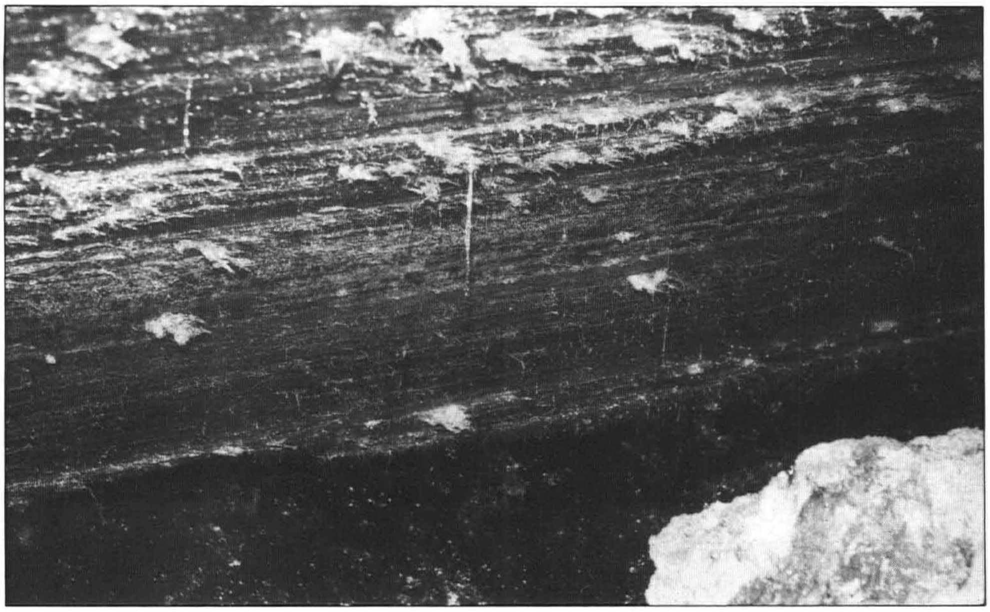
Until the early 1980s, low, tunnel-like caves were common under the southern side of Austerdalsisen (formerly known as Østerdalsisen), the largest outlet glacier of Svartisen. Throughout much of the present century, the glacier's southern margin was retreating down-slope; several streams flowed down the slope and disappeared under the glacier. However, in July 1982, Austerdalsisen lost contact with the slope, and the glacier tongue broke up. It now terminates in a lake (Theakstone and Knudsen, 1986).

Some caves are formed as glaciers lose contact with an irregular surface over which they are sliding. They are particularly common where the bed gradient increases, and many are formed against rock steps. At its eastern margin, Austerdalsisen descends a slope which resembles a gigantic staircase; in consequence, a series of glacier caves exists, each with an up-glacier wall and floor of rock and an arching ceiling of ice. Some of the caves are inter-connected, but most are separated from others by areas of contact between the glacier and bedrock. The tendency of the glacier margin to collapse at cave entrances is evident from the frequency with which detached ice blocks can be seen there. At their inner ends, most caves become very low and narrow. Some terminate in water, the level of which is liable to vary as a result of changes of glacier sliding rates or local stress fields. The resultant water pressure variations themselves influence the speed of glacier sliding. Cave length and cross-sectional form depend on the height of the up-glacier wall, the gradient of the floor along the ice flow direction, and the rate of sliding. Because glacier sliding rates vary seasonally, decreasing in winter when the supply of water to the bed is low, cave cross-sections tend to be smaller in winter than in summer; the increased contact between the glacier and its bed itself plays a part in seasonal decreases of sliding rates.

In summer, air temperatures within natural cavities beneath sliding glaciers generally are close to 0°C: as most caves extend below the level of the glacier margin, cold air is not easily displaced by warmer, less dense air. Because humidity usually is high, hoar frost formation and rime deposition on cold surfaces are probable. Occasionally, this gives rise to spectacular conditions, almost all surfaces within a cave supporting a lattice-work of plate-like ice crystals. As the summer ends, falling external air temperature causes a decline of cave temperature; water freezes onto cold rock surfaces. Ice on glacier cave floors may make the use of crampons, or an ice axe, essential aids to exploration: thicknesses of the order of 30-50cm have been observed on cave floors beneath Austerdalsisen in late winter (Bennett, 1968).

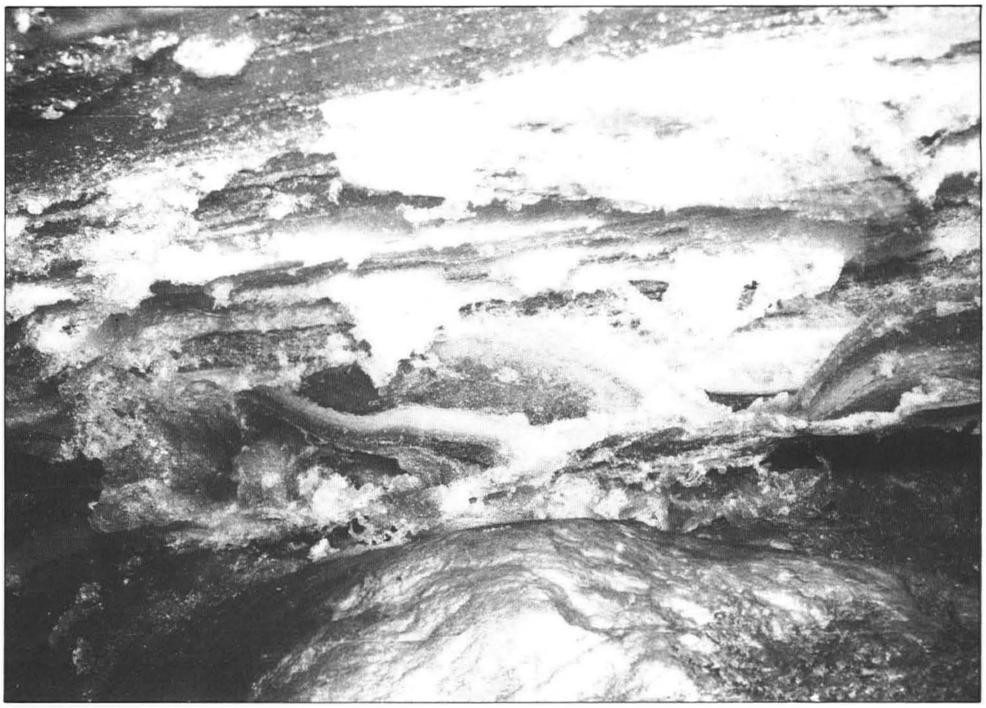
The nature of the ice at cave ceilings may differ markedly from that of true glacier ice. Much of the basal ice of glaciers originates by refreezing of meltwater previously circulating at the bed. On the down-glacier face of protuberances at the bed, the pressure is lower than that on the upstream face. Ice which already is at the melting point temperature therefore melts at the upstream face, because the melting point temperature is pressure-dependent. Having trickled round the obstacle, the water re-freezes at its downstream end. During the freezing process, debris may be incorporated into the regelation ice. Successive regelation episodes may give the basal ice a banded appearance. In contrast, most glacier ice, metamorphosed from snow, has a low debris content. The different modes of origin of the basal ice and the adjacent glacier ice are reflected in crystallographic contrasts, and in differences of chemical and isotopic composition (Souchez and others, 1973; Hallet and others, 1978; Theakstone, 1979; Jouzel and Souchez, 1982; Sugden and others, 1987; Tison and Lorrain, 1987). Within the cavities, basal ice may become detached from the overlying, often cleaner, ice (Theakstone, 1965, 1966; Bennett, 1968; Griffiths, 1979, 1980).

Ice in contact with the bed up-glacier of a cave is moulded to the form of the protuberances over which it slides, because the ice deforms under the overburden pressure. Both water and debris are forced away from the higher parts of the protuberances to the adjacent lower parts, where the water is likely to re-freeze. The surface topography which is produced may be retained as a series of longitudinal ridges and grooves on the cave ceiling, elongated along the line of flow (McKenzie and Peterson, 1975; Andreasen, 1983), a feature noted by Desor (1845) under the Aar glacier. The reduction of stress on basal ice as it loses contact with the bed at the up-glacier side of a cave may cause water to



The basal surface of Austre Okstindbreen, Okstindan, Norway in a subglacial cave. Glacier flow is from left to right. The basal ice surface reflects the form of the bedrock past which it flowed immediately up-glacier of the cave: minor projections and indentations in the rock produce flow-parallel grooving of the ice. Water extruded by the pressure gradient in the ice re-freezes in contact with the air in the cave, which is below the melting point temperature, giving rise to ice accretions on the basal surface (upper part of the photograph). Very thin, hair-like regelation spicules and longer ice 'stalactites' (centre), which also result from regelation, lengthen with time. Frozen sediment is present at the cave floor (bottom).

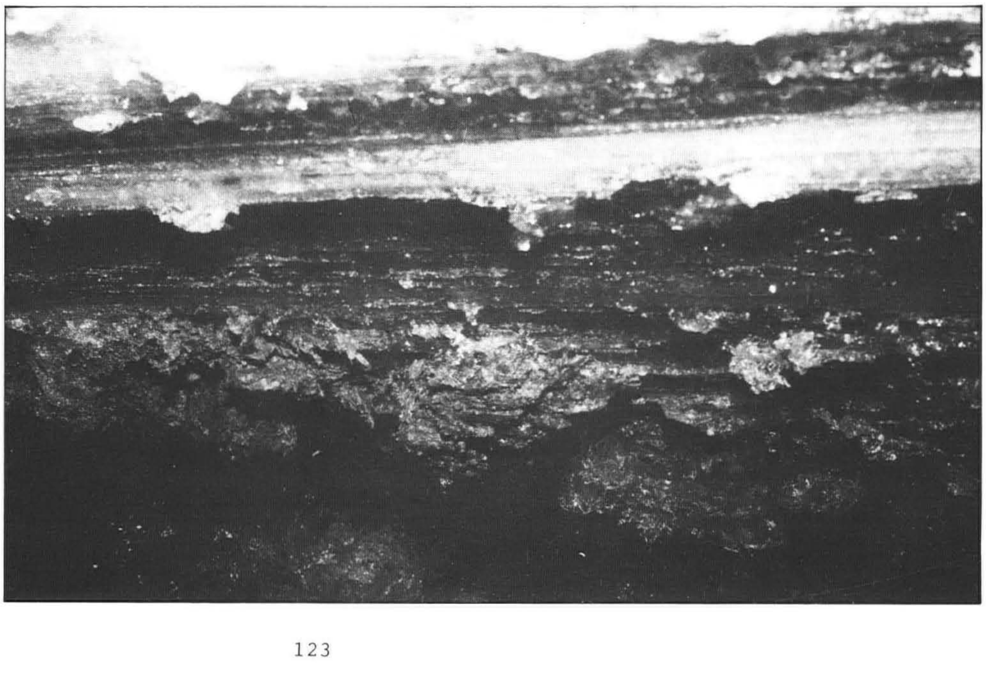
Basal ice deforming against a bedrock 'hump' (bottom) in a cave beneath the glacier Austre Okstindbreen, Okstindan, Norway. Ice accretions attached to the glacier sole (top) result from regelation.



freeze. Needle-like regelation spicules are a characteristic features of such conditions (Kamb and LaChapelle, 1964; Theakstone, 1979).

On making contact with the bed at the down-glacier side of a cave, ice deforms under stress (Theakstone, 1966). Deformation varies with such characteristics as debris content, air bubble concentration, ice texture and fabric. The deforming ice tends to be squeezed into cavities. Where tunnels have been excavated through bedrock to the bottom of a glacier, as at Bondhusbreen in south-west Norway, ice deforms into them in winter, when little water is entering them (Hagen and others, 1983). Some solution shafts in bedrock beneath the 300m thick ice of the Columbia Icefield are plugged by clear glacier ice (Smart, 1986). Because the melting point of the deforming ice is lowered by the imposed stress, water forms; it tends to move towards the zone of lower pressure at which ice is in contact with air rather than rock. On reaching the free surface, the water may refreeze, as does that expelled from cave ceilings by the pressure gradient in the ice (Theakstone, 1985). The water which refreezes on making contact with the air forms ice stalactites or other excrescences. A variety of such features was observed in a cave beneath Austre Okstindbreen, the largest glacier of Okstindan, in which the summer air temperature was close to the melting point (Andreasen, 1983). Some basal ice deforming within cavities becomes detached from the glacier, leaving a clean sole of glacier ice to move on in contact with the bed.

Ice which forms as water freezes on the upper part of the rock wall over which a glacier is sliding may become attached to the glacier bottom. As sliding continues, it is pulled away from the wall, and freshly-weathered rock is added to the basal ice. Subsequently, the distance between the rock wall and the ice attached to the glacier bottom is a useful measure of the amount of sliding (Bennett, 1969; Drake and Ford, 1970). Some stones which are incorporated into basal ice and are transported to the next cave down-glacier are expelled from the ceiling there, because the stress on their upper surface is greater than that on their lower one (Vivian and Bocquet, 1973). Although deposits are not generally abundant on the cave floors beneath Austerdalsisen, and it is evident that some of the debris present has been transported by streams which cut through moraines or other deposits en route to the glacier,



Basal ice in a cave beneath the glacier Austre Okstindbreen, Okstindan, Norway. Flow is from right to left. On encountering air at sub-melting-point temperature in the cave, water which has been expelled from the basal ice under the local pressure gradient freezes, and regelation ice accretions are formed.

substantial bodies of sediment are present below some glaciers. During an advance in the late 1970's, Corneliussens Bre, one of the Okstindan glaciers, pushed some material in front of it, like a bulldozer, but some sediment became lodged at the bed and was over-ridden by the ice (Knudsen and Theakstone, 1982). Subglacial sediment may become frozen to the bottom of a thin glacier in winter; if the sediment was deposited in water, sedimentary structures may be preserved (Harris and Bothamley, 1984).

The location of former subglacial cavities may be recognisable from bedrock colour contrasts, which result from differences of chemical reactions at areas of ice/rock contact and areas where the bottom of the glacier generally was not in contact with the bed. This is the case at places east of Austerdalsisen and, more strikingly, in front of Austre Okstinbreen. Since the sites of the former cavities are at the down-glacier side of breaks of slope, they are visible only from the side or from the up-glacier direction.

SUBGLACIAL SEDIMENTS

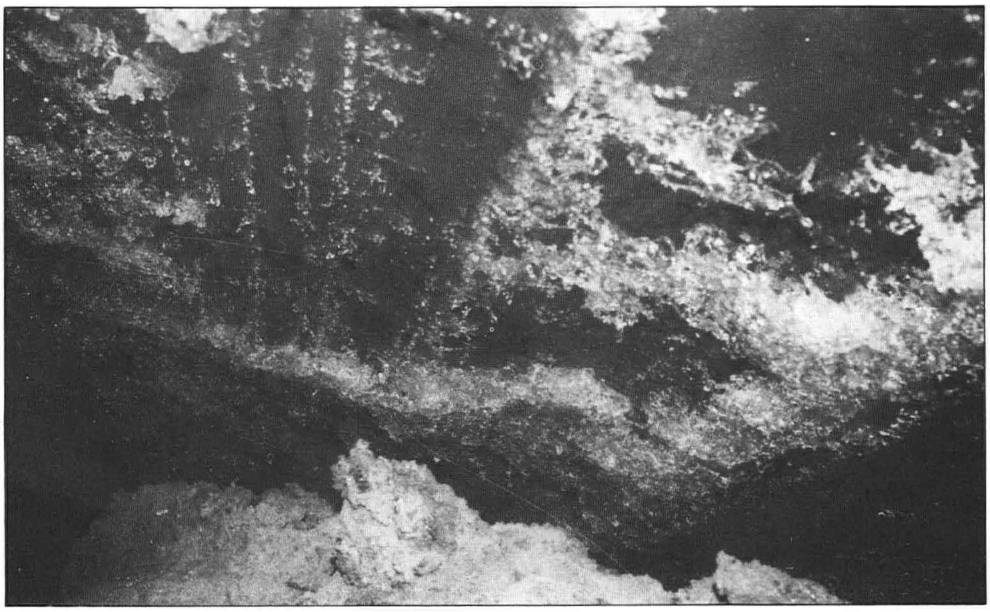
Although there are extensive areas of bare bedrock beneath some glaciers, the intervention of weathered rock and/or sediment between ice and solid rock is common. Water-soaked sediments are susceptible to deformation, and may flow into cavities at the bed under the influence of the local stress field (Boulton and others, 1979; Boulton, 1982). Even when the temperature of subglacial sediments is below the freezing point, they may be subject to considerable deformation, thereby making a substantial contribution to movement observed at the upper surface of the overlying glacier (Echelmayer and Wang, 1987). Where subglacial temperatures are below the pressure melting point, or where glacier loading decreases the permeability of subglacial sediments, water movement at the bed may be inhibited. The associated increase of water pressure may increase glacier sliding rates and, in an extreme case, may lead to the phenomenon of glacier surging (Kamb and others, 1985).

Whilst zones of below melting point temperature exist at the beds of some glaciers, particularly where the ice is thin, sliding of ice at the pressure melting point is probable in deep troughs and downglacier of sharp, steepening breaks of slope at the bed. Over long periods, glacier basal temperature distributions may change, particular zones experiencing an alternation between melting point and below melting point conditions, with consequent effects on subglacial processes, including sediment-incorporation.

HYDROLOGICAL SYSTEMS IN GLACIERS

Most of the water discharging from a glacier is formed by melting of snow or ice at its upper surface. In the accumulation area, the melt water percolates through the snow and firn (old snow which is gradually being transformed to glacier ice) until it reaches the underlying, much less permeable ice. Although likely to be stored for a time in the lower parts of the aquifer above the ice, the water eventually drains through crevasses or other channels into the body of the glacier. The assumption that the ice above the equilibrium line is hydrologically inactive (Smart, 1984) is incorrect: melting above the equilibrium line altitude accounts, for example, for more than half of the total summer mass balance at Engabreen, the largest outlet glacier of the west Svartisen ice cap. Whilst the depth of air-filled crevasses is limited, water-filled ones may extend to the bed, reflecting the density difference between ice and water. In icefalls above changes of basal gradient, the large surface area results in high rates of melt water production, and the crevasses provide abundant opportunities for water penetration into the glacier. As the stress field within the ice influences crack propagation, routeways taken by water within icefalls, which are common features at outlet glaciers of plateau ice caps such as Svartisen and Okstindan, may vary relatively little from year to year (Röthlisberger and Lang, 1987).

In the ablation area, supraglacial stream courses generally are short, discharging into moulins or crevasses which direct the water into englacial conduits. Conduit cross-sections tend to be enlarged by heat transfer from the flowing water but are subject to closure by plastic deformation under the effect of ice overburden pressure. Within them, therefore, water may flow under atmospheric pressure or, if they are water-filled, under higher pressure. In summer, diurnal variations of surface melt rates, which are notable even at the Nordland glaciers where there is no daily period of darkness, result in diurnal discharge variations in glacier drainage systems; some conduits may be water-filled only at the higher discharges. Most conduits supply major trunk streams flowing at the glacier bed, but not all feed directly into such streams, of which there are few at any one glacier. Much of the water at the bed moves towards a major trunk stream in a thin sheet, or in small channels. Subglacial channel systems are likely to consist of larger segments (cavities) linked by smaller ones, their course determined in part by the small-scale topography of the bed. Should the bed be smooth, then water flow directions may be determined by pressure gradients there, which will



The ceiling of a cave beneath Austre Okstindbreen, Okstindan, Norway is formed by the bottom of the glacier. At the up-glacier end of the cave, the basal ice is in contact with sediments (bottom). The ice is moving towards the camera position.

depend in part on spatial variations of glacier thickness.

Glacier river discharge varies on seasonal and long-term time-scales, as well as on a daily basis in summer (Röthlisberger and Lang, 1987). Little water discharges from glaciers in winter, and their hydrological systems tend to close down during that season. The area of contact between the glacier and its bed increases and sliding velocities decrease. As winter ends and snow melt starts, the capacity of the hydrological systems is inadequate to accommodate the water supplied. Water pressures rise to the point at which other parts of the glacier bottom become separated from the bed, opening up new drainage routes, in which a considerable amount of sediment, much of it newly abraded during the winter, can be transported (Hooke and others, 1985). With the increase of basal cavity-formation, glacier sliding rates increase. However, water-filled cavities may be unable to drain rapidly through the linking zones of smaller cross-section.

Changes of the geometry of glacier hydrological systems are most likely to occur during snow melt, at the end of the winter season. Throughout most recent summers. the more northerly of the two rivers issuing from Austre Okstindbreen has been the larger, but in two years the southern river accommodated most of the water discharging from the glacier. In only one year in the last twelve (1985) has a change occurred during the course of the summer, and that was associated with a major storm. Some subglacial rivers occupy the same course year after year, but others are subject to change: the river at the bed of the Glacier d'Argentière in the French Alps changed course in April 1976, and water ceased to enter the subglacial intake of a hydro-electric power station, which had been in use for the previous decade (Hantz and Lliboutry, 1973).

Away from the principal river, water at a glacier's bed may flow in discrete channels or in a thin sheet; systems of linked cavities are likely to exist (Walder, 1986). Cavity formation is favoured by abrupt local steepening of the glacier bed, which causes loss of contact between the basal ice and the underlying surface (Vivian and Bocquet, 1973; Theakstone, 1985). Temporary storage of water in subglacial cavities is accompanied by water pressure variations. At times, the cavities are only partly filled by water but, when the rate of supply exceeds that at which water can leave them, the pressure within them is high.

SUBGLACIAL WATER

Dye tracer tests have shown that water entering a glacier from a site at its upper surface may emerge at more than one place (Burkimsher, 1983), and that, whilst some water moves rapidly from the surface to the point of discharge of the glacier river, some is delayed in transit (Theakstone and Knudsen, 1981). Chemical analyses indicate that surface melt water retains a low solute content as it flows without delay through englacial conduits, but that ionic concentrations in water which flows slowly at the bed are increased (Collins, 1979). The water leaving a glacier at any time is a mixture of components, some of which have moved rapidly through the glacier from its upper surface, some of which have spent a considerable time in transit. Some of the water has resulted from snow melt, some from glacier ice melt; at times, groundwater and rain water may contribute to glacier river discharge. Stable isotope investigations demonstrate that, whilst water formed by melting of ice within a few hundred metres of the front may leave the glacier in the main river within a few hours, much glacier river water has not been generated by ice melt and has had a longer travel time (Theakstone, 1986).

Because debris concentrations in glacier ice are very low, and its melt water is of high purity, there is little chance of chemical reactions when water enters the body of a glacier from its upper surface, although the water can acquire solutes readily. This situation changes markedly when the water mixes with sediment-rich subglacial water, even if the latter itself has little further capacity for solute acquisition. As long as reactive rock debris is available in the subglacial component, mixing can produce chemical reactions (Raiswell, 1984). The total dissolved load of water discharging from the glacier reflects the subglacial role of factors which influence solute acquisition, including water composition and flow rate, the duration of storage, and the grain-size, abundance and mineralogical composition of rock debris. In those parts of subglacial hydrological systems which the residence time of the melt water is in relatively long, the availability of fine-grained material is high and the reactivity of the mineral grains is maintained at a high level as processes of abrasion, crushing or fracture continuously generate fresh surfaces, the rate of CO_2 consumption by weathering reactions exceeds that of CO_2 renewal by dissolution. Where there is a large subglacial reservoir, as at Glacier d'Argentière (Vivian and Zumstein, 1973), or more than one subglacial river, as at Austre Okstindbreen, the variability of the duration and nature of the contacts between the different water components and rock materials should result in their possessing different compositions.

At the bed, water can be in the form of a film which effectively lubricates the glacier-rock interface by submerging small irregularities which impede sliding, or it can flow through a system of distinct channels (Hallet, 1979). Groundwater flow in Castleguard Cave, which is developed in the Cathedral Formation beneath the Columbia Icefield, Alberta, Canada, occurs both as streams in large discrete conduits and as smaller diffuse drips and seeps commonly associated with stalactites; Smart (1983) suggested that conduit flow in the glacier and groundwater were linked, and that diffuse seepage was associated with the glacier's basal regelation film.

The large areas of formerly subglacial terrain exposed around the margins of glaciers which have retreated in recent years provide evidence of glacier basal drainage systems. Remnants of subglacial channels in which water must have flowed both up-slope and down-slope exist within a few hundred metres of the present limits of Austerdalsisen, indicating that, because of high water pressures, subglacial water may follow routes which would be impossible in a subaerial situation. However, many of the features left by former basal drainage systems on abandoned glacier beds are characteristic of open-channel flow, suggesting that water in subglacial conduits generally may be under low (probably atmospheric) pressure (Smart, 1986).

By mapping some 5000m^2 of limestone bedrock adjacent to the retreating Blackfoot Glacier, Montana, U.S.A., Walder and Hallet (1979) were able to reconstruct in considerable detail the spatial patterns of formerly-active subglacial processes. They concluded that a nearly-continuous, non-arborescent network of cavities and incised channels probably had been the primary means of drainage of meltwater, and that at least 20% of the glacier bottom had been separated from the bed by water-filled cavities. Typical channels were 50-250mm deep, 100-200mm wide and 2-5m long; Walder and Hallet (1979) considered that many of the channels accommodated water only temporarily, perhaps intermittently, and that, when they were inactive, they were filled with actively-sliding basal ice. There were many furrowed, subglacially-precipitated calcite deposits on the down-glacier side of bedrock protuberances. These are likely to have formed during freezing of melt waters associated with active sliding: where the carbonate content of subglacial waters is high, regelation resulting from variations of subglacial pressure or temperature may induce supersaturation and precipitation on bedrock within cavities, as solutes are selectively rejected into the melt during freezing (Ford and others, 1970; Hallett, 1976).

Investigations of 10000m^2 of limestone surface recently exposed by the retreat of the northern Castleguard Glacier, at the southern margin of the Columbia Icefield, suggested that about 30% of the bottom generally had not been in contact with the bed (Hallett and Anderson, 1982). In contrast with the situation at the Blackfoot Glacier, most of the cavities at Castleguard apparently were not occupied intermittently by ice. As at Austerdalsisen, their location was determined largely by the form of the glacier bed, a series of step-like ledges. Chemically-altered areas, present in zones recently exposed by glacier retreat and contrasting in colour with the bedrock, represented subglacial deposition at the down-glacier side of bedrock protuberances.

CONCLUSIONS

Although their accessible length rarely extends beyond a hundred metres from the glacier margin, glacier caves afford opportunities for study of conditions at the bed, from which much can be learned about the nature of subglacial processes. Former parts of the bed exposed by recent glacier retreat may provide evidence of the nature of the hydrological systems which exist beneath glaciers, systems to which direct access is both difficult and hazardous. The hydrological systems within and below glaciers play a fundamental role in both glaciological and geomorphological processes. This has important consequences for cave formation and development in calcareous rocks beneath glaciers.

Few trunk streams flow at the bed of a single glacier, but numerous minor channels, characterised by small conduits and linked cavities, carry water across it. Where the bed is of soluble carbonates, therefore, there are abundant opportunities for streams of generally low discharge to encounter fissures, joints or other sites susceptible to weathering. The frequency of fissures controls the opportunities for water to penetrate below the bed surface level. In winter, many subglacial channels are dry, but both discharge and water pressure increase rapidly with the onset of snow melt. Water reaching the bed from englacial conduits has a very low solute load; if there is little weathered material or sediment at the bed, and the water spends little or no time in storage, chemical reactions may be rapid. Interactions between basal sediments and meltwater which has passed through the glacier from its upper surface affect the potential for subsequent changes of the water's solute load. If fine-grained particles are abundant and water movement restricted, weathering reactions may consume all available carbon dioxide.

Basal ice may be forced into cavities and solution features at the bed. Subglacial sediments may disrupt the normal patterns of glacier drainage as they are squeezed into channels incised into the basal ice, and become lodged within those incised into the bed, perhaps preventing access of water to fissures. Low permeability sediment bodies may inhibit water movement and, by causing water pressures to rise, may increase the rate of glacier flow.

Because the hydrological conditions within a glacier are subject to temporal change at a variety of scales, ranging from the daily, through the seasonal and multi-year, to periods of many centuries, it follows that, as demonstrated by Lauritzen (1982) for the cave system of Pikhaugane, Svartisen, the hydrological conditions in soluble carbonate bedrock beneath a glacier also are changeable. Glaciers and their hydrological systems are unlikely to be sufficiently stable for a long enough period both to initiate cave formation and also to cause extensive development or modification in relatively unchanging conditions. Caves in soluble carbonates affected by glacial processes which are not immature are likely to have experienced periods of development in widely-different conditions: as stated by Ford (1987), glaciers may destroy, inhibit, preserve or stimulate karst development. Further studies of the subglacial environment, of glacier hydrology, and of water quality variations at glaciers will provide important evidence relating to these variable conditions.

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The glacier sole, Austre Okstindbreen, Okstindan, Norway. Flow is towards the camera. Deformation of ice up-glacier of the cave results in its conforming to the shape of the bed with which it is contact. Each irregularity of the bed is mirrored by the ice surface, which exhibits a grooved form, elongated along the flow lines. The cause of the transverse protuberances is uncertain. Many of the pebbles embedded in the basal ice are extruded from the glacier sole in the cave.

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Paleokarst in Norway

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Abstract: Previously published evidence for paleokarst and Tertiary karst in Norway includes unconformities reported in the Ordovician/Silurian boundary of the Oslo region and in the lower Silurian of the Troms area. Karren, scallops, grykes, as well as the more common breccias have been recognized. The Helgøya unconformity (Oslo Region) represents a karstic relief of some 3 m, whilst the Troms case is a sulphide (Pb,Zn) mineralized breccia, associated with a supratidal environment. In spite of the lack of direct stratigraphic or chronological evidence, a few karst macroforms are suggestive of a preglacial or Tertiary age.

No systematic morphogenetic study of the paleokarsts in Norway has yet been done. However, unconformities of a karstic origin have been recorded en passant in stratigraphic studies. Most of the limestone caves known in the country are relic, evidently of pre-Holocene age, and a few of them can be distinguished as probably belonging to a pre-Pleistocene genetic regime.

GEOLOGICAL SETTING OF THE CARBONATE ROCKS

The geographic and stratigraphic distribution of limestones and phases of karstification are shown in Fig. 1 & 2. Carbonate deposits exist through most of the stratigraphic column particularly in the Precambrian and the Cambro-Silurian. Carbonates within the Caledonian orogenic belt show several phases of plastic deformation and profuse recrystallization into marbles. However, in a few locations, these rocks are less altered, providing fossils which indicate a Cambro-Silurian age (Strand 1960; Oftedahl 1980). Because of the strong deformation possible original karstic unconformities are lost within most of the Caledonides.

PRE-TERTIARY BURIED AND SUBJACENT KARST

Karstic unconformities are documented from the Ordovician/Silurian boundary and from the lower Silurian. Skjeseth (1963) and Henningsmoen (1960) both referred to a karstic contact between middle Ordovician limestone and lower Silurian quartzite at what is called the Mjøsa

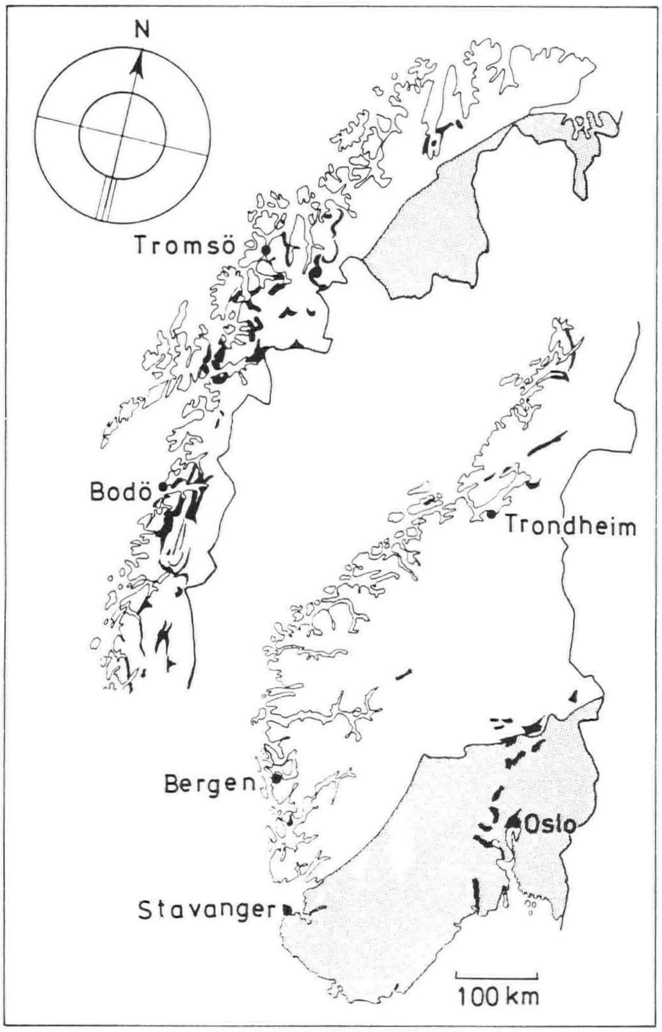
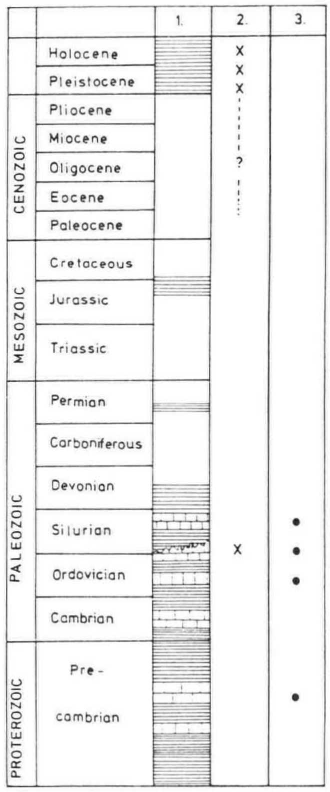


Figure 1. Distribution of carbonate outcrops in Norway. Black: carbonate rocks. Unshaded areas: the caledonian orogenic belt.

Figure 2. Stratigraphic distribution of sedimentary rocks and karstification in Norway. 1: occurrence of sedimentary deposits on the continental land surface. The relative thickness of carbonate/non-carbonate is not to scale. 2: phases of karstification through time. 3: Distribution of lithologies that show affinity to Pleistocene and Holocene karstification.



limestone/Helgøya quartzite unconformity. A section shows a paleokarstic relief with grykes and small caves within a relief of 3 m (Fig. 3).

Opalinski (1977) described this irregular contact in more detail. It is characterised as a series of pipes, cracks, bowl-like depressions, "floating" limestone blocks and deeper cave conduits, all filled in with sandstone of lower Silurian age. The vertical pipes resemble grykes, or possibly, a jagged littoral karst. They exhibit serrated walls and narrow down towards the base. The gryke forms are tens of centimetres wide, whilst the kamenitza-type forms attain a width of 1-1.5 m and a depth of 70-80 cm. Sandstone-filled caves were detected as deep as 6 m below the top of the limestone. The forms and their stratigraphy were interpreted as a phase of karstification prior to stage 6c of the middle Llandovery (Opalinski and Harland 1981).

Hanken (1974) also referred to karren-like channels and scallop-like forms in the upper Ordovician of Ringerike, South Norway. The channels were 20-30 cm wide and several metres long; they were filled in with shale and siltstone. From the lower Silurian dolomites of Southern Troms, North Norway, Bjørlykke and Olaussen (1981) reported a cave-filling breccia of bimodal size distribution and a tendency to coarsen upwards. This breccia was probably formed during the Silurian by leaching of anhydrite and gypsum resulting in a collapse and brecciation of the overlying dolomite. It is therefore possible that this paleokarst is of the subjacent (= inter-stratal) type. Lead-Zinc mineralization is associated with the dolomite breccia. Lead isotope composition in one sample of galena suggests an age of 430 m.a., which is near the supposed age of the host rock (Moorbath and Vokes 1963).

It should be borne in mind that true terrestrial facies for the known paleokarst have not been proven for any of these deposits. Rather, Bjørlykke and Olaussen (1981) suggest an intertidal environment with periodic supratidal conditions. In the author's opinion, neither the features described by Skjeseth (1963) nor by Opalinski (1977) can yet be distinguished from karstic forms characteristic of a littoral environment.

TERTIARY LANDFORMS

The youngest continental pre-Quaternary deposits known in Norway are a few small Jurassic-Cretaceous pockets on Andøya, Northern Norway (Oftedahl 1980). However thick Mesozoic-Cenozoic deposits on the continental shelf demonstrate that the continental land surface has been subjected to denudation since the early Tertiary. The remnants of this denudation are named Norway's paleic or pre-glacial surface (Gjessing 1967). On a larger scale, the paleic surface is characterised by extensive peneplanation, wide valleys or basins, and a smooth, undulating hilly topography. Glacial valleys and fjords are superimposed onto these landforms and truncate them. The paleic landforms were ascribed to a warm, probably semi-arid climate (Gjessing 1967, and references therein).

On a smaller scale, the surface bedrock in Norway is glacially polished with few sites of preserved pre-glacial sediments. However, relic weathering profiles are sometimes encountered, exhibiting a mineralogic assemblage (kaolinite,gibbsite), which may be ascribed to a pre-glacial, warm, humid climatic regime (Reusch 1903; Gjems 1963).

Roaldset et al. (1982) described gibbsite, smectite and kaolinite from a profile of in situ weathered granitic and gabbroic rocks in Western Norway. This mineralogy supports the concept of lateritic/bauxitic weathering in a warm and humid climate. Such conditions have not prevailed since the late Tertiary.

Because of the lack of dateable deposits, no decisive proof of pre-glacial karst has yet been presented. However, 60 million years or less of deep weathering should almost certainly have produced a deep karstic relief in concert with other paleic landforms. It is unlikely that these macroforms have not been able to survive the Pleistocene glaciations, even in a fragmentary form. Based on analogy with cave morphology in the semi-arid or warm humid areas of today, the likelihood for such pre-glacial karst may be proposed (Lauritzen 1983).

Most relic cave conduits in Norway are comparitively small, with cross-sectional areas rarely exceeding 20 m^2. Uranium series dating of speleothem deposits demonstrates that such cave fragments are several glacial cycles old (Lauritzen and Gascoyne 1980; Lauritzen 1984). Based on kinetic and hydraulic grounds, it is likely that such small caves may well have

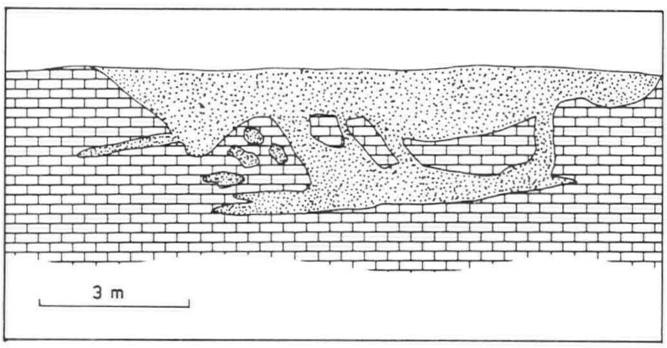


Figure 3. Buried karst in the ordovician/silurian boundary: the Mjosa limestone is deeply karstified with a fill of silurian quartzite (redrawn from Henningsmoen, 1960).

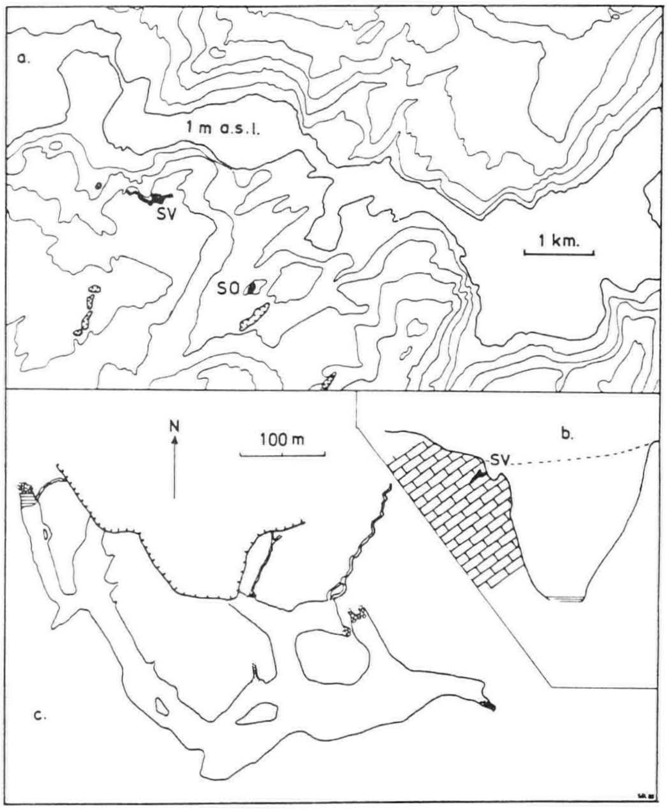


Figure 4. Probable paleokarstic cave fragments along the Fauske fjord-lake, northern Norway,
a) topographic position of the caves SV:Svarthamarhola; SO: Solvikhulen. Contour intervals 100 m.
b) schematic cross-section of the fjord and paleic (= preglacial) surface, showing the position of the conduits. Dotted line: inferred floor of the paleic valley. Vertical scale 5 times horizontal.
c) Survey of Svarthamarhola. The large conduits are extensively modified by collapse, but the original cross-sections exceed 2000 m^2 in area. Survey plan modified from Heap (1970).

developed within the glacial/interglacial sequences of the Pleistocene.

On the other hand, a few but exceptionally large cave fragments are situated in hanging positions close below the paleic surface (Fig. 4). Their cross-sectional area exceeds 2000 m^2; the gigantic size and the topographic position of these conduits distinguish them from all other caves in the country and suggest a great age. The association of the paleic plain surface and the large conduits is, for instance, strikingly similar to the situation found in the Nullarbor Plain and its caves in Southern Australia (Jennings 1967). A subsequent glacial incision into this plain would leave cave fragments in a very similar position to the Norwegian ones.

CONCLUDING REMARKS

The buried types of paleokarst known in Norway belong to the Ordovician/Silurian boundary. It is not distinctly proven whether these unconformities were true terrestrial or only littoral/supratidal types. In Northern Norway paleokarst breccias are associated with Pb/Zn mineralization. Other occurrences of mineralization within the Caledonian orogenic belt may also reflect a paleokarstic facies, although, alternatively, the genesis of primary sedimentary sulphides has been demonstrated for some deposits (Juve 1967).

Tertiary paleokarst is not yet proven by direct stratigraphic or chronological evidence, but some macroforms are very suggestive for a pre-glacial age. Systematic karst research is only just beginning in Norway, and most of the carbonate outcrops have not yet been studied in detail from this point of view.

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Geological Controls on Speleogenesis in the Marbles of Lower Glomdal, Rana, Norway

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Abstract: The lower part of Glomdal, Rana, N. Norway, contains a large number of phreatic cave segments. Many of thes are now dry "fossil" caves but others have been invaded by modern drainage and in some cases extensively modified. The caves are formed in highly deformed marbles and the geology of the area is briefly described. Both lithological and structural features of the marbles are shown to have exerted strong controls on the genesis and morphology of the caves. Major cave development is confined to the purest marble bands, the exception being development of rift type passage along major fractures in less pure lithologies.

INTRODUCTION

Lower Glomdal, in Rana, north Norway (Fig. 1), contains an area of karst developed in marbles of considerable geological complexity. In such a situation geological factors are likely to exert major controls on speleogenesis and the aim of this paper is to examine the relationships between cave development and both lithological and structural features of the marbles. The majority of the cave passage in the area is "fossil" being of phreatic origin and now abandoned and dry.

Caves and present day hydrology

The major geographical and hydrological features of the area are dipicted in Fig. 2. The lower part of Glomdal under consideration here lies to the south of the lake of Glomdalsvatnet between the steep walls of the old glacial valley. Most of the valley floor is occupied by marble karst which forms small hills up to 250m high. On the west side of the valley is the incised canyon of the Glamoga river, which takes drainage from the Svartisen glaciers southward to Langvatn. The whole of this area is below the tree line and covered by dense birch and scrub and some pine forest.

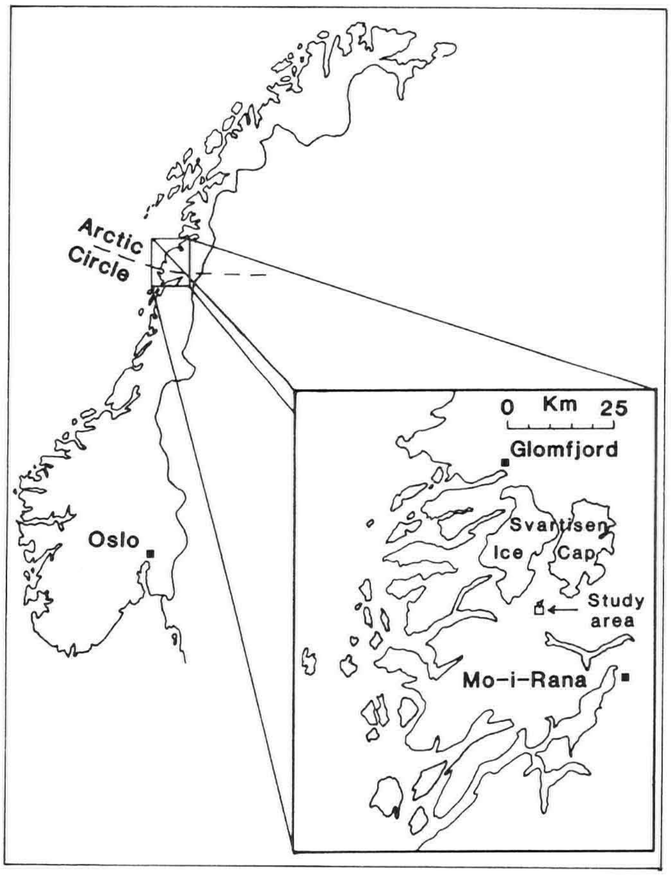


Figure 1. Location map for Glomdal.

The caves and hydrology of the central part of this area have been described by Bottrell (1987) and the underground outlet from Glomdalsvatnet described in detail by Lauritzen et al. (1985); a schematic summary of the present day hydrology is included in Fig. 2. Glomdalsvatnet is fed by drainage from Austerdalen (much reduced in modern times since drainage from Austerdalsisen glacier was diverted eastward to prevent flooding) and by water from the central Glomdal karst area. The lake drains southward through an active phreatic cave system and resurges at a small lake to flow westward into the Glomaga river. In the karst area to the south of here the main drainage is from south to north; the stream draining the fell to the east of Glomdal flows north and sinks to resurge on the south side of Glomdalsvatnet (in flood this stream overflows past the sinks and runs westwards to join the Glomdalsvatnet resurgence lake); drainage from the marshy area (Fiskjornfjellet) to the south-east of the karst sinks at Kjokkenvasken and flows through the Neverslette-systemet to resurge 1.1Km further north and join the Glomdalsvatnet resurgence water. The cave systems which carry drainage northward through lower Glomdal were not formed under the present hydrological regime but are "fossil" phreatic cave segments which have been invaded by modern drainage and in some cases extensively modified by the incision of vadose stream canyons.

GEOLOGY

The geology of the Glomdal marbles as a whole will be described in detail elsewhere (Bottrell and Lauritzen, in prep.); below is a brief summary of the different lithologies present and the main structural features in lower Glomdal.

Lithologies present

Three major lithological types were distinguished by the field mapping:

Mica schists: composed of quartz, biotite, muscovite and feldspar with occasional garnet the schist is generally fine to medium-grained and with a strong foliation defined by alignment of the micas.

Grey marbles: these are the purest marbles present, often composed of >98% calcite of 0.5 to 10mm grains with small amounts of quartz, mica and other silicate minerals. Some grey marble units are single massive beds of this pure lithology, while others are banded on a scale of 5-100mm with darker bands which are slightly richer in mica though always with >95% calcite.

Yellow marbles: these are less pure than the grey marbles and always contain a substantial (>c.20%) non-calcite component, though these units are often strongly banded with some minor bands (generally <10cm thick) which correspond to the purer grey marble compositions. The variation in mineralogical composition of the yellow marbles is wide; all these units contain calcite in varying proportions (from 25 to 75%) together with dolomite, mica and quartz. The two commonest types are a brown, rough weathering marble (containing calcite with large amounts of quartz and mica) and a paler yellow dolomitic marble. There are also thin (1-5cm) bands of essentially mica schist with little or no carbonate content.

The grey marbles occur in bands 1-5m thick and tend to be massive and lithologically homogeneous. In contrast the yellow marbles form thicker units of 3-30m which are lithologically heterogeneous, comprised of "beds" from 10cm to 5m thick of the different marble types discussed above. All of the units show variations in thickness, probably partly originating from original sedimentary variation with some tectonic effects such as thickening around fold hinges and shearing out along fold limbs.

Structure

The Glomdal marbles have been subjected to three major phases of ductile deformation and subsequent brittle fracturing. The first ductile phase produced tight to isoclinal (F_1) folds and the dominant fabric (S_1) in all the foliated rocks is axial planar to these. The second phase of folding produced tight, asymmerical folds (F_2), which fold the S_1 foliation. Both F_1 and F_2 folds have approximately N-S trending axes with generally shallow plunge. The third phase of ductile deformation produced broad open folds with E-W to NE-SW trending axes and wavelengths of hundreds to thousands of metres giving rise to a regional "warping" of the rocks.

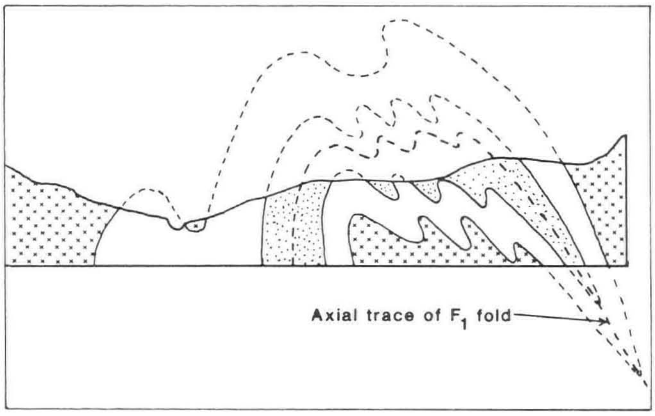


Figure 3. East - west structural section (looking north) across lower Glomdal at 757 north (Fig.4). Key as for Fig.4 Some effects of F_3 deformation have been omitted for clarity.

The major brittle features are N-S trending fracture zones which generally show little (max. 5m) or no displacement. Additionally there are complex joint and fracture patterns in the marbles. These are often highly consistent within small areas (c. 10m x 10m) but show no consistency over larger distances, suggesting that they were formed in a response to local rather than regional stress fields. Both minor shear and tensional fractures were identified.

The first two phases of deformation were almost coaxial and therefore result in a relatively simple outcrop pattern, dominated by the asymmetric F_2 folds and resulting in a series of N-S trending bands which generally dip to the east at between 30° and 60°. However the major bands are repeated around F_1 folds, as shown in the E-W section in Fig. 3. The major effect of F_3 folding in the area is a gradual lessening of the general angle of dip fron north to south.

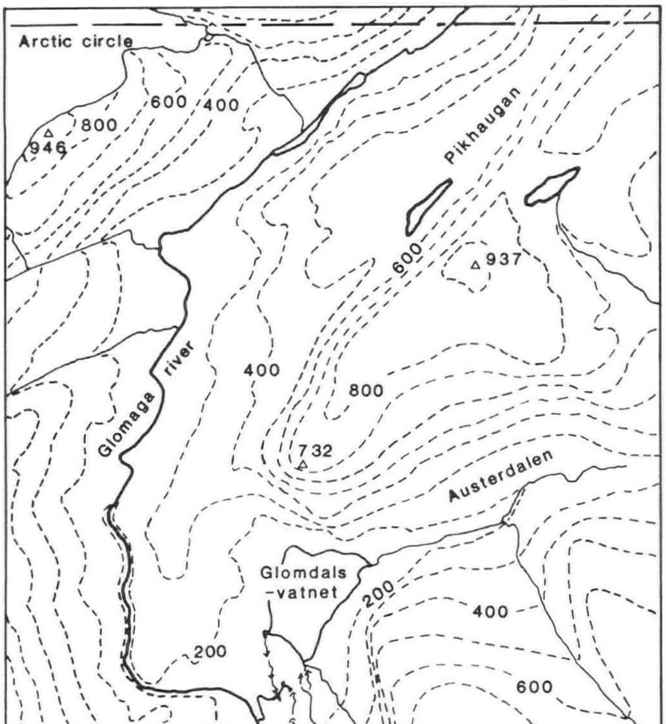


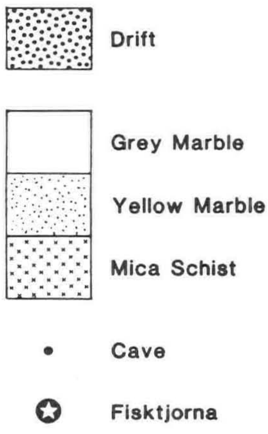
Figure 2. Map of the Glomdal area. Contours and summit altitudes in metres a.s.l. Known underground drainage routes in the area of interest are indicated with wavy arrows.

GEOLOGICAL CONTROLS ON THE GENESIS OF THE PHREATIC CAVES

The Glomdal marbles have little primary porosity; however solution takes place by the flow of aggressive water along planes and lines of secondary porosity. The rate of enlargement of the initial porosity will be determined by a variey of factors; the interconnectivity and hydraulic conductivity of the initial voids and their orientation relative to the hydraulic gradient may be important in determining early flow paths and the initial flow rates. Chemical factors will also be important; the mineralogical composition and mineral texture of the rock will determine the rate at which void walls are corroded. In Glomdal the presence of a variety of marble lithologies interbedded and interfolded gives an ideal opportunity to assess the importance of lithological variation in speleogenesis, while the complex structure and fracture patterns give ample opportunity for structural control of passage formation.

In general, geological controls on speleogenesis can be divided into two types; lithological controls, where compositional variation exerts an effect on speleogenesis, and structural controls, where structural features such as fractures, shears or position of cave passage relative to folds may be important in determining cave development. In this discussion

Figure 4. Simplified geological map of lower Glomdal (based on mapping by S. Bottrell in 1984 and S. Bottrell and S.-E. Lauritzen in 1986) showing distribution of known caves (from Lauritzen, 1983 and Bottrell, 1987). Grid is Norwegian UTM.



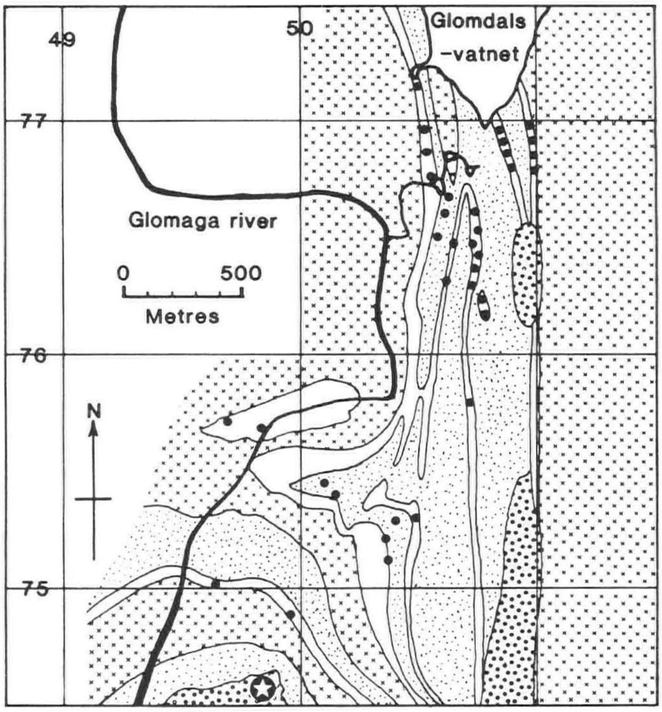
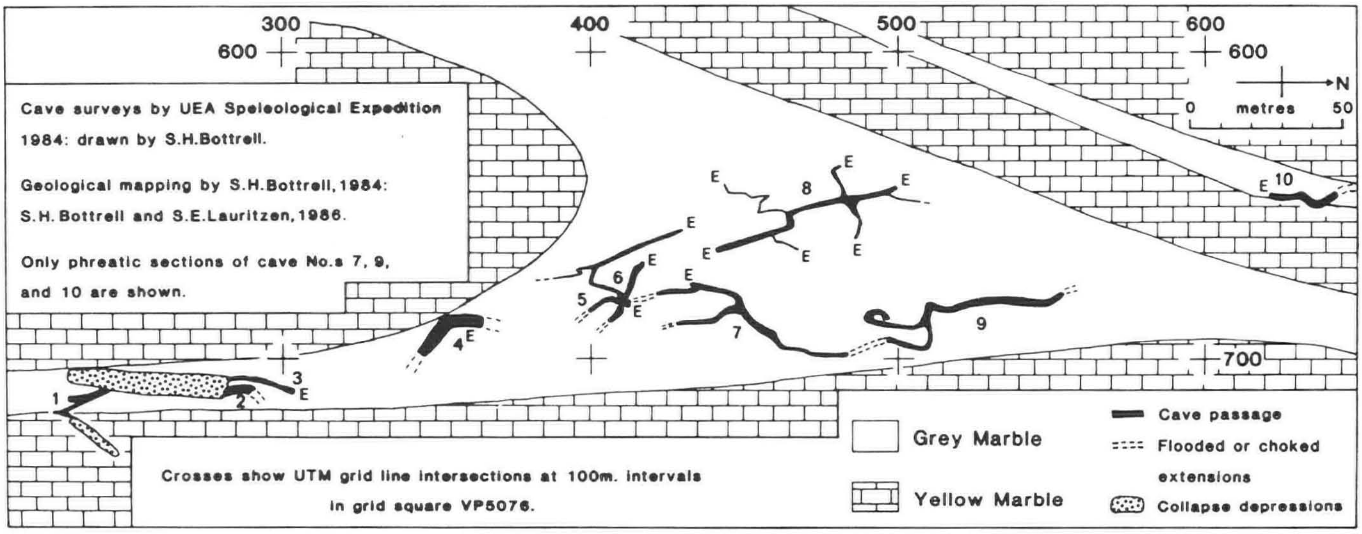


Figure 5. Geological map of the Neverslette area of lower Glomdal with superimposed surveys of phreatic cave segments.



the effect which geological features have on speleogenesis is also split into two categories:

i) "Genetic" controls, which determine the site of cave development.

ii) "Morphological" controls, which determine the nature and geometry of the passage which is formed.

In assessing the potency of different geological variables to control speleogenesis in the Glomdal marbles only the phreatic sections of the caves are considered since these caves can be considered "primary", the vadose caves carrying present day drainage are, in general, modified from pre-existing cave passage and therefore of a "secondary" origin.

Lithological controls

Cave passage is found in both the grey and yellow marble lithologies but not within the non-carbonate schist. The most effective test for a genetic lithological control on cave formation is to compare the distribution of known cave passage between the different lithologies. This test is only rigorous if certain implicit assumptions are satisfied. The first assumption is that structural variables are effectively constant between the different rock types. The different marble bands are are all intimately interfolded (see Fig. 3) and hence variation due to steepness of the dip or position within fold structures is virtually eliminated. Fracture patterns within the different marbles are similar and major fractures persist through different units so differences in fracture type or density are unlikely to be important. The second implicit assumption is that caves in different marble types have the same preservation potential, otherwise a sampling bias may be introduced. This is more difficult to address, but again the interfolding of the units should ensure that cave passage has not been lost at differential rates from different marbles by subsequent preferential erosion of one rock type.

The positions of known caves in the area relative to the different marble lithologies are illustrated in Figs. 4 and 5. Fig. 4 shows the whole of lower Glomdal and the positions of the caves. In general the individual caves are developed within a single unit, though in Kjokkenvasken there is a significant amount of passage developed in yellow marbles to either side of the thin grey marble band in which the main cave is formed and the Bjornhagen caves are located at the upper contact of a grey marble and partly formed within the overlying yellow marble. The preferential development of cave passage in the grey marble is clear from Fig. 4 and Fig. 5 shows how the best preserved area of the fossil phreatic system, in the Neverslette region, is essentially confined to one grey marble band. Here the yellow marbles act almost as aquicludes as can be seen in Anneksgrotte where the phreatic tube rising from the downstream sump pool rises through the grey marble band to its junction with the yellow marbles then follows this plane (Fig. 6a). Similarly, parts of the other phreatic tubes are controlled by the lower grey/yellow marble junction (Fig. 6b). These caves exhibit lithological controls similar to the control of the Glomdalsvatnet outlet cave by a micaschist aquiclude as described by Lauritzen et al (1985). Where cave development has occurred in the yellow marbles it has often proceeded along specific bands within a unit (often the calcite-mica-quartz lithology, see examples under lithological control of passage morphology, Fig. 7b below) demonstrating further the high degree of lithological control on the location of cave development.

Structural controls

The type and degree of structural control on genesis of cave passage may be analysed in two ways, One is to make detailed observations within the cave of the relationship between structural features and the position of cave passage (e.g. the identification of "guiding fractures"). The second approach is to compare the directions of cave passages, from cave surveys, with stuctural data from the surface. The latter method may be regarded as more quantitative as the two sets of data may be compared statistically (though unfortunately sample bias may easily be introduced to the structural data taken on surface as fractures approximately at right angles to the outcrop surface are far more easily noticed (and measured!) than those sub-parallel to it). In the highly deformed marbles of lower Glomdal the second approach is also limited by the variation in fracture pattern over distances as small as c. 10m, only the major N-S fracture zones are consistent over the whole area. The following discussion relies on the first, relatively qualitative, approach to this problem.

Guiding fractures can be identified for almost all of the cave passages formed in the thick grey marble band in the Neverslette region. Observation underground indicates that the commonest fracture trend followed is the approximately N-S trending set as may be seen from the orientation of passages in the surveys on Fig. 5. Approximately 50% of the passages in the caves are aligned in this direction with the remainder following other fracture trends. In the thinner marble bands to the south of Glomdalsvatnet the caves generally follow fractures other than the N-S trending set (though the amount of passage which may be entered here is small). In Kjokkenvasken many rift passages in the relatively thin grey marble band do not appear to have followed major fractures, though others have followed both the N-S trending and other fracture sets.

DISCUSSION

The observations noted above shows that both lithological and structural features of the Glomdal marbles have exerted controls on the genesis of cave passage. In these marbles, where a wide variety of lithological types are present within the sequence, the lithological controls are particularly important. Most cave formation took place in the grey marbles (or within purer bands in the yellow marbles) with less pure marbles often acting as aquicludes. In these cases fractures are of a secondary importance: they determine the position and orientation of passages within the speleogenic horizons. This geological situation differs markedly from many cases where speleogenesis within massive homogenous limestone units has been investigated and fractures exert a dominant control in a lithologically isotropic medium for speleogenesis (e.g. Senior, 1987, and general comments in Lowe, 1987). In Glomdal exceptions are found where fractures have been utilised to form rift type passages crossing through less pure marble types: here the fractures clearly exert the dominant control.

Controls on passage morphology

Factors controlling passage morphology have been assessed by detailed study of the inter-relationship of geological features and passage form. Phreatic passages developed in an isotropic medium would have an ideal tubular form, but geological controls on morphology may be identified where phreatic passages deviate from this ideal due to the influence of geological features.

Lithological controls. Where phreatic passages have developed totally within the grey marble lithology (even along a guiding fracture) a close approximation to an ideal tubular form is generally found. In the colour-banded variety of this lithology the additional small proportion of mica appears to have no noticeable effect. Where the passage forms at the junction of the grey and yellow marbles minor modification of the passage section is apparent (Fig. 6). Even where passage is developed in a single lithological unit within the yellow marbles near perfect tubes are developed (Fig. 7a). However once the passage dimensions reach the confines of the speleogenic band major modification of its morphology takes place, as enlargement is constrained to procede within one horizon (Fig. 7b). As would be expected, resistant quartz and mica rich bands weather out in units with compositional banding on a scale smaller than passage dimensions.

Structural controls In the majority of cases cave passage has formed along fractures within the marbles and thus the position and orientation of the phreatic passages is structurally controlled. The exceptions are "bedding-rift" passages which have formed by dissolution of a single band within the marble where passage morphology is lithologically determined. Modification of the sectional shape of the phreatic conduits along structural features ranges from negligible for many tubes in the grey marbles to extreme in the case of entirely fracture-controlled rifts in the yellow marbles. Virtually all intermediate degrees of passage modification along fractures are seen, as "drawn out" or lenticular sections enlarged along the fracture direction. A common

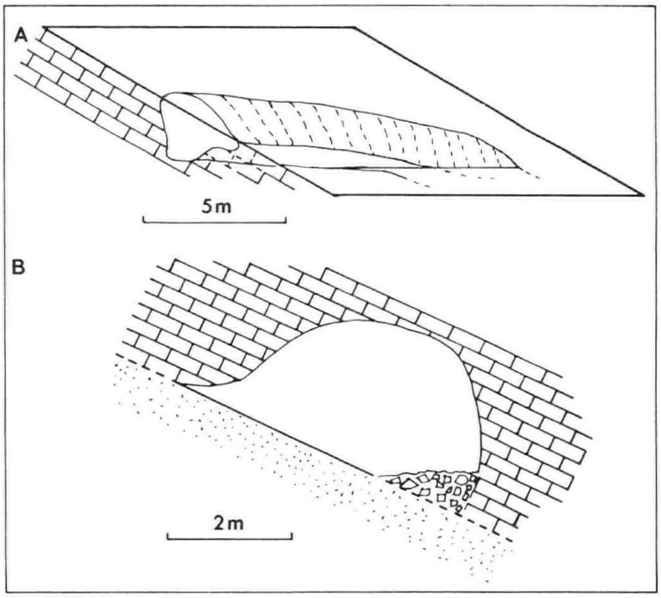


Figure 6. Modification of passage sections of contacts of grey and yellow marble lithologies. Grey marble denoted by brickwork pattern. A shows the passage above the downstream sump in Anneksgrotte, where the yellow marble overlying the grey acts as an aquiclude. B shows modification of passage section at base of grey marble band (yellow marble shown stippled).

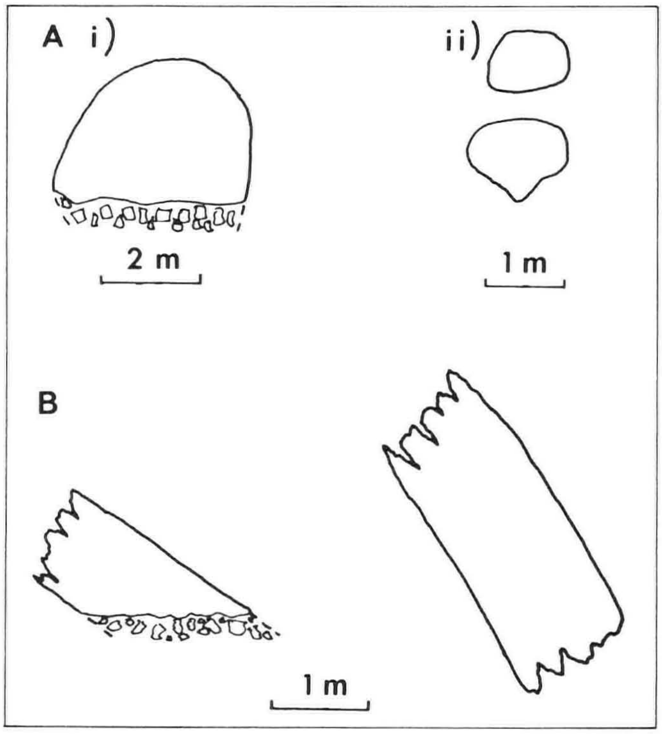


Figure 7. Phreatic passage sections in yellow marbles. (A) shows tubular sections where passage section is unaffected by lithological variation: (i) is a large choked passage (Loc.14, Bottrell 1987; (ii) are passages from the Galleries Francais. Kjokken-vasken). (B) shows passage sections restricted to one lithological band (Kjokken-vasken).

feature of the tubes in the grey marbles is the development of enlarged sections or small chambers at intersections of the main guiding fracture with other oblique fractures.

Thus in the grey marbles passage orientation is controlled by fractures but there is generally little modification of passage section except where a yellow marble unit acts as an aquiclude. In the yellow marbles both lithological and structural features have exerted controls on passage orientation and morphology.

CONCLUSIONS

From the discussions above it emerges that lithological variation is the single most important control on speleogenesis within the marble sequence. The speleogenic grey marbles are almost pure calcite and therefore more susceptible to corrosion than the less pure lithologies, which contain both less readily soluble dolomite and insoluble silicate minerals. Within the grey marbles passage orientation is controlled by fractures which presumably provided the initial secondary porosity for water flow. Given that the initial secondary fracture porosities within both yellow and grey marbles were probably similar then the higher corrosion rates of the latter lithology will allow more rapid development of a conduit network. Once an interconnected conduit network had been established in the grey marbles its high hydraulic conductivity would allow most flow to be accomplished via this route, reducing flow through the less well-developed networks in the yellow marbles and thus retarding further conduit development.

The north-south fracture sets are more widely utilised for passage formation than other fractures and provide the major pathway for cave development in the yellow marbles. These fractures may be particularly speleogenic for two reasons:

i) where these fractures have been examined in detail they are found to be comprised of a zone of many minor fractures from 0.5 to 1m wide. These minor fractures are well interlinked and would provide an initial flow path with relatively high hydraulic conductivity. Other fracture types are either simple fractures or very narrow fracture zones.

ii) these fractures are continuous for considerable distances in the north-south direction. Paleoflow direction in the phreatic systems was dominantly north to south, so these fractures were aligned close to hydraulic gradient.

Both these effects would tend to produce a high initial flow through these fractures at the earliest stages of conduit formation. This high initial flow appears to have been sufficient in some cases to outweigh the lower corrosion rates of the yellow marbles and lead to significant conduit development in this lithology.

ACKNOWLEDGEMENTS

I would like to thank those who supported two years fieldwork in Glomdal: the Bill Bishop Memorial Trust, Sir Phillip Reckitt Educational Trust, British Geomorphological Research Group (all 1986) and the Ghar Parau Foundation (1987). Thanks are also due to Stein-Erik Laritzen for advice and discussion at various times.

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A History of Cave Exploration and Study in Norway

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Abstract: The history of cave exploration in Norway can be divided into four main periods: c. 1870 - 1941 mainly by Norwegian geologists, archaeologists and naturalists particularly John Oxaal and Gunnar Horn; 1951 - 1965, with the notable exception of Jean Corbel by, mainly British, caving club, school and university expeditions; and 1965 to date, with continuing exploration by foreign cavers, particularly the British, but also including Swedish and French expeditions, and increasing activity by Norwegian cavers and speleologists. There were reports and descriptions of caves prior to 1870 and details of some of these are given. The article is based on information recorded in the *Norwegian Cave Index and Karst Bibliography* started in 1963 and collected by research, correspondence and during 20 caving expeditions to Norway.

Karst caves are commonly found throughout Norway wherever the Cambro-Silurian marble outcrops occur. However it is in the county of Nordland between the parallels 65°N to 69°N where the greatest number have been recorded (Figure 1). Sea caves, usually fossil, left high above the present sea level, are common in other rock types along Norway's coastal margins (Sjøberg, 1988) and caves caused by frost-wedging, landslip and weathering also occur (Schrøder, 1988). Caves in glacial ice are common but because of the retreat of the glaciers many of those described in the literature have already disappeared or changed (Theakstone, 1988). This history of the exploration, survey and study of Norwegian caves is based on information recorded in the *Norwegian Cave Catalogue and Bibliography* started by Shirley St. Pierre and the author in 1963. At the present time this records more than 2000 caves and references to caves. Space precludes a complete account and some important items may have been omitted.

An earlier article in *Cave Science* details the exploration and survey of 23 Norwegian caves over 100 m deep and 34 caves over 1000 m long (St. Pierre & St. Pierre, 1985).

Early History: 12th Century - 1870

References to Norwegian caves can be found scattered throughout the early literature. In the 12th Century *Orkneyinga Saga* (translated by Palsson & Edwards, 1978) mention was made of a visit to the Dollz hellir (Dolsten Cave, pp. 101 & 208) by Kale Kolssøn, afterwards known as Rognavald, Earl of Orkney, who went there in search of treasure supposed to have been hidden in the cave on Sandøen, near Molde on the west coast (D7 Fig. 1).

In south Norway, Mikaelshulen, situated in a steep cliff on the east side of Norsjø, Telemark, was described by Bishop Øystein in the 14th Century when it was in use as a church. Ludvig Holberg was inspired by a small cave near Bergen when he wrote his novel *Nicolai Klimii iter subterranium* (Niels Klim's journey under the ground) in 1741 (Hjorthen, 1981, St. Pierre, 1981) and *Norges Naturlig Historie* by Dr. Erich Pontoppidan (1752, pp. 76-80) included descriptions of "Dolsteen Huule", Torghattenhulen (Fig. 1 - D9, and also the limestone cave Limurshulen. Gerhard Schøning mentioned the cave in Undershaug, Snåsa, in the description of his travels in the 1770's and Hammer (1797, pp. 101-106) noted several small caves including Jutullet near Lundberg, Oppland.

By the 1800's cave references became more common. Further descriptions of the Dolsteen Cave

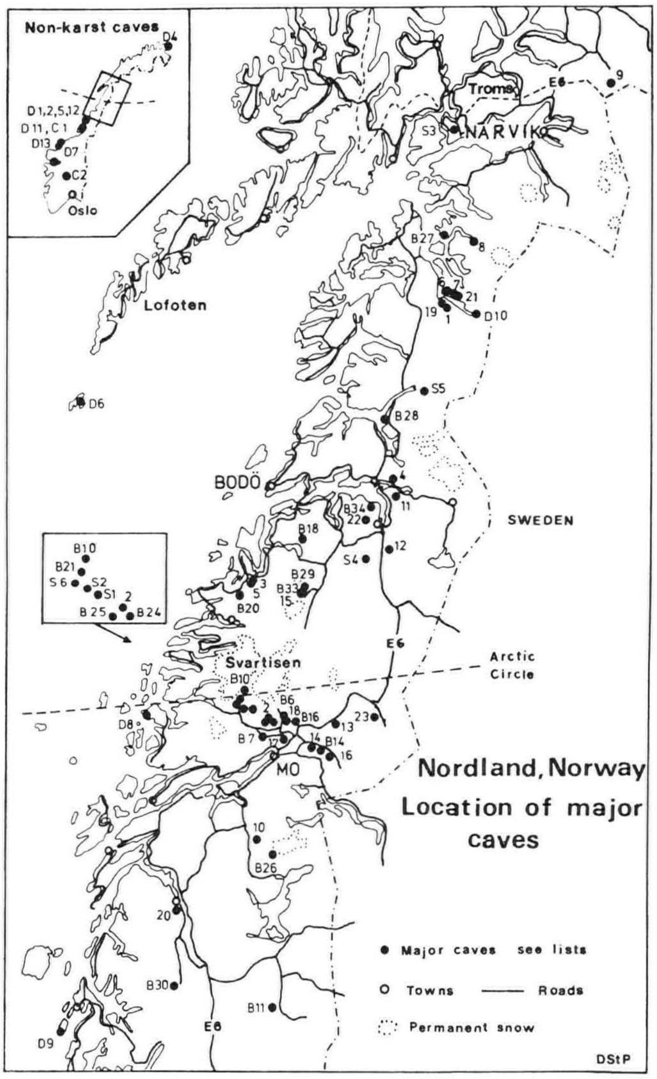


Figure 1. Map of Nordland (Norway inset)

were published e.g. by T. Smith (1803, pp. 270-271) and by A. de Cappell Brook (1823, pp. 208-212) who also described Torghattenhullet the well known fossil sea cave piercing the hillside near Brønnøysund. Descriptions of Limursholet by Bishop Neumann appeared in *Budstikken* (1825), the "cold and warm holes" at Ouse by Hertzberg in the *Magasin for Naturvidenskaberne* (1926) and the "løngang" at Orstaeidet, by M. Aarflot (1846) and Stiftamtmand Christie (1847).

B. M. Keilhau (1832) briefly described the underground course of the Renseleven at Vallervatn and Bishop Neumann (1837) also recorded Skjonghelleren (D 13 Fig. 1), Dollsteinhulen, Sinnerhilleren, Jutulsgrotten and Lammetun-hule. In 1865, Theodor Kjerulf mentioned Kinne-kloven, Sogn & Fjordane, and jordbru (rockbridges) in Nordland and at Boeverdalen, and D. Krefting, described Horbakhulen. *The Knapsack Guide to Norway,* published by Murray (1872) included a description of Torghatten and stated that "in several districts of Nordland the rivers flow in subterranean passages for some distance, and then reappear; the two largest of these are Jardbruelv, in Saltdal, and the Prugra, in Ranen".

1870-1941

Larshølet (Norway's second deepest cave - 2 Fig. 1)) was discovered by Lars Bjornes in the 1870's and the nearby Lapphølet (B25) together with Grønligrotta (B9 - a tourist cave since the 1870's) and Risagrotta (part of the Hammernesgrotta system - B7) was noted in

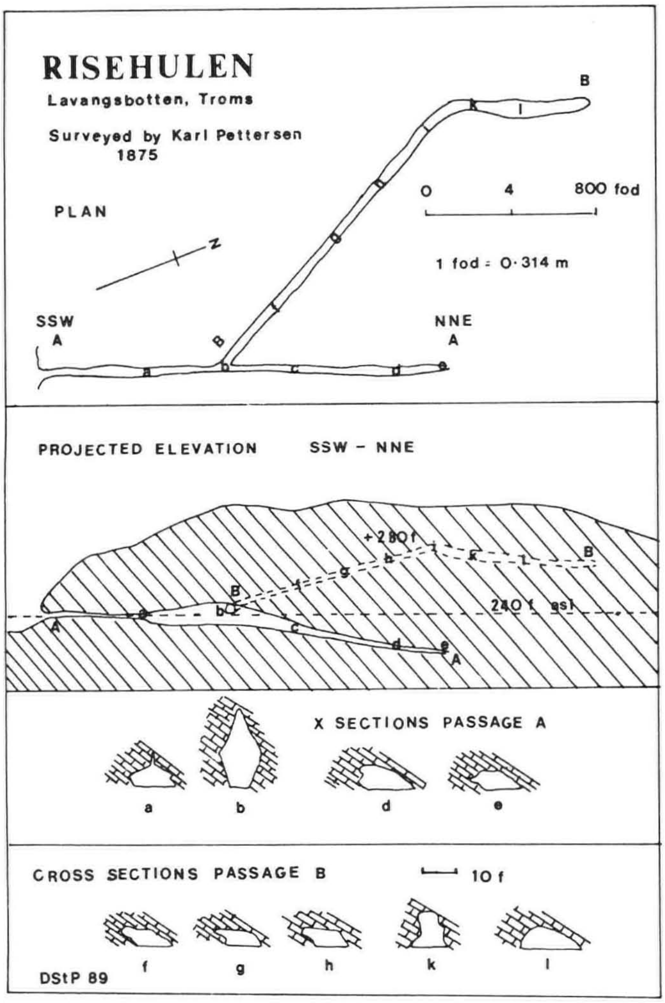


Figure 2. Pettersen's 1875 survey of Risehula.

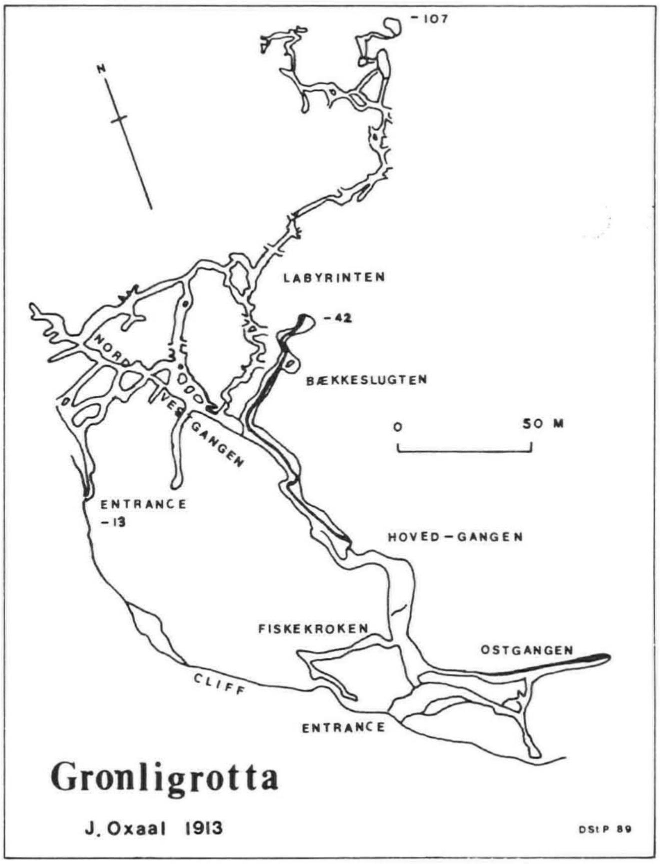


Figure 3. Oxaal's map of Grønligrotta

Tønsberg's *Illustrated handbook for travellers* in Norway published in 1875. Corneliussen visited Laphullet in 1874 and published descriptions in 1875 and 1891. An unpublished description of a visit to Risehula, Troms Fylke by Aslachsen in 1873 was given by Pettersen (1876) (Fig. 2). Hans H. Reusch (1874) described Kårahola near Hermansverk, Sogn & Fjordane and his *Traek af Havets Virkninger paa Norges Vestkyst* (1877) included many surveys, illustrations and descriptions of fossil coastal caves. Princess Therese of Bayern reported Bubbelen a pseudo-karst resurgence at Bognelvdalen, Finnmark in 1889 and "En eiendommelig huledannelse i Graataadalen i Beiren" was described by Johann Vibe (1892), (B19). The nearby Løvstadgrotta, discovered in 1862 has been a minor tourist attraction since 1923 though it is now closed to the public.

The publications of the Norwegian Geological Survey (Norges Geologiske Undersøkelse) started appearing in the 1890's. In 1891, No. 4, *Om Nordlands amts Geologi* included Corneliussen's description of Risagrotten, Grønlihulen and Laphullet and No. 22, 1897 *Norsk Marmor* by J.H.L. Vogt was a detailed description of the limestone outcrops and marble industry. Caves and underground streams were briefly mentioned, and included Laphullet, Grønligrotta and Risagrotta in Rana, Risehulen at Lavangsbotn, Limurhulen near Storfjorden, Marmorgrotta and Troldgrotten in Fraena and, with a map, the underground course of Kvanndalhola in Skjerstad.

Much of this early work was referred to in the volumes of *Norges Land of Folk* particularly in the sections *Huler* (Caves) and *Elv som gaar under jorden* (Underground Rivers). Published around the turn of the century these were statistical topographical descriptions of each of the Norwegian fylker (amt. before 1918 - counties *Eng.*) many of which were edited by Amund Helland.

Th. Petersen described the archaeological significance and iron-age deposits of a number coastal caves, e.g. Solsemhulen, Fingalshula, Svarthulet and Haugshulen in Nord-Trondelag during the period 1910-1926. However, the first serious speleological study published on Norwegian limestone caves was the work of the geologist John Oxaal who studied caves in the Rana district of Nordland in the early 1900's. *Kalkstenhuler i Ranen*, (1914) contained a systematic description and survey of Grønligrotta (Fig. 3) as well as brief descriptions and surveys of other caves including Larshullet, Lapphullet and Bredekhulen together with his theories as to the initiation of the caves during the last interglacial with major development at the glacial margins. Some discussion of his ideas took place at meetings of the Norsk Geologisk Forening.

John Rekstad's geological memoirs included a number of references to sea caves, limestone caves and underground rivers (1910: 14-16; 1912: 8 & 57-68; 1913: 25-26). L. Reinhardt Natvig published descriptions with surveys of Ravnaagrotten (1916) and Hammernesgrotterne (1923) in Den Norsk Turistforenings Arbok after he had explored the caves with Ole and Niels Ravnaa who collected the skeletal remains of bears and other animals in the local caves (Horn, 1947: 67-68).

Norges Steinalder by Gutorm Gjessing (1940) included many references to the caves and rockshelters such as Vistehåla, and Kirkhellaren, Traena in which archaeological finds had been made.

I. Rye of the Institute of Physical Geography, Oslo University prepared the manuscript on his studies of the karst caves in the Rindal area south west of Trondheim in 1941. The classic description of Norwegian caves however was Gunnar Horn's "Karsthuler i Nordland", published in 1947 (after his death) by the Norges Geologiske Undersøkelse. Horn explored, surveyed, studied and published articles on caves in the Rana district, and near Navnløsvatn, Meløy herred, between 1933 and 1939. He distinguished between the vadose (active) caves and those particularly in the Rana district which had been developed under conditions of complete waterfilling. Now drained and often with glacially truncated entrances he proposed a largely subglacial development for them.

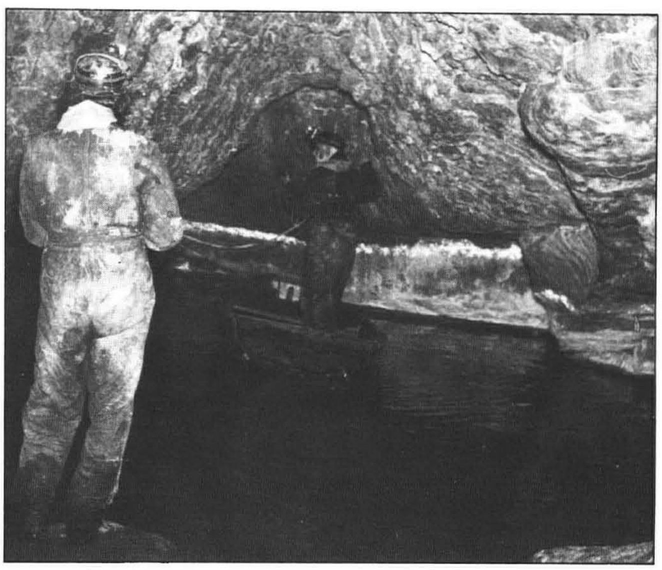
1941-1965

Horn's work attracted the attention of foreign cave specialists and students notably Jean Corbel and Lewis Railton who visited Nordland in 1951. Together with Odd Stormo, Anton Svartisdal and Marjorie Railton they extended Larshullet to a depth of 326 metres which was at that time the world's sixteenth deepest cave. Professor Corbel made an extensive study of the Norwegian karst including Svalbard and his work was included in *Les Karsts du Nord-Ouest de l'Europe* (1957), a major treatise which considers the role of climate in the erosion of the limestone. In general Corbel proposed a recent development of the caves, often in relation to a falling permafrost level, in the wet conditions following the recent deglaciation of the area.

Cambridge University Caving Club Expeditions visited the south Svartisen area of Nordland in 1956, 1957 and 1958. The expedition members included Oliver Wells who published descriptions and surveys of Larshullet and Lapphullet in the C.R.G. Transactions (1957); R.J. Kirkland who wrote his B.A. dissertation on the South Svartisen Karst (1958) and supported Horn's views; and David Jenkins (1959) who published a description and survey of Pikhauggrottene (B10) which was extended from 230 m as surveyed by Gunnar Horn to more than 2000 m. Kirkland considered that cave origin took place during the Tertiary period beneath the water table; pseudo-phreatic development proceeded beneath the Pleistocene ice-sheets, with perhaps limited development during interglacial phases, and that the present phreatic features dated from the last glaciation with periglacial vadose modification during the post-glacial period. Jenkins suggested that it was equally possible in the case of the Pikhaugane caves that they had formed as an outlet for a proglacial lake. The work of these early expeditions was summarised by Wilf Theakstone (1964) and by Shirley St. Pierre (1967). A subsequent Cambridge Expedition in 1961 visited the vast limestone plateau extending north west from Navnløsvatn. (Hansen, 1962, St. Pierre, 1983). David Heap who has made many subsequent major explorations in Norway was a member of this expedition which found mainly small active caves at very shallow depth.

In 1962 and 1964 parties from the Haberdasher's Askes School, (London) extended Jordbrugrotta (B3) in Plurdal, Rana to a length of about 3000 m (Poston & Williamson 1964, Wolfe 1967). This remained the longest surveyed cave in Norway until the discovery of Okshola-Kristihola (B1) by Ulv Holbye in 1967 and its subsequent exploration (Heap, 1970, 1988) and Greftkjelen (3) (Heap, 1972, 1988; Holbye, 1983; St. Pierre, 1984).

The first SWETC Caving Club expedition visited Norway in 1963. Concentrating on Graataadalen, a remote valley in Beiarn, approached at that time only by sea, they explored, mapped and studied over 40 caves including Rønnålihølet (15), Stormdalhølet-Jordbruhølet (B29) and Satisfaction Cave (B33) in an area of 2 km^2. At the end of the expedition David St. Pierre and Shirley Drakes walked south along Blaakaadal to visit caves in the Grønli area



Surveying in Lovstadgrotta, 1963.
Shirley St. Pierre & Jennifer Watkinson.

of Rana. In 1964 they returned to south Svartisen with Dick Kirkland before visiting Graataadal, and in 1965 they made a 600 m extension in Setergrotta (B6), (St. Pierre, et al 1966).

In 1965 other explorations in Norway were carried out by the Northern Speleological Group (A14),(Mitchell, 1966); Ermysteds Grammar School, Skipton (Heap, 1965) and Orpheus Caving Club.

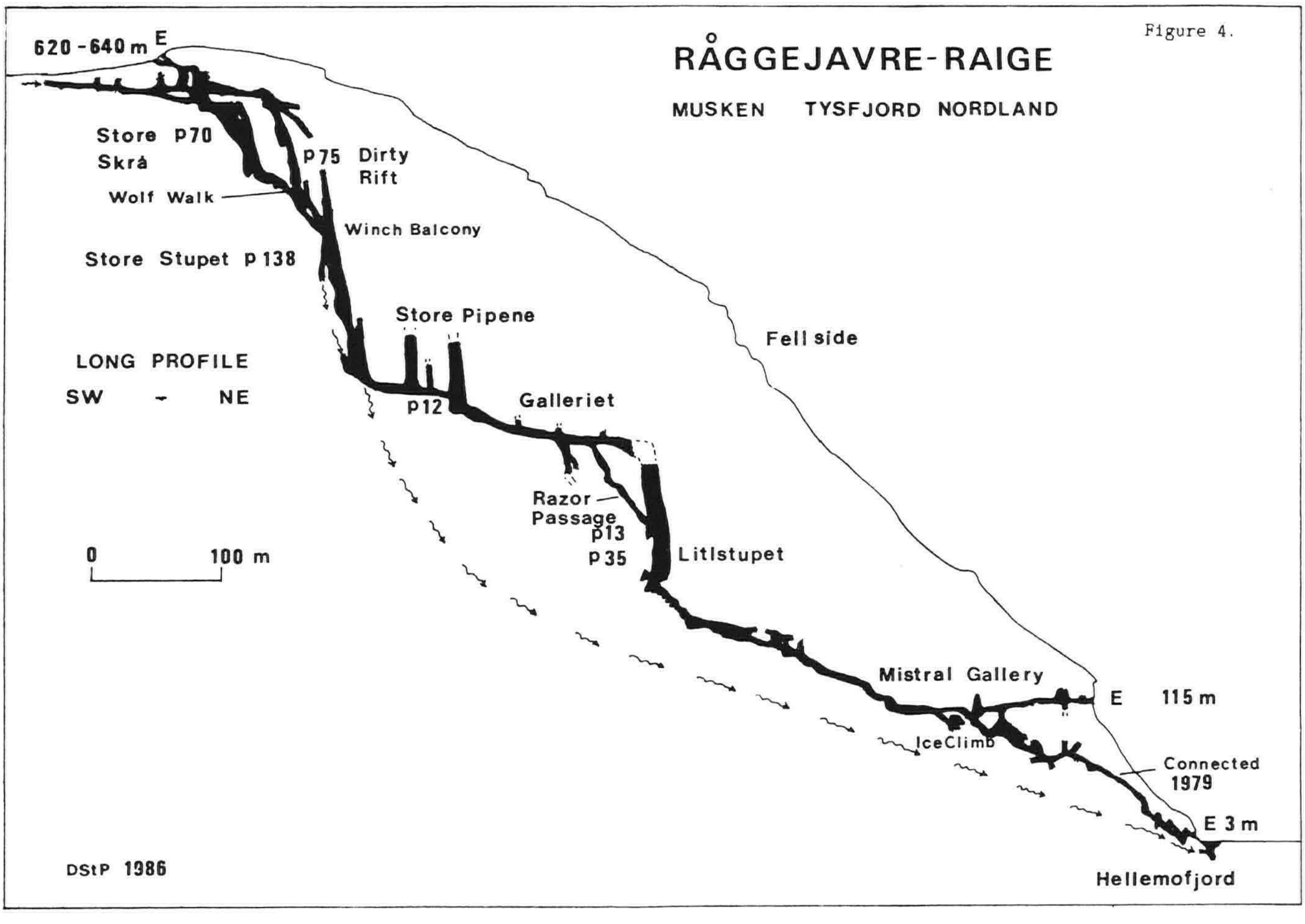
1965 to 1989 - A brief history

The increasing activity and contacts with local caving enthusiasts generated by the Tourist Office at Mo i Rana led to the formation of Rana Grotteklubb in 1966 and Mo Speleologisk Selskap in 1968 (Hjorthen, 1968). *Caves of Rana* (St. Pierre & St. Pierre, 1969; 1972) now out of print, described what until then had been Norway's most important caving area.

Other British Clubs began to take an interest in Norway, notably Eldon Pothole Club (since 1966), the Gritstone Club (since 1970), Craven Pothole Club (1971) and the SWETC and Kendal interest continued. Expeditions from other countries particularly France, Sweden and Poland (to Svalbard) also began to appear regularly. (See for instance: Stchouzkoy et al, 1967, who also made detailed karst water analyses in the Rana district; Andreasson, 1984; and Pulina, 1982).

Råggejavre-raige (1), Norway's deepest cave (Fig. 4), was noted by the Norwegian geologist Steinar Foslie in 1942 but it was not explored until 1968/69, by Kendal C.C. (Heap, 1970, 1988) and in 1976 a small party of Norwegians abseiled through the system (Grønlie et al, 1977). The cave was connected in 1979 to a lower fjord-side entrance by a small British party (Rogers, 1980) to give a classic 620 m deep through trip since repeated by other groups from Norway, Belgium, Britain, France and Sweden (St. Pierre, 1988). The first issue of the national caving journal *Norsk Grotteblad* appeared in 1977 and the national speleological society Norsk Grotteforbund was founded in 1981. The Norwegian Karst Research Project was initiated by Stein-Erik Lauritzen in 1977 and has produced a number of important karst research papers (e.g. Lauritzen, 1983). A Norwegian Sump Index was published by Trevor Faulkner in 1979. In 1982 the first of a series of cave diving expeditions visited the Glomdal area (St. Pierre, 1982; Lauritzen et al, 1983) and materials were collected for palaeomagnetic studies (Noel and St. Pierre, 1984, Løvlie et al, 1988). Comprehensive collections of invertebrates from Norwegian Caves have been made since 1984 by Finnish biologists (Hippa & Koponen, 1988) and by Norwegian biologists (Østbye, et al, 1987). An arctic and alpine karst symposium was held in Oslo and in the field in 1983 (Lauritzen et al, 1984).

The main British activity in recent years, often in co-operation with Norwegian cavers, has been by members of the Hemel Hempstead, Gritstone, Kendal, "SWETC", Westminster and Wessex caving clubs and the South Nordland Expeditions organised by Trevor Faulkner. The Norwegian cavers active today are found in clubs and small loosely knit groups such as Bodø og Omegn Bre-, Tinde- og Grottegruppe, Båsmo Grotteklubb, Harstad Grotte og Klatreklubb, Rana Turistforening Fjellsportgruppe, Østlandske Grotteklubb, and those at Beiarn,



NORWAY'S LONGEST AND DEEPEST CAVES 1914

LONGEST			
Grønligrotta	(18)	Rana	1210 m
Larshølet	(2)	Rana	465 m
Lapphølet	(B25)	Rana	340 m
Halvikhulen	(D1)	Osen	340 m*
Gutvikkirken	(D2)	Austra	325 m**
Hammarnesgrotta	(B7)	Rana	300 m***

* Fossil sea cave, Sør Trøndelag.
** Fossil sea cave, Nord Trøndelag.
*** 445 m 1915.

DEEPEST			
Grønligrotta	(18)	Rana	-107 m
Larshølet	(2)	Rana	-82 m

NORWAY'S LONGEST AND DEEPEST CAVES 1947

LONGEST			
Larshølet	(2)	Rana	2300 m
Hamarnesgrotta	(B7)	Rana	2200 m
Grønligrotta	(18)	Rana	1500 m
Setergrotta	(B6)	Rana	1500 m
Olavsgrotta	(B24)	Rana	425 m
Stokkvikgrotta		Rana	400 m
DEEPEST			
Larshølet	(2)	Rana	-284 m*
Grønligrotta	(18)	Rana	-107 m
Hamarnesgrotta	(B7)	Rana	-80 m

* Depth plumbed to - 293m.

NORWAY'S LONGEST AND DEEPEST CAVES 1967

LONGEST			
Jordbrugrotta	(16)	Rana	3000 m
Larshølet	(2)	Rana	2900 m
Setergrotta	(B6)	Rana	2400 m
Hamarnesgrotta	(B7)	Rana	2200 m
Grønligrotta	(18)	Rana	2000 m
Pikhauggrotta	(B10)	Rana	2000 m
Lapphølet	(B25)	Rana	1000 m
DEEPEST			
Larshølet	(2)	Rana	-326 m
Jordbrugrotta	(16)	Rana	-130 m
Krystallgrotta	(14)	Rana	-115 m
Grønligrotta	(18)	Rana	-107 m
Øvre Svartvassgr.		Beiarn	-97 m

NORWAY'S LONGEST & DEEPEST CAVES 1988

LONGEST			
Okshola/Kristihola	(4)	Fauske	9500 m*
Greftkjelen	(3)	Gildeskål	4282 m**
Greftsprekka	(5)	Gildeskål	3800 m***
Jordbrugrotta	(16)	Rana	3000 m
Larshølet	(2)	Rana	2900 m
Setergrotta	(B6)	Rana	2400 m
Hamarnesgrotta	(B7)	Rana	2380 m
Salthulene	(8)	Tysfjord	2056 m
Sverrehola	(S5)	Sørfold	2016 m

* Estimated length 11000 m.
** Estimated length 5140 m.
*** Estimated length 4440 m.
Plus 25 caves 1000-2000 m long.

DEEPEST			
Råggejavre-raige	(1)	Tysfjord	-620 m
Larshølet	(2)	Rana	-326 m
Greftkjelen	(3)	Gildeskål	-315 m
Okshola/Kristihola	(4)	Fauske	300 m
Greftsprekka	(5)	Gildeskål	-250 m
Lauknesfjellgrotta	(6)	Tysfjord	-214 m
Østholet	(7)	Tysfjord	-210 m
Salthulene	(8)	Tysfjord	-195 m
Stordalsgrotta	(9)	Bardu	-184 m*

*Estimated depth -260 m. Troms fylke.
Plus 14 caves more than 100 m deep.

Except where indicated all the caves listed are in Nordland fylke.

The numbers correspond to the locations shown in Fig. 1.

Fauske, Narvik and Tromsø in addition to individual interest. Contact can be made through the Norsk Grotteforbund, Boks 321, Sentrum, 0103, Oslo 1, Norway and the author. Copies of Norsk Grotteblad are available in Britain from the author.

The achievements of recent years have sometimes been facilitated by the vast improvement in communications which has opened up large areas of Norway to vehicular traffic but nevertheless many of Norway's caves and karst areas remain remote and unspoilt.

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Some Kendal Caving Club Discoveries in Norway

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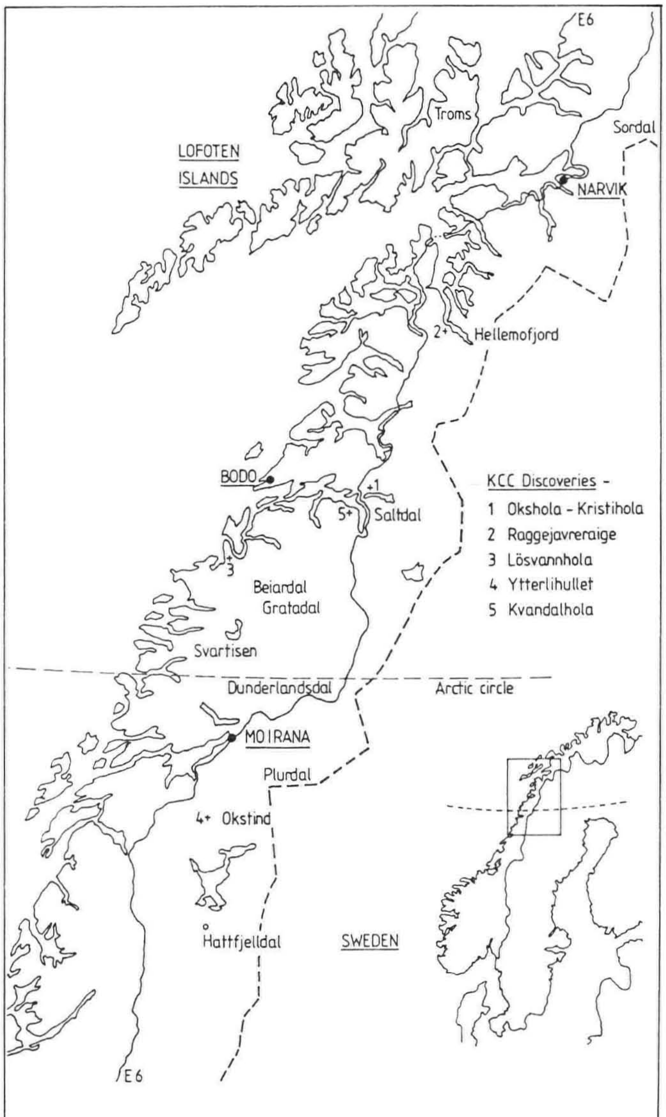
Abstract: The discovery of three major caves by Kendal Caving Club is described, together with a commentary on their subsequent exploration and prospects. The evolving nature of Norwegian caving expeditions becomes apparent as earlier and later discoveries are related in a style evocative of the feelings of the original explorers.

During the period 1965-79, ten expeditions of the Kendal Caving Club and school parties associated with it visited Nordland (Fig. 1) and discovered some 25 km of caves. These included Raggejavreraige (the deepest), Okshola-Kristihola (the longest), and the system which has since become Norway's most fascinating (and probably its hardest), the Cave of the Lost Waters. Originally, this was given the name Lösvannhola - suitably lyrical, but meaning loose rather than lost waters! The new name, Greftkjelen (after a nearby lake), is topographically and linguistically correct, if somewhat lacking romanticism! The exploration of Greftkjelen beyond the 2.2 km surveyed by the K.C.C. in 1972, and the attempt to join it to the nearby Greftsprekka has become the greatest epic of Norwegian caving to date.

These "big three" caves have been briefly described in a previous B.C.R.A. publication (D. & St. Pierre, 1985). All have been fairly frequently visited since their original exploration. More than 4 km, mainly in upstream passages, has been added to the 7 km explored by the K.C.C. in Okshola-Kristihola in 1968-69. (Heap, 1969; Holbye, 1974). In Råggejavreraige, a through-trip is now a comfortable abseiling expedition, safe in the knowledge that one does not have to climb back up the 138 m pitch. The bottom exit discovered in 1969, Mistral Gallery, 115 m above fjord level, is still the commonly used exit (Heap, 1969, 1970); but in 1979, three British cavers made a tight connection between the former bottom of Råggejavre and the lower Fjord Cave (Roger, 1980), giving a through trip depth of 617 m. There is also some development upstream of the plateau entrance and an overall depth of 620 m is now quoted (D & St. Pierre, 1985).



NORWAY - PRINCIPAL CAVING AREAS

Greftkjelen

The Greftkjelen-Greftsprekka system in Gildeskål was discovered by K.C.C./William Hulme's Grammar School in 1971 (Heap, 1972). The original explorers, near the end of an expedition and far from base, stopped in a tight and awkward streamway (Bekkegangen). The 1972 party abandoned this passage and proceeded via a deserted upper series (Galleriet) to an (over-)estimated depth of -340 m. Two kilometres of passages were added, in what is now known as Nordre Greftkjelen (& Vagangen). It was assumed in 1972 that both Bekkegangen and Vriomstupet would merely give alternative and more exacting routes to the lower reaches of the cave, and that Greftsprekka would merely be an alternative and tighter entrance - assumptions that were later proved to be dramatically wrong.

In 1976, Holbye, Grønlie (jnr.) and Lauritzen pushed the Greftsprekka entrance shaft and followed up with international teams to reach a depth of -250 m and a length of 2.6 km (Lauritzen, 1977; Holbye, 1983 & 84). In 1979, Bobtog of Bodø transferred attention back to Greftkjelen and made minor extensions in the northern part, surveyed by K.C.C. Most significantly, they proved that the water entering Vagangen is not the "lost water" of Greftvand (the lake near the entrances), but a second stream, the Tillöpsbekk. In 1980, they reached the deepest point, in South Greftkjelen, by exploring an extensive, separate series below the big pitch of Vriomstupet. This area of the cave is known as Ny-Jomfruland. (Holbye, 1983, 1984). In 1981, a tube entering Jomfru East was discovered, leading to an upstream sump at a similar level to the downstream end of Greftsprekka. Even after ten years' work, the Lost Waters remain largely lost. Geological structure militates against an easy connection, and downstream of Vriomstupet, it is not known where they go before the resurgence. Since 1981, two extensions have been made: Jomfru West in the far south and Himmelstigen in the northern series. The saga of the Lost Waters continues unresolved, in Norway's most charismatic cave.

The changing times

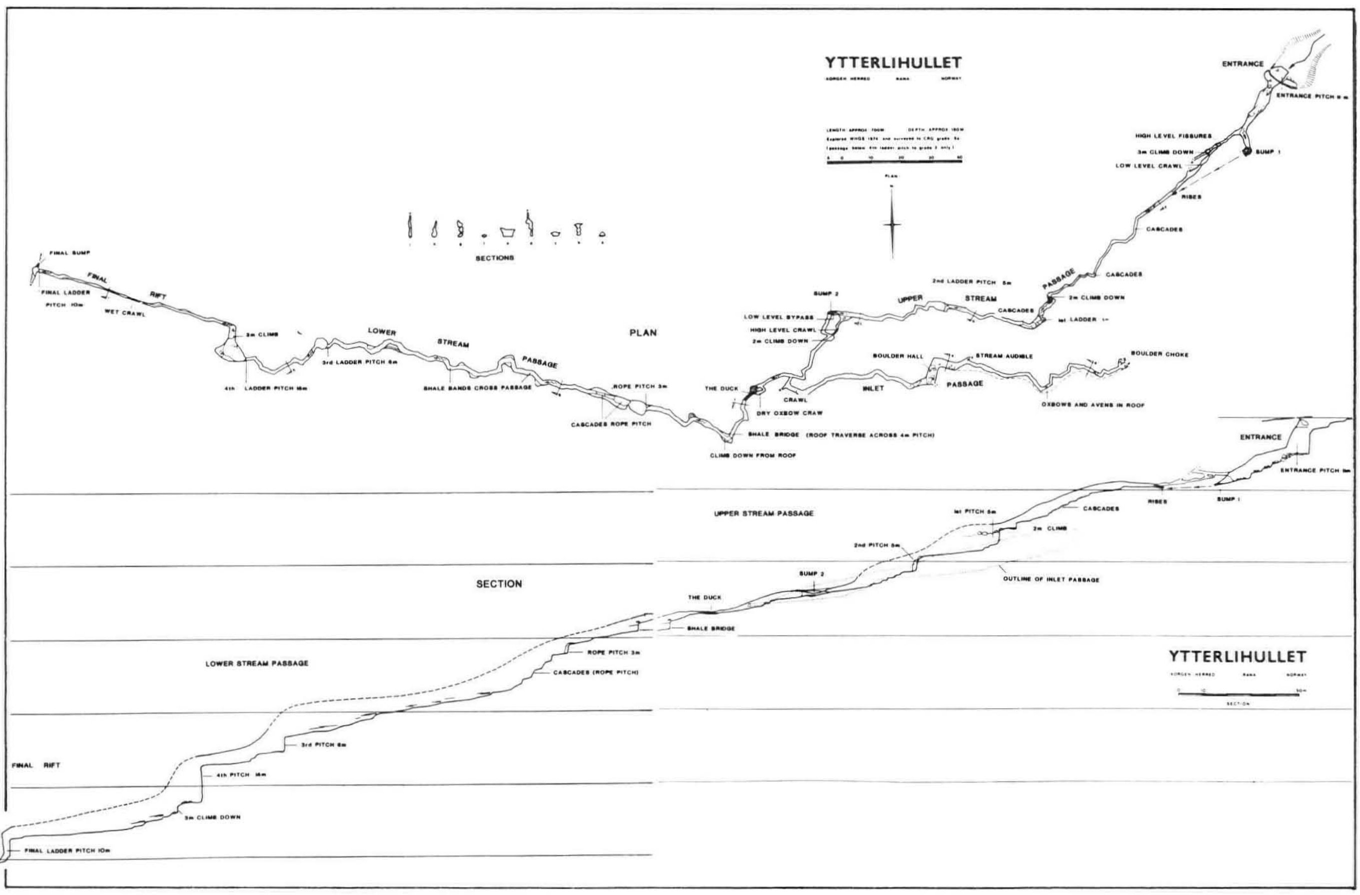
The sixties in Norway was a pioneer era. A visit to even the more accessible regions involved first driving over hundreds of miles of dirt road on the old E6. The adventure of original exploration underground was enhanced by the aura of remoteness at the cave entrances. Nowadays, the explorer can buy not only diesel but also coca-cola at the jetty at Musken-i-Hellemofjord, the base village for the Råggejavre. The first explorers emerging from the Mistral Gallery (the bottom entrance of Råggejavre) at night were greeted by the reflection of the moon in the dark waters of the fjord; now, the most striking sight from the fells above Musken is the row of newly erected electricity pylons and the cables spanning the fjord.

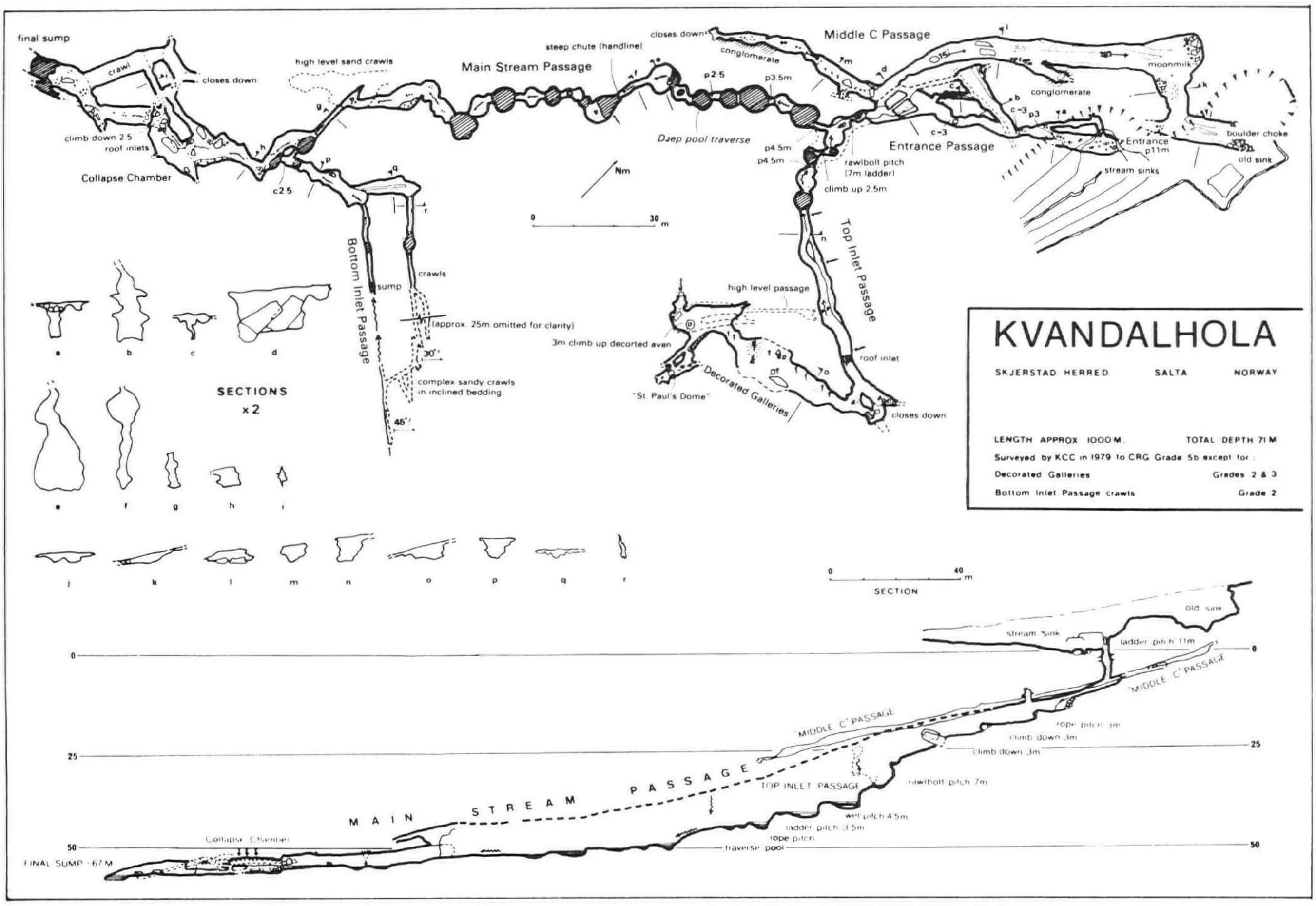
In the early days, there were extremely few Norwegian cavers and English visitors could "pick the plums", as one Norwegian caver has called it, "rape and run"! Discoveries are less readily made in the eighties. The major finds, Stordalsgrotta in Stordal, north east of Narvik; Vuoitasgallo on the Swedish border nearby; and Salthulene in Inner Tysfjord have been made by Scandinavians. The certainty of new discoveries was a great comfort to early K.C.C. parties (though there were few others!). The necessity of self-reliance, the absence of previous work in most of the region and the limitations of manpower and equipment during the early explorations evoked an intimacy between the caver and his environment. Flood conditions in the Kristihola Streamway on the first visit in 1968, with noise and spray apparently filling this magnificent passage, intensified the adventure of exploration. In Råggejavreraige, the 1968 party ran out of tackle in a bank of mist a quarter way down the Big Pitch and returned, chastened, to the plateau, where cold moonlight illuminated their tents, coated in hoar frost. Completion of exploration the following year, in ideal conditions, with a large, highly competent and well-equipped party was a necessary but anticlimactic conclusion to the mystical joy of anticipation experienced by discoverers dwarfed by their discoveries in hostile mood.

Lisengrotta

Some of the K.C.C. discoveries are less well known than the "big three". The first major find, Lisengrotta near Krokstrand in Dunderlandsdal (Heap, 1965) is a genuine classic in miniature. It has the gustiness and angularity typical of Norwegian stream caves, vadose in character and largely post-glacial in development. (The "big three" are in many ways untypical of Norwegian caves, being much larger, older and more complex in origin). The fact that Lisen is a resurgence, explored upstream via eight climbable waterfalls to a height-gain of 77 m adds to its interest. Fluorescein dye tests from the main feeder sinks were made in 1969. The caves near the Pista sink, which sump after short distances, were proved to be hydrologically connected with a time of 6 hours to the Lisen resurgences. Much closer, near the main sink of the Tõrbekk, the K.C.C.'s 1967 discovery, Tõrdenhullet, can only discharge at Lisengrotta and was not tested. There are sumps sloping at about 10-15 degrees down and up at the ends of Tõrdenhullet and Lisengrotta. An extremely tight crawl near the end of Lisengrotta could provide a route around the upstream sump. Any connection with the caves of the Tõrbekk and the Pista would provide a classic solution as satisfying in the annals of Norwegian caving as the connection of Gaping Gill and Ingleborough Cave in Yorkshire. The inaccuracy of the N.G.O. map, which places the Lisen resurgence at too low an altitude, makes computation of distances between sinks and resurgence very difficult. There is, however, probably a drop of 170 m between Tördenhullet entrance and Lisen entrance, a horizontal distance of a kilometre. The drop from the Pista sink must be about 230 m and a distance of nearly two km. A dye test at the Akslagrotten sink proved negative, but the resurgence for this water certainly could be Lisen with a drop of 210 m and a distance of three km. Here and elsewhere in Dunderlandsdal, one of the more accessible areas, there are fascinating problems still to be resolved.

Two major K.C.C. discoveries have received little attention from other cavers and deserve to





be more often visited, both for their sporting attractions and their aesthetic appeal.

Ytterlihullet

Ytterlihullet in Brygfjelldal, near Korgen in Rana, was discovered by William Hulme's Grammar School in 1974 (Heap, 1975). It is the tenth deepest cave in Norway, at 180 m and is 700 m long (Fig. 2). It is a very wet hole, tight in places, and would be a highly popular trip if it were situated in Yorkshire. Sharp rock, wet pitches, rapids, a tight crawl and a "duck" give it a fine sporting character; the ever-present, turbulent stream, which assumes the proportions of a river in the predominantly narrow rift passages, lends to its exploration the exhilaration of the best Yorkshire potholes. The location of Ytterlihullet, 600 m up from the Brygfjelldal valley, may help explain the infrequency of visits since 1974 (indeed, I know of no subsequent exploration - surely a challenge to someone!).

The entrance is a fine pothole where the stream sinks at the end of the valley. An 11 m ladder pitch leads to a steep descent of boulders and a high rift passage, which sumps after 50 m. Phreatic tubes in the roof by-pass the sump and re-enter the streamway, where the torrent boils down a series of cascades to a 5 m pitch and a second sump, which can be by-passed by either of two tight crawls. Shortly afterwards, an inlet passage enters from the east and leads to a Boulder Hall and high avens, which might offer connections to the surface. There is a large collapse shakehole a short distance below the Ytterli sink.

The next obstacle in the main passage is a low bedding plane taking the full stream: there are a few inches airspace in normal flow. Downstream, the Shale Bridge is passed by a traverse and a free climb. More rift passage leads to rope pitches of 3 m and 10 m and a ladder pitch of 6 m. A further pitch soon follows. The river gushes out from its narrow trench into an impressive blackness and, though the pitch is only 15 m deep, the ladder hangs free in a heavy spray in an airy chamber and the impression is of a much bigger drop. A short climb then leads to a tight rift and a wet, awkward pitch of 10 m to a deep sump, with an air of finality. This must be very close to the level of resurgence - probably within 20 m - but a considerable horizontal distance remains. The section of Ytterlihullet (Fig. 2b) is a curve of declining gradient. The cave is, in general, a fine example of vadose down-cutting by vertical corrasion, with few phreatic features. Ytterlihullet is a youthful cave, formed rapidly and presumably post-glacially, in conditions which provide seasonal floods and an abundance of abrasive material. It is far more typical of Norway than are Greftkjelen and Okshola-Kristihola.

Kvandalhola

The other lesser known K.C.C. discovery is Kvandalhola, south of Skjerstadfjord, near Rognan in Saltdal. (Wilcock, 1979; Cowle and Wilcock, 1982). This cave is a splendid contrast with Ytterlihullet. It is much more spacious, more rounded, with well-developed passages similar to those of Kristihola, on a smaller scale. Its depth of 71 m and length of 1 km (Fig. 3) place it near the end of the St. Pierres' list of Norway's longest caves, but its visual beauty and the quality of the sport which it offers would rank it much more highly. When it was found by a K.C.C./Handsworth Grammar School party in 1979, the entrance involved a long walk through rough forest, but recent road development, though incomplete, makes the walk much easier. It is a reasonably accessible and very beautiful cave, worthy of more frequent visits than it has received. A King Edward's, Lytham, party in 1987 found it to be almost as rewarding as Kristihola. The idyllic woodland setting and the Saltfjord sunsets add to its allure.

The 1979 party noticed the huge closed depression in which Kvandalhola is situated from several miles away, across the fjord. The entrance is in a shakehole on the N.E. side of the doline, with a small stream sinking (the main sink being further back in the doline). The 11 m entrance pitch is followed by a crawl (sometimes over ice) and three short rope descents. The passage increases dramatically in size to the head of Rawlbolt Pitch, which requires 7 m of ladder and a bolt. A large inlet on the left at the bottom was originally scaled using a tree tailored to size; a 6 m scaling pole would be preferable! This leads to an unusually well-decorated dry upper series.

The main Stream Passage from Rawlbolt Chamber (an attractive place, with sharp rock outlines, colourful mineral banding and crystal pools) is a short rift, leading to a wet ladder pitch of 4.5 metres, which lands in the first of many plunge pools. Three further pitches/water chutes require short ladders or ropes, and a handline is useful for traversing around the deepest of the plunge pools. The other pools can be waded, though one is chest deep.

The main stream enters through the Bottom Inlet Passage, which can be followed up through fissures and inclined bedding plane crawls until it becomes too tight. The bottom section of the Main Stream Passage is wider, lower, murkier than the upper sections, with many large loose rocks - all presaging the final sump. There is a short deserted series of sandy crawls, which might conceivably be forced to make a connection with Middle C Passage, a deserted upper level near the entrance. The chief attraction of the cave will, however, continue to be the delightful main streamway.

Kvandalhola seems to follow the slope of the bedding at 10° - 15° back into the hillside, away from the resurgence. Phreatic development has predominated, centred on Middle C and Top Inlet Passages, and may well have preceded subglacially. On the retreat of the ice, melt-water from the closed depression effected major vadose modification in the Main Stream Passage. Much of the water which sank in earlier post-glacial times at the present entrance now sinks further back in the doline, south westwards, nearer Middagstind, and enters the system through the Bottom Inlet Passage, in which development is clearly less mature than in the rest of the cave. Three active sinks were explored, the most significant being a 15 m pitch into a rift, shortly becoming too tight. No dye tests were carried out and the map suggests two possible resurgences. The more likely one is situated about 150 m above the fjord, near Viken, i.e. about 100 m below the Kvandalhola entrance, suggesting a drop remaining of some 30 m from the final sump. The water which rises above Viken emerges in several places from tight cracks. There are two small caves, a few metres long, in narrow, hading beds above the resurgence. The shallow valley from the area of the doline to the resurgence was not investigated.

<u>In conclusion</u>

Much of the K.C.C. work was carried out at some speed, in fairly short expeditions which concentrated on exploration and survey, rather than detailed scientific observation. That was entirely reasonable, as caving is primarily a sport, and cave science follows more often than it precedes exploration. In the 1960s and 1970s, caves still lay open, awaiting their discoverers. The expeditions tended to move from one area to another, carrying out primary exploration, rather than exhaustively and meticulously studying one area at a time. Consequently, there remains a good deal of follow-up work which could profitably be done on K.C.C. caves, both through observation and measurement and in terms of relating underground passages to surface features. In the process, additional discoveries may be made, though later K.C.C. parties have found that previous expeditions were surprisingly thorough, in view of the time and resources at their disposal.

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Cave Photography in South Wales prior to 1860

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Abstract: In 1839 Fox Talbot of Lacock announced his invention of photography. Details quickly spread to Swansea, where Talbot had many friends and relatives. Some of these began to experiment further and to take their own pictures. Between 1839 and 1856 several photographs were produced of the sea caves of Gower and Dunraven, some of which were being examined for archaeological remains at this time. This paper discusses the influence of the newly formed Royal Institution of South Wales, in particular the activities of J.W.G. Gutch, J.D. Llewelyn, and his father L.W. Dillwyn, who was involved with earlier excavations at Paviland Cave. It is shown that Gutch was capable of having taken an early cave photograph, as reported by J.D. Davies. Llewelyn produced some of the earliest known photographs of cave entrances.

INTRODUCTION

The earliest underground cave photograph, produced using artificial light, was made in 1865 (Howes, 1985). Prior to this time powerful artificial lights such as arc lights were difficult to transport. Other sources, such as limelight, lacked a blue component and were thus unsuitable for the photographic processes then in use. However, cave pictures which showed entrances to caves and which could be taken using daylight alone had been made before 1865, for example that of the Grotte de l'Arveiron by Adolphe Braun in 1858 or 1859 (Shaw, 1986).

The earliest such cave entrances to receive the photographer's attention were probably those of South Wales, the area being important due to strong links between Gower and the inventor of photography, William Henry Fox Talbot, who lived at Lacock in Wiltshire. In order to understand the reasons for the early attention paid to this area it is necessary to examine the timing and circumstances surrounding the invention of photography, Talbot's connections with Swansea, and the activities of the Dillwyn and Talbot families.

Fox Talbot's Invention of Photography

Fox Talbot began his photographic experiments in 1834, with some limited success, continuing in 1838. He was obtaining results when on January 7th 1839 the Daguerreotype process was announced in France. This stimulated Talbot to announce his own, independent, invention to the Royal Society on 31st January 1839. Following this he continued his experiments, searching for better fixing agents (Buckland, 1980). The essential features of Talbot's discovery were that an image could be 'fixed' and retained, and that many copies could be made from the ensuing paper negative. The negative was normally waxed or oiled to make it translucent, then contact printed with another sheet to produce a positive image. The print was therefore not as clear as the Daguerreotype, but its reproducability was to prove an immense advantage. The earliest prints were called photogenic drawings. In 1840 Talbot discovered a means of chemically developing a latent image, and from then prints were first called 'calotypes', later 'Talbotypes'.

However, whilst the official announcement of his discovery was not made until the end of January 1839, his close friends and relatives in Swansea already knew of his successes (Morris, 1980), as shown in a letter from Talbot's aunt to himself (Cole, 1839).

Talbot's Connections with Swansea and Llewelyn

Several of Talbot's relatives lived in South Wales. For example, Fox Talbot spent his early holidays at Penrice Castle on Gower with a branch of the family. In turn, the Penrice Talbots were friends with the wealthy landowner, Lewis Western Dillwyn, who lived at Penllergare, just outside Swansea.

Dillwyn's second child was John Dillwyn. John's surname changed to John Dillwyn Llewelyn in 1831 when he added his mother's family name upon inheritance of his grandfather's estate. Llewelyn (1810-1882) (Plate 1). was also related to Fox Talbot, having married Talbot's first cousin, Emma Talbot (Painting, 1982). Almost immediately after the announcement of photogenic drawing Llewelyn and his wife were engrossed in the details of picture production. Indeed, several members of the family were producing pictures using Fox Talbot's techniques by the end of February 1839 (Morris, 1980). Thus, detailed knowledge of photographic techniques was present in South Wales at a very early stage.

The Royal Institution of South Wales

During the first half of the last century many societies were begun which were dedicated to science and philosophy, especially after the British Association for the Advancement of Science was formed in 1831 (Beanland, 1935). One such

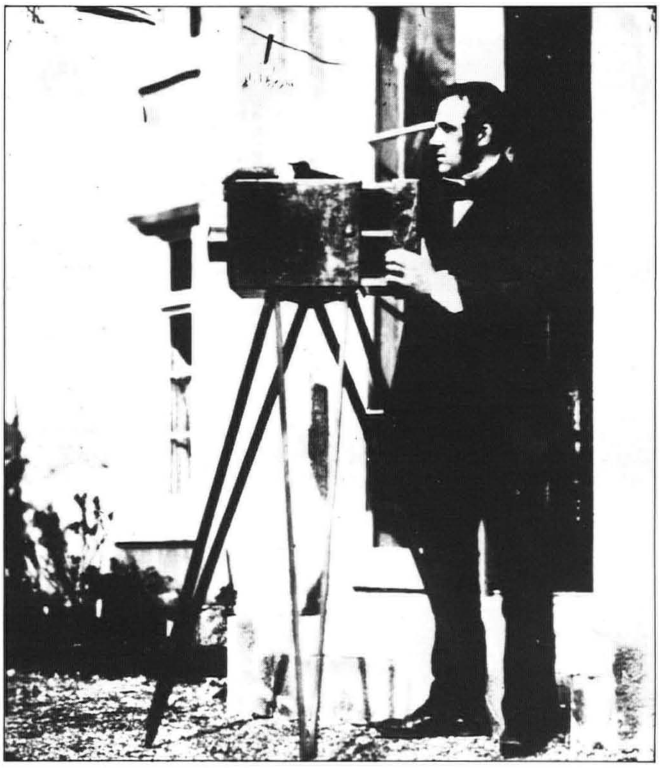

Plate 1 John Dillwyn Llewelyn with camera. From a collodion negative, 113 x 133mm, courtesy National Museum of Wales. Photographer unknown.

group was the Swansea Philosophical and Literary Institution, inaugurated on the 1st June 1835.

One aim of the Institution was 'the elucidation of the history and antiquities of Wales'. Dillwyn was a founder member and President; Llewelyn became Vice President. Before long, moves were made to raise the money for a building for the Institution, Dillwyn laying the foundation stone on 24 August 1838. Granted royal patronage, the Philosophical and Literary Society was renamed the Royal Institution of South Wales.

The men who founded the Institution clearly devoted a great deal of time and energy to their common interest. Although the minute book entries for this period are sparse, a lot was accomplished and many meetings were held. Extensive reports were published annually, and the presence of the Institution encouraged members to pursue 'the general diffusion of knowledge' (Anon, 1840a).

With these incentives it would be surprising if Fox Talbot's invention was not introduced to the members at an early stage. Indeed, newspapers and journals were filled with details of the production of these photographs. For example, the annual report of the RISW for 1838-39, published in 1839, states that "... the effect produced by light on the muriate of silver, as applied by M. Dagguerre (sic) and Mr. H.F. Talbot, for the production of what are called photographic drawings, is now so well known as to require no explanation, ..." (Anon, 1839b).

The annual meeting, at which the report was read, was held in June. This was only a few months after Fox Talbot's invention was made public, indicating the extent to which its details had been disseminated. With Llewelyn an ardent supporter of the new art and a Vice President of the RISW it can be assumed that there was every opportunity for personal demonstration to other members and elaboration of the techniques involved.

It should be remembered that photography at this time, and for the forthcoming years, was a pioneering technique that was suited only to those men who had the time and money to devote to it. Although the concept of producing realistic images from light captivated the public, the total number of people involved in production of photographs was limited. With both the influence of the Institution and Talbot's association with Dillwyn and Llewelyn, detailed practical knowledge of the technique arrived in Swansea perhaps faster than elsewhere.

JOHN WHEELEY GOUGH GUTCH

One member who gave the Institution a great deal of his time was John Wheeley Gough Gutch (1809-1862) (Plate 2). He was born in Bristol, son of the journalist J.M. Gutch. Trained as a surgeon in his home town, he became a member of the Royal College of Surgeons (now R.C.S. of London) before moving to Swansea. Gutch joined the Institution in 1837, becoming the joint Honorary Secretary with W.E. Logan. As well as Logan, who was himself to become an eminent geologist, Gutch was able to associate with others who were acknowledged as experts in their fields of study, through the RISW. Gutch himself was also placed in charge of entomology and botany, in connection with which he became a Fellow of the Entomological Society and a member of the Botanical Society (Britten & Boulger, 1893; Stephen & Lee, 1885-92). Apart from these duties, he kept detailed meteorological readings for the society.

Gutch lived at 27 Wind St., Swansea, near to the Institution's then meeting rooms as well as the site of the new Institution building. He was well known to Dillwyn, and dined with him at Penllergare on several occasions, once even treating him when the family doctor was unavailable. He is known to have been a keen photographer. With his connections with the RISW and thus with Llewelyn it seems that he learned of the process at least in part from his colleague.

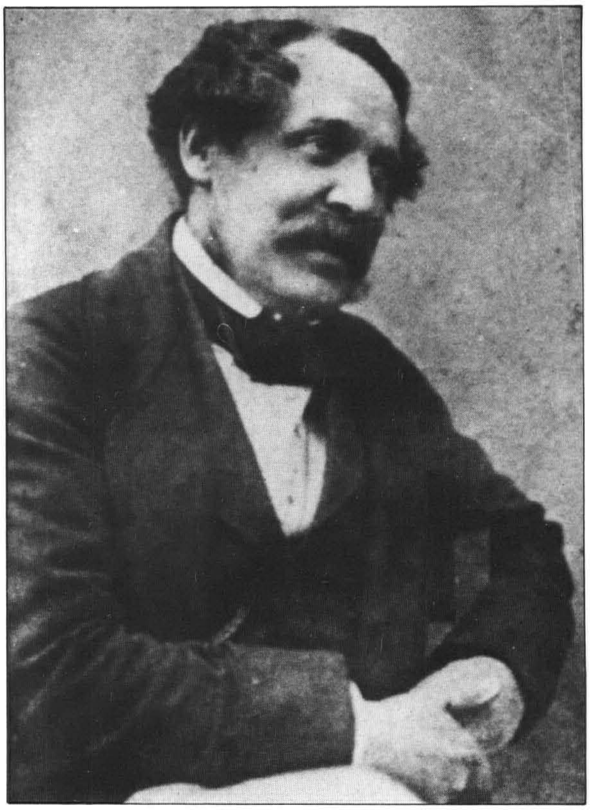

Plate 2 John Wheeley Gough Gutch. Courtesy Swansea Museum. Photographer unknown.

THE DISCOVERY OF SPRINTSAIL TOR CAVE

Much of Gower was the scene of industrial activity during the last century (Morris, 1971) and even remote areas had working quarries. During quarrying activities in 1839 a cave was broken into on Spritsail (or Prissen's) Tor in West Gower. William Hullin and George Evans, both quarrymen, reported signs of fire and human habitation in the cave (Davies, 1879), which attracted the interest of the Institution.

With caves such as Paviland of known importance on Gower (Campbell, 1977), news of the discovery of a new cave at Spritsail Tor with potential for archaeological remains would have been enthusiastically received by the Institution. Several prominent members such as Buckland, Conybeare and De la Beche were geologists, as well as being interested in archaeology, and Dillwyn their President had already been involved with one excavation (Howes, 1988).

Another man living locally in Swansea, Henry De la Beche, was engaged in a geological survey of the area, and was friends with Dillwyn. Dillwyn was probably responsible for introducing De la Beche to the Institution, which made him an honorary member on 1st July 1838 (Sharpe, 1985). It was De la Beche who led the first group to examine Spritsail Tor Cave.

The shallow cave was little more than a rock shelter, although it was later described as having 'all the characters of a long-tenanted hyaena's den. It is the most perfect illustration of the kind that I have seen, either in Gower or elsewhere among British caverns' (Falconer, 1868).

Dillwyn gives the following account of the brief archaeological visit, which was made on March 21st 1839, in his 'Contributions To A History of Swansea' (1840), although his diary entries do not mention the cave. He was not present in person, being housebound with a knee injury (Dillwyn, 1839). However, he is thought to have kept notebooks from which his diaries were later written at convenient times, and he would also have had access to the RISW records to aid writings and maintain accuracy. His 'History' was being written during this period, so it would have been possible for him to make a direct entry without using his personal diary:

> My friend Mr. De la Beche, after having employed some quarry-men to enlarge the entrance, and accompanied by Mr. Logan, Mr. S. Benson, Mr. Moggridge, Mr. Gutch, and Mr. G.G. Francis, this day explored a a cavern at Spritsail Tor, near Lanmadock, (sic) and found the bones of hyenas and of a rhinoceros, and other bones very similar to those which were discovered at Paviland. A human lower jaw was also found, with the teeth singularly worn down as if they had been employed to masticate some very hard substances.

All the men present were members of the Institution, Logan being in charge of Geology. Moggridge had been with Dillwyn on his continental tour (Howes, 1988). The relics were removed from the cave and became part of the Institution's museum collection, donated by De la Beche in 1840 (Anon, 1840d). The examination of both this cave and Bob's Cave on Mumbles Head were reported in greater detail later that year (Anon, 1839b). Although it was noted that 'the cavern at Spritsail Tor has been regularly opened, under the direction of Mr. De la Beche, ...' it was acknowledged that it had 'not been sufficiently explored to afford a complete description'.

A further examination was made in 1849 by Colonel E.R. Wood of Stout Hall, Reynoldston (Allen & Rutter, 1947; Penniman, 1933), which the archaeologist Hugh Falconer (1860) felt was much more thorough than De la Beche's. During this excavation a second entrance and connecting passage was 'discovered' (Plate 3). The report of the discovery of a second entrance may be misleading, for it is a major opening which was probably created by further quarrying between 1839 and 1849.

The Report of Gutch's Photography

In 1879 John David Davies (1831-1911), the Rector of Cheriton and Llanmadoc, published part II of the four part 'Historical Notices of Llanmadoc and Cheriton'. He was son of the John Davies who had first investigated Paviland (Anon, 1959). A local man, J.D. Davies included the excavations of Spritsail Tor in his book, this being within his parish. One sentence, included within a detailed description of the excavation, mentions the Royal Institution report of the 1839 visit with one surprising addition:

> There is a notice of this visit in one of the reports of the Royal Institution, with an early photograph by Mr. Gutch.

The general tone of his report is very accurate and well informed; Davies appears a careful observer. He is also known to have had an interest in caves, having previously examined Culver Hole, Llangenith (Davies, 1885). However, his statement concerning photography bears examination in the context of the implied date.

An Assessment of Gutch's Photograph

If Davies' implication is correct as to date and photographer, this would be an incredibly early example of a cave photograph. Photography in 1839 was limited to the level of experimentation, and although simple cameras were in use most of the photogenic drawings were of objects which were readily available, or were photograms produced by contacting an object with sensitised paper. No such photograph of Spritsail Tor is known to exist, and there is no such print with the RISW report. This latter fact is not surprising, since 1839 was far too early to reproduce photographs in print and an original slipped between the pages would easily be lost. But, to produce a photograph of a Gower cave well away from the beaten track on the 21st March 1839, only three weeks after Talbot formally announced his process, should be considered unbelievable. It would be several years before photography had progressed enough to permit the attempt of such subjects.

However, certain facts can be shown which could support the statement. Firstly, Gutch was present on the first examination of the cave. He is also known to have been an early exponent of photography, several of his pictures having been sold in the auction rooms (eg. Anon, 1976-82).

Davies stated that Gutch had taken an 'early photograph', with no specific date attached. There was more than one examination of the remains under the control of De la Beche during that year, any one of which Gutch might also have been present on. Indeed, since there is no mention of a photograph being taken (and this would presumably have been noteworthy) in the annual

Plate 3 The double entrance to Spritsail Tor Cave, January 1988, showing the possible location of Gutch's photograph. Photo; Chris Howes.

report read to the members on June 8th (Anon, 1839a), it is presumed that the picture was taken after that date.

In 1840 Gutch resigned from both the Entomological and Botanical Societies. The fifth annual meeting of the Institution reported that they received 'with unfeigned regret, the resignation of the Honorary Secretary, Mr. Gutch ... [and] to his unwearied zeal this Society is much indebted for its present condition; and this Meeting further elects him an Honorary Member.' (Anon, 1840d).

A reporter for 'The Cambrian', the local paper, covered the meeting in more detail, noting that the members 'felt greatly indebted ... to the Honorary Secretary, Mr. Gutch, who is about to leave Swansea ...' (Anon, 1840b). The exact date of his departure from the area is unknown. He was still present on June 20th, when his name appeared on a public letter in 'The Cambrian' (Anon, 1840c), and he had certainly gone before the following June when Buckland was present at a meeting and made an Honorary Member (Anon, 1841).

However, the photograph need not have been taken during these first few months after the invention of photography. Davies was writing in 1879, and may have confused the examination by De la Beche with that of Wood. No mention of any photography at the 1849 excavations exists in the RISW records (Anon, 1849a,b; Anon, 1850), but this is not conclusive since other photographic attempts are known to have gone un-reported.

It is not known where Gutch went after he left Swansea, although he was a Queens Messenger and for a time went to Florence. Certainly, he was living near Bristol in the 1850's, and produced numerous photographs of the West Country and Wales. Two of his albums are dated 1857 and 1858. He died in London in 1862 leaving a widow but no children.

Although the exact nature or date of the photograph cannot be ascertained, it can be concluded that it was possible for Gutch to have taken a picture, as claimed by Davies. However, it is likely that Gutch visited Swansea and his old colleagues during the 1850's and the photograph dates from then rather than from his initial visit to Spritsail Tor. With his previous interests, accompanying Wood on one of his excursions during 1849 or later, or even photographing artifacts at the Institution, is the most likely explanation for the circumstances surrounding the attempt.

LLEWELYN'S CAVE PHOTOGRAPHS

By comparison, the cave photography of J.D. Llewelyn can be documented with somewhat more certainty. He retained his initial interests in the new art after 1839, taking Daguerreotypes as well as calotypes from 1840 or 1841 (Morris, 1980). His subject matter covered his family and home, as well as parts of Gower near to Swansea. When Frederick Scott Archer invented the collodion wet-plate photographic process in 1851, radically speeding up exposures and producing clearer images on glass, Llewelyn was again one of the first to use it.

With the wet plate process, Llewelyn photographed many of the more accessible parts of Gower, as well as areas such as Cornwall that he visited on holiday. His changeover from the calotype process was not instantaneous, for several of these paper negative print exist from 1855 and later, for example one of caves at Caswell Bay taken on the 30th November that year (Plate 4).

Whilst he did not initially have any direct interest in caves (although his father had excavated at Paviland and Caswell), Llewelyn nevertheless used them as subject matter for many of his photographs around the South Wales coast, and did have a general geological interest. He also later became friends with Hugh Falconer, the archaeologist who excavated many Gower caves during the 1850's. Falconer is believed to have taken Llewelyn with him on some of his visits, and

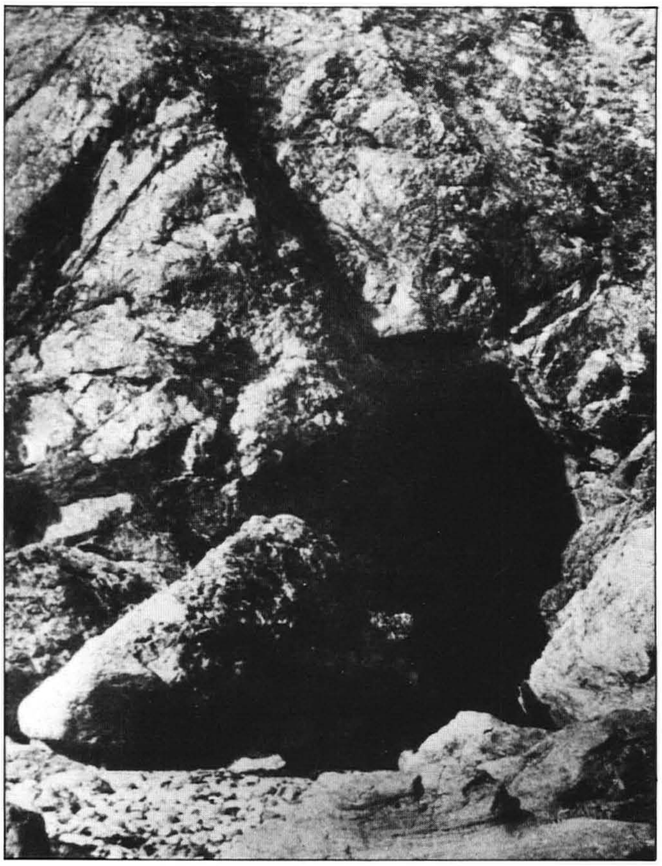

Plate 4 An unknown sea cave, c1852. From a calotype print, courtesy National Museum of Wales. Many sea cave photographs of this nature were produced by the photographer, J.D. Llewelyn.

Plate 5 'Cathedral Cave, Dunraven', 1852. Courtesy Swansea Museum. Calotype, 167 x 206mm. Photo; J.D. Llewelyn.

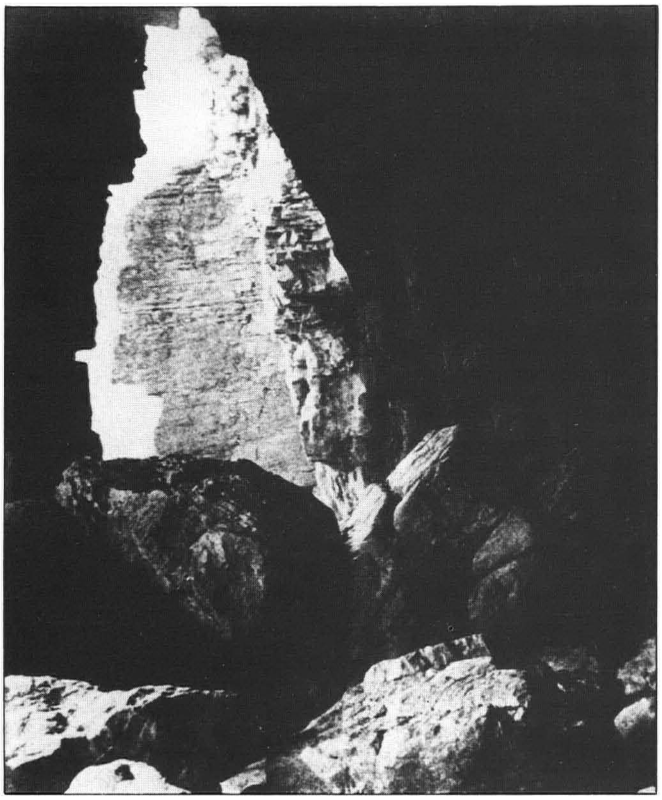

Plate 6 'Inside the Great Cave, Dunraven'. Although aided by light from another entrance, this is one of the earliest entrance pictures looking out. Calotype, 167 x 206mm. Sept 14, 1852. Courtesy Swansea Museum. Photo; J.D. Llewelyn.

several of Llewelyn's prints are in the Falconer collection in Forres.

The earliest of Llewelyn's cave prints are calotypes, produced from paper negatives c1852. Two main areas were photographed, the coasts of Gower and Dunraven. Dunraven is an area near Southerndown between Swansea and Cardiff. It is riddled with sea caves, and Llewelyn photographed many of these (Plate 5). It was a convenient location, for he had friends living at the nearby Dunraven Castle. Llewelyn annotated his third album (held by the RISW at Swansea Museum) with details of some of these, naming one as the Cathedral Cave. Another is a superb view from 'Inside the Great Cave, Dunraven' (Plate 6), taken looking out of one of the two entrances. This is possibly the earliest such photograph to be produced from within a cave. 'The Great Cave at Dunraven', probably from the same visit, is dated as Sept 14, 1852.

Further afield, caves on St Catherine's Island at Tenby were photographed, and during October 1852 Llewelyn visited Cornwall. On the 16th he produced 'Cave at the Lizard - with Lobster Pots'. Neither picture showed more of the sea cave than the dark space of the entrance.

The Photographic Society of London Exhibition

On 20th January 1853 a new club was formed, the Photographic Society of London, later to become the Royal Photographic Society. Amongst the inaugural members was Llewelyn. The following year the Society began planning their first annual exhibition, to be opened by Royalty on January 3rd 1854. This evidently gave Llewelyn the spur to produce even more photographs, exhibiting several at the exhibition. His cave photograph entries were as follows (Anon, 1854):

283, Cave in Mountain Limestone, Caswell Bay (Plate 7).

288, Llias & Mountain Limestone, Dunraven, Glamorganshire.

582, Cave in Mountain Limestone, Calotype.

661, Simstrue Cave & Portrait, Collodion.

Number 288 was identical to the print previously named as Cathedral Cave. The location of 'Simstrue Cave' is unknown, but that of Caswell Bay is on Gower, beneath the rock known to climbers as the Great Slab.

Caswell Bay was an area well known to Llewelyn, just to the west of Swansea. Caswell Cottage, which used to stand on the site of the present car park, was owned by his father, L.W. Dillwyn. It was no doubt used as a base for Dillwyn and Buckland's excavations of Caswell Bay Bone Cave in 1832 (Howes, 1988). The cave has

Plate 7 'West Corner of Caswell Bay', showing the point and cave. Dillwyn's Caswell Bay Bone Cave is just off the photograph to the right. This is probably one of the prints shown in 1854 exhibition, 215 x 169mm. Courtesy Swansea Museum. Photo; J.D. Llewelyn.

largely been lost due to erosion.

The original print (Plate 7) is a sepia colour, as were most photographs due to the chemicals used to permit slow development by sunlight. It shows the remnants of a larger cave on the point. At the extreme right, just above the shoreline, is the location of Dillwyn's bone cave, now almost totally eroded away. At some time Llewelyn photographed virtually all the sea caves at Caswell, recording their location in his album.

Llewelyn received a great deal of praise for his exhibition prints, and showed he had mastered many aspects of photography such as 'instantaneous' pictures of waves at Caswell. Such pictures were considered to be of great significance; hitherto, only near-stationary objects could be photographed with clarity.

<u>The Oxymel Process</u>

After the exhibition, Llewelyn continued with his photography of Gower, for example photographing the arch of Three Cliffs on the 19th April 1854. In addition to his growing record of Gower, he also continued with his photographic experiments.

The wet plate collodion process was superior to the calotype, but suffered in that plates had to be prepared immediately before use and processed within a few minutes. This meant a photographer had to carry not only his camera, but also a photographic dark tent and all chemicals for the process. Llewelyn found a way to prepare collodion plates and keep them in usable condition using a coating of vinegar and honey. This was named oxymel; the modified collodion plate was now produced by the oxymel process (Llewelyn, 1856).

Prior experiments used collodion mixed with glycerine, and a photograph was produced by this method of the 'sweet water fountain' at Caswell (the cave opening bow being capped). The print, now in Forres Museum, is dated 30.11.55 (Boylan, 1977). An oxymel cave photograph of Culver Hole is known from c1856, the year Llewelyn announced his invention (Plate 8).

Gower possesses two caves named Culver Hole, one being near Llangenith in West Gower (first examined by J.D. Davies), the other near Port Eynon having a distinctive stone structure built into its entrance. This is thought to have been constructed as a pigeon house. The latter cave is the one photographed by Llewelyn, which interestingly shows more of the structure than is present today. In the 1850's there were two more 'windows' at the top, which survived until this century, as shown by an early Harvey Barton postcard c1920's.

This print is often incorrectly dated as c1852. However, in a letter in 1855 Llewelyn mentions that '...altho' I have made photographs in most parts of England, yet I have never worked my camera in the western parts of Gower...' (Llewelyn, 1855). Photographs of the area around Paviland Cave and Bacon Hole as well as Culver Hole will therefore also date from this period. Llewelyn appears conversant with all three caves, although unfortunately pictures of the former two areas do not include the entrances. Identification of the use of oxymel provides a more accurate date than 1852, although this technique was still in use in 1862 when the fossil cave Bosco's Den was photographed with an eight minute exposure on the 27th June (Boylan, 1977).

THE SIGNIFICANCE OF LLEWELYN'S PHOTOGRAPHS

Llewelyn may well have taken other photographs of cave entrances; it is only recently that he has received the attention and acclaim that he deserves, and many prints may have been lost. Many by Gutch are still awaiting recognition, and it is hoped that more information about the man will slowly appear along with his prints.

Whilst Llewelyn's primary interest was not in the caves themselves, they did make a convenient subject for his camera and form an early record of cave entrances produced near the time of their excavation. It cannot be conclusively proved that Gutch produced a picture of Spritsail Tor Cave, but those by Llewelyn of Caswell, Culver Hole, and the Great Cave of Dunraven, indicate that South Wales was perhaps the earliest such cave area to receive a photographer's attention. The prints

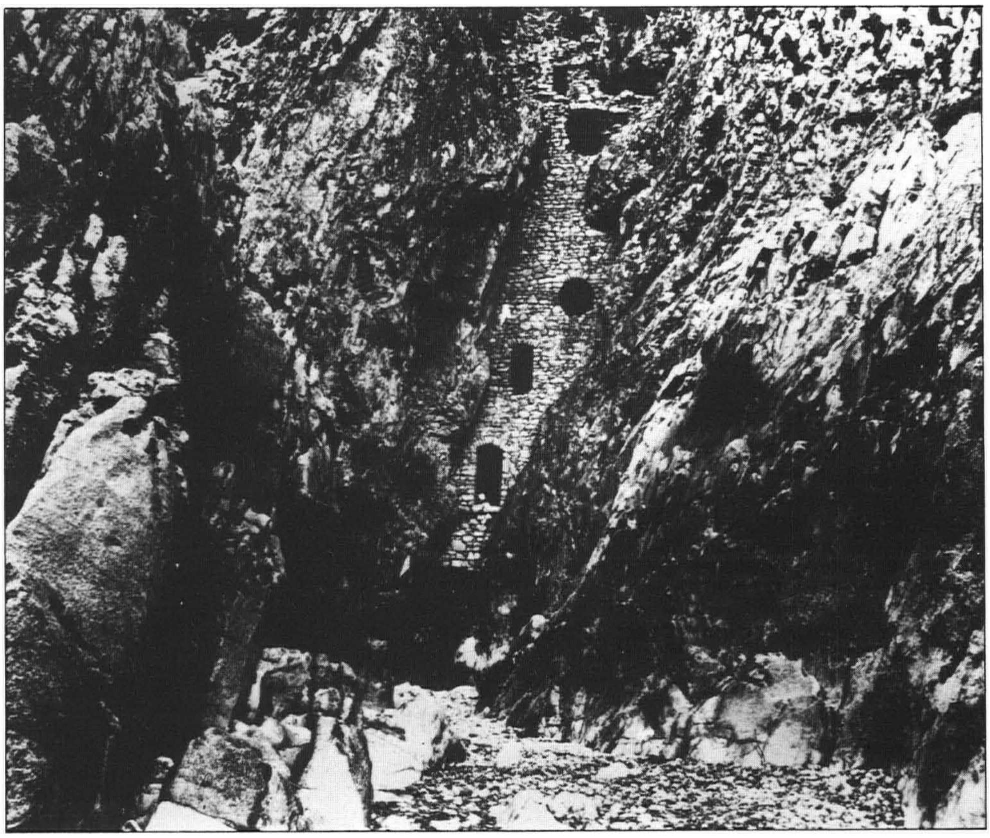

Plate 8 Culver Hole, Gower, c1856. The top two openings are no longer present. From a 252 x 202mm oxymel glass plate negative (identified as such in a photograph album), courtesy National Museum of Wales. Several original prints from this plate are still in existence. Photo; J.D. Llewelyn.

indicate details which would otherwise be lost, for instance the changing face of the sea cave entrances, and show the appearance of the sites from the period of their first examination for archaeological remains.

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Research Funds and Grants

THE JEFF JEFFERSON RESEARCH FUND

The British Cave Research Association has established the Jeff Jefferson Research Fund to promote research into all aspects of speleology in Britain and abroad. Initially, a total of £500 per year will be made available. The aims of the scheme are primarily:

a) to assist in the purchase of consumable items such as water-tracing dyes, sample holders or chemical reagents without which it would be impossible to carry out or complete a research project.
b) To provide funds for travel in association with fieldwork or to visit laboratories which could provide essential facilities.
c) To provide financial support for the preparation of scientific reports. This could cover, for example, the costs of photographic processing, cartographic materials or computing time.
d) To stimulate new research which the BCRA Research Committee considers could contribute significantly to emerging areas of speleology.

The award scheme will not support the salaries of the research worker(s) or assistants, attendance at conferences in Britain or abroad, nor the purchase of personal caving clothing, equipment or vehicles. The applicant(s) must be the principal investigator(s), and must be members of the BCRA in order to qualify. Grants may be made to individuals or small groups, who need not be employed in universities, polytechnics or research establishments. Information and applications for Research Awards should be made on a form available from S.A.Moore, 27 Parc Gwelfor, Dyserth, Clwyd LL18 6LN.

GHAR PARAU FOUNDATION EXPEDITION AWARDS

An award, or awards, with a maximum of around £1000 available annually, to overseas caving expeditions originating from within the United Kingdom. Grants are normally given to those expeditions with an emphasis on a scientific approach and/or exploration in remote or little known areas. Application forms are available from the GPF Secretary, David Judson, Rowlands House, Summerseat, Bury, Lancs BL9 5NF. Closing date 1st February.

SPORTS COUNCIL GRANT-AID IN SUPPORT OF CAVING EXPEDITIONS ABROAD

Grants are given annually to all types of caving expeditions going overseas from the U.K. (including cave diving), for the purpose of furthering cave exploration, survey, photography and training. Application forms and advice sheets are obtainable from the GPF Secretary, David Judson, Rowlands House, Summerseat, Bury, Lancs BL9 5NF and must be returned to him for both GPF and Sports Council Awards not later than 1st February each year for the succeeding period, April to March.

Expedition organisers living in Wales, Scotland or Northern Ireland, or from caving clubs based in these regions should contact their own regional Sports Council directly in the first instance (N.B. the closing date for Sports Council for Wales Awards applications is 31st December).

THE E.K.TRATMAN AWARD

An annual award, currently £25, made for the most stimulating contribution towards speleological literature published within the United Kingdom during the past 12 months. Suggestions are always welcome to members of the GPF Awards Committee, or its Secretary, David Judson, not later than 1st February each year.