Merging the concepts of pseudokarst and paleoseismicity in Sweden: A unified theory on the formation of fractures, fracture caves, and angular block heaps

Nils-Axel Mörner¹ and Rabbe Sjöberg²

¹Paleogeophysics & Geodynamics, Stockholm, Sweden

²Obbola, Umeå, Sweden

Abstract: Sweden has thousands of caves cut into the bedrock, two thirds of which occur in the crystalline bedrock, and hence represent pseudokarst phenomena. The formation of these caves can only be understood in terms of paleoseismics. In this paper, we review the parallel evolution of the concept of pseudokarst caves and of the concept of paleoseismic activity in Sweden, and combine both concepts into a unified theory on the formation of fractures, fracture caves and angular block heaps.

Keywords: pseudokarst, fracture caves, block caves, paleoseismics, methane venting tectonics

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INTRODUCTION

The Swedish Speleological Society has a database including 2871 classified caves (SSF, 2018). Out of those, 410 (14.3%) refer to true karst caves, 309 (10.8%) refer to shore caves (including “tunnel caves”), and the vast majority of sites (1919 or 66.8%) refer to block and fracture caves. This is an effect of the fact that Swedish bedrock predominantly consists of crystalline bedrock, especially gneisses and granites. The word “pseudokarst” has a somewhat unclear definition. It implies, however, that it is not a question of dissolutional weathering, but coastal erosion (shore caves), bedrock fracturing (the cave formation of which has been termed quite differently; viz.: granite caves, bedrock caves, boulder caves, block caves, block heaps, etc) and scree deposits.

In this paper we review the evolution of observing, documenting and understanding such pseudokarst caves and scree accumulations in Sweden. Previous standard references were by Sjöberg (1994a, b), Mörner (2003) and Mörner & Sjöberg (2011).

The Swedish speleological society (Sveriges Speleolog-Förbund, SSF) was formed in 1966 by Leander Tell. It issues a journal named “*Grottan*” (The Cave), has a publication series named “*Svenska Grottor*” (Swedish Caves) and a database “*Grottdatabasen*” (SSF, 2018). In 2007, SSF hosted the Baltic Speleological Congress on the Island of Gotland (Gustafsson, 2007), and in

2011, it hosted the *Second International Conference on Granite Caves* (Mörner & Sjöberg, 2011).

Figure 1 shows the distribution of caves registered in the SSF database (SSF, 2018). Table 1 gives the distribution of numbers and lengths of pseudokarst caves in Sweden: the majority are less than 25 m long and the longest 2,633 m long. The lengths of the 10 longest pseudokarst caves are given in Table 2.

Fracture caves and block caves are formed by tectonic processes and typically consist of fracture patterns and angular blocks with sharp edges, as illustrated in Fig. 2. Tunnel caves (Sjöberg, 1986a, 1990) are formed by littoral erosion as illustrated in Fig. 3.

Leander Tell is regarded as the “Father of Swedish Speleology” with a benchmark book (Tell, 1955), followed by other books (Tell, 1962, 1969) and a number of cave catalogues (Tell, 1963, 1966, 1970, 1974).

Caves have, of course, been observed far back in history. In the early 17th century, King Karl XI was carried up to a shore cave hanging in the mountainside at 120 m a.s.l. in Ångermanland (Fig. 4), where the rate of uplift has been at its maximum. During his travel to Lapland, Carl von Linné visited this cave and several other caves along the Bothnian coast (Linnaeus, 1732). Caves were often hiding places for robbers and malicious people. In pre-historic times, however, they seem to have been avoided for mythological reasons, rather than used for habitation

or other cultural activities. Only occasionally do we find ancient tools in Swedish caves.

Fig. 1. Distribution of 2871 caves (red dots) registered in the Swedish cave database (SSF, 2018). The caves named refer to the six caves in the “gallery” examples plus two MVT sites discussed in the text.

Table 1. Distribution of pseudokarst caves (in total 2054) with respect to their length.

Length in m	Number
>2500	1
1000-2500	1
500-1000	4
250-500	4
100-250	25
50-100	38
25-50	144
10-25	463
<10	1323

FRACTURE CAVES AND BLOCK CAVES

There are numerous caves in the Precambrian crystalline bedrock of Sweden associated with fractures and block tectonics. There are also heaps of huge blocks, within which there are caves. These structures have nothing to do with weathering and dissolution, but refer to broken up fragments from the bedrock surface. They are all examples of “pseudokarst”, although they usually have been termed “fracture caves”, “block caves”, “boulder

Table 2. List of the 10 longest pseudokarst caves in Sweden.

Name of cave	County	Length (m)	Type of cave
Bodagrottorna	Hälsingland	2,633	fracture cave
Hölickgrottan	Hälsingland	1,340	fracture cave
Almekärrgrytet	Småland	610	fracture cave
Örnnäset	Hälsingland	520	talus cave
Strångbergsgrottan	Jämtland	510	fracture/block cave
Gillberga gryt	Uppland	500	fracture/block cave
Ö. Klövbergsgrottan	Södermanland	362	block cave
Frugrottan	Södermanland	320	fracture/block cave
Töllsjögrottan	Västergötland	300	talus cave
Stora Trångbergsgrottan	Västmanland	250	talus cave

caves”, “granite caves” and “talus caves” (it should be noted that the word “boulder” has been used in Sweden for big blocks without respect to presence or absence of rounding).

Because Swedish geological mapping is divided into a solid rock branch and a Quaternary branch, caves and loose block heaps happened to fall in between those units, and therefore were largely ignored in the geological mapping. Instead, the study of Swedish block caves came to be driven by the spirit and curiosity of individual persons like Bergsten (1943), Agrell (1981, 1982), Isacsson (1982, 1990), Sjöberg (1987a, 1994a), and Mörner (2003).

Deformational till and bouldery moraines

In a very few cases boulder heaps can be explained as “deformation till” in the sense of Dreimanis (1969) and Mörner (1973). This concept has been generally ignored in Swedish Quaternary geology, however.

Fig. 2. A typical seismotectonic cave consisting of huge angular blocks torn out of the bedrock due to a major paleoseismic event in postglacial time. Only a seismic event is capable to move these huge blocks anti-gravitationally upwards (which is the case here, as it is in many other cave sites).

Some De Geer moraines (terminal end moraines) consist of big boulders and have become known as “bouldery moraines”. The majority of “pseudokarst caves” in Sweden have nothing to do with ice-marginal till accumulations, however. Neither have they anything to do with “glacial tectonics”.

In a few cases, however, bouldary moraines of a proposed seismic origin have been described by De Geer (1938, 1940) and Mörner (1990), suggesting that the bedrock surface was broken up into loose blocks by earthquakes when still in subglacial position (Mörner, 1978, 2017b, c).

Fig. 3. The Räckeborgskyrkan tunnel cave located at an elevation of 180 m a.s.l. It is the largest and highest elevated tunnel cave in Sweden. It can be regarded as an example of a tunnel cave.

Bedrock fracturing, seismotectonics and paleoseismology

Open bedrock fractures, granite caves, boulder caves, block caves and block heaps imply fracturing of the former surface of the crystalline bedrock. In association with glaciation and deglaciation, the Scandinavian bedrock became smoothly polished and striated (Mörner et al., 2008, Fig. 9). Therefore, fractures and faults in this glaciated bedrock surface provide evidence of postglacial fracturing. This fracturing of previously solid bedrock must be understood in terms of seismotectonics (Mörner, 1978, 2003; Sjöberg, 1987a, 1994a). Today, Sweden is a country of low to moderately-low seismic activity. At the time of deglaciation, however, Sweden has, in the last decades, turned out to be an area of high-seismicity (Mörner, 1991, 2003). Therefore, there is no longer any geodynamic problem in referring Swedish “pseudokarst” phenomena to seismotectonics (Mörner & Sjöberg, 2011). This applies not only to the deglacial phase (e.g., Mörner, 1991, 2003) but also to the Late Holocene (Mörner, 2007, 2009, 2017b).

Fig. 4. A shore cave (“Kungsgrottan”) is hanging in the steep slope of Mt. Skuleberget at a level of +120 m, which is the level of the first Littorina sea level peak at 7000 C14-yrs BP. This implies a minor retardation in the rapid shorelevel displacement (relative uplift), providing time enough for a littoral cave to be eroded.

From parallel concepts to unified theory

The earliest observation of postglacial fracturing and interpretation in terms of earthquake origin come from De Geer in 1879 (De Geer, 1940, p. 124). De Geer observed that big angular blocks were sometimes concentrated in the end-moraines. He termed such moraines “seismic moras”.

In 1929, von Post published interesting data from Säffle in SW Sweden. Old drawings (dated 1915) from the clay pit of Älvängen record extensive sedimentary deformations in the form of folds and faults (von Post, 1929). The site was later revisited by Mörner (Mörner, 2003, p. 256).

Bergsten (1943) was the first to demonstrate that the block cave of Torekulla was a product of tectonics. A similar view was expressed for the Trollgator (Trollgatore) cave site (Mårtensson and Nilsson, 1971; Bergsten, 1976). Other observations and suggestions of a seismotectonic origin were given by Agrell (1981, 1982), Sjöberg (1987a), and Isacsson (1990).

In 1994, Sjöberg took his PhD at the institute of Paleogeophysics & Geodynamics at Stockholm University on a thesis entitled “*Bedrock caves and fractured rock surfaces in Sweden: occurrence and origin*”. He identified six possible causes to the cave formation: (1) glacial tectonics, (2) freeze and thaw processes, (3) methane venting, (4) postglacial unloading (and stress release), (5) hydrofracturing, and (6) seismotectonics. The external examiner (Dr. Douglas Grant from Canada) said: “*I think you have identified all possible processes, and I cannot think of any others*”. In his thesis, Sjöberg (1994a) evaluated the possible processes against the characteristics of 53 pseudokarst caves distributed over almost the whole of Sweden. The result is given in Table 3. It shows that seismotectonics is the most probable origin for 52 sites (and possibly for the remaining one site, too). Therefore, seismotectonics emerged as the most probable origin of the Swedish fracture caves, block caves or boulder caves, whatever name we may use for these pseudokarst caves in the crystalline bedrock, or within heaps of loose angular blocks.

This was a major step forward in the understanding of Swedish non-karstic cave formation. It marked a paradigm shift in Swedish speleology.

Table 3. Sjöberg's semi-quantitative analyses of possible mechanisms behind the formation of 53 Swedish fracture and block caves (Sjöberg, 1994a).

Process	Impossible	Possible	Probable
Glacial tectonics	37	15	1
Frost deformation	30	20	3
Methane venting	40	11	2
Stress release	10	29	14
Hydro-fracturing	10	30	13
Seismotectonics	0	1	52

A paradigm shift in Swedish seismology

In the 1950s and 1960s, the Fennoscandian Shield was generally assumed to be of exceptional stability. Shoreline diagrams by Nilsson (1968) in Sweden and Hyypä (1966) in Finland were claimed as evidence of this stability. However, Mörner (1979, 1980) and Donner (1980) demonstrated that those diagrams are no longer tenable.

In the 1960s, two major steps forward were made: (1) the repeated levelling identified irregularities (Asplund, 1968; Mörner, 1977a), and (2) C14-dated shorelines identified the presence of tectonic fault-lines where the uplift isobases were bent (Mörner, 1969, 1977a).

In the 1970s, there were several important events: (1) the project on "postglacial earth movements" was initiated in 1973 as a part of the International Geodynamics Project (GDP), (2) because of the achievements within the project (Mörner, 1975), the international GDP group asked Mörner to organize an international conference in Sweden, (3) this conference was held in Stockholm in 1977 together with a field-excursion through southern Sweden (Mörner, 1977b, 1980), (4) Mörner (1977c) reviewed uplift irregularities and traces of possible paleoseismic events in Sweden (it seems that this was the first time the word "paleoseismic" was used), (5) Lundqvist and Lagerbäck (1976) published the first account of the Pärve Fault in northern Sweden, (6) Mörner (1978) published the first account on paleoseismics in the Stockholm area, (7) Mörner became the leader of the INQUA Neotectonics Commission and started issuing the Neotectonics Bulletin, which became an international source for the evolution of the understanding of neotectonics and paleoseismics. The Bulletin came out in 19 annual issues from 1978 to 1996. Mörner (1985) summarized available solid rock evidence, geomorphic evidence, sedimentological evidence and geophysical evidence indicating paleoseismic events in postglacial time. Additional observational data followed from sedimentary data (e.g., Mörner & Tröften, 1993; Tröften, 1997), block cave generation (Sjöberg, 1994a) and bedrock faulting (Lagerbäck, 1990; Mörner, 1990).

In 1991, Mörner presented a mechanism for the interpretation of the observation that the deglacial period was characterized by frequent high-magnitude seismic events, whilst the present period

is characterized by low to moderately low seismicity. He proposed (Mörner, 1991) that the rate of glacial isostatic uplift with rapid extensional forces in the vertical, radial and tangential dimensions initiated the high seismicity during deglaciation when the rate of uplift peaked and amounted to tens of cm per year (0.5 to 1.0 mm per day). This is illustrated in Fig. 5.

Fig. 5. Uplift of the Fennoscandian shield in the last 13000 years with contours in hundreds of meters of total uplift (from Mörner, 2003), giving rise to extension in the vertical, radial and tangential directions (Mörner, 1991).

In 1999, we felt ready for an international demonstration and discussion of our field data on seismotectonics and liquefaction (Mörner et al., 2000). An international excursion was organized (Mörner, 1999). It gave a thorough profile across the whole of Sweden from Umeå in the north to Båstad in the south. The excursion was attended by 40 specialists from all over the globe. The discussions were very fruitful, and lay the ground for extended analyses (Mörner, 2003).

Our working methodology was novel in the combination of fault data, sedimentary data, liquefaction structures, turbidite levels, varve chronology and tsunamite data (Mörner et al., 2000; Mörner, 2003, 2011). Magnetic grain rotation was also documented (Mörner & Sun, 2008).

A unified picture takes form

As an outcome of the description of the Boda cave by Sjöberg (1994a), we were able to force the nuclear waste handling organization to finance a major research project on the Boda cave and related phenomena in the surrounding areas (Mörner et al., 2003).

A group of international experts (Professor Franck Audemard from Venezuela on liquefaction, Doctor Sue Dawson from Scotland on tsunami deposits and Professor Andrej Nikonov and Doctor Dmitri Zykov from Russia on block motions and seismicity) joined our research group at the Institute of Paleogeophysics & Geodynamics at Stockholm University in 2000-2001.

The Boda cave was investigated and documented in detail. Thanks to the varve chronology, the creating earthquake could be dated at varve year 9663 BP

(Mörner, 2003, 2013a, 2016a). It was linked to a major liquefaction event deforming sediments over an area of at least 80x40 km. It also set up a tsunami wave of at least 12.5 m height that was recorded over an area of 125x30 km. A turbidite was spread over the seafloor over a distance of 210x40 km right in the annual varve of varve-year 9663 BP. Simultaneously, fracture caves and block caves were created and recorded over an area of 50x50 km. The primary fault has a scarp height in the order of 10-20 m. All this speaks clearly of a causation earthquake of $M > 8$ (Mörner, 2003), later fixed at M 8.5-8.6 (Mörner, 2017a).

The Boda cave investigation (Mörner et al., 2003) probably represents one of the most well-documented paleoseismic events in the world. It is thus the “core stone” for the formation of a unified picture of the mechanisms, characteristics and distribution of paleoseismic events in Sweden (Mörner, 2003; 2013b; 2016b, 2017a).

International anchoring

The above-mentioned international excursion in 1999 marked an important step in our formulation of the concept of a high-seismic activity in Sweden in former times (Mörner, 2003).

As a part of the 33rd International Geological Congress in Oslo in 2008, we organized an excursion on *Paleoseismicity and Uplift of Sweden* in two parts: A, from Umeå to Stockholm, and B, from Stockholm to Båstad (Mörner et al., 2008; Sjöberg, 2008). It marks another key point in our studies.

In 2011, Mörner & Sjöberg (2011) organized and hosted the Second International Conference on Granite Caves in 2011. It offered another occasion to direct the limelight on Swedish fracture caves and block caves. The guidebook (*op. cit.*) provides a

representative illustration of various forms of “granite caves” in Sweden.

SCREE DEPOSITS

In his study of pseudokarst caves in Sweden, Sjöberg (1994a) included “caves in collapsed rock walls” as his “type 2” caves, and identified 21-23 of them. In the present SSF database, there are 33 scree accumulations registered. The distinction between talus deposits successively accumulated over time and the sudden breaking-off and falling down of huge rock masses is sometimes a fine one. In the first case, it is a matter of time and gravity. In the second case, there must be a release force, which seems logical to ascribe to seismic ground shaking (at least, nowadays, when this process has become well documented all over Sweden).

The sites Pyhävaara, Slåtterdalsgrottan and Ulorna (Sjöberg, 1994a, Figs. 26, 27, and 29), indeed, seem to represent momentous breakings-off of huge rock volumes, which are likely to have been triggered by paleoseismic events. The movement of the Pyhävaara scree can be directly connected with the Lainio Fault movement (Lagerbäck & Witschard, 1983), which strongly supports the conclusion of Sjöberg (1994a).

In association with the 9663 BP paleoseismic event in the Hudiksvall area, huge scree masses were detached at Blackåsberget and Storberget (Mörner et al., 2003, p. 109-111), hosting caves. A characteristic feature observed was that the scree accumulations at the foot of the scarps were not located at the logical (gravitationally straight-down) position, but lay tens of meters outside, as though moved by an extra ground shaking motion (i.e., paleoseismics). The Blackåsberget rock scarp and scree are shown in Fig. 6.

Mt. Blackåsberget +350 m

Fig. 6. The Mt. Blackåsberget bedrock scarp is traversed by slope-parallel fractures with a big-boulder scree accumulation beneath, hosting caves (modified from Mörner et al., 2003; Sjöberg, 1994a). The scarp is high and steep and strongly fractured (left). The scree has not just fallen down gravitationally, but also been moved tens of meters laterally (blue arrows to the right) due to earthquake forces.

The Eastern Klövberget caves occur in a huge scree deposit (Fig. 7). Here we are able to demonstrate that the entire mass moved in one big scree unit, the movement of which is most likely to have been initiated by a strong earthquake. The simultaneous mass movement is indicated by the preservation of the original fracture patterns in the scree masses (Fig. 7). According to Mörner & Sjöberg, (2011; Stop 6

of the Local Excursion) this may imply a novel model of proving that a scree moved as one huge unit in response to an earthquake.

It should be stressed that numerous scree accumulations, some of which may contain block caves, represent successive gravitational talus movements of rock fragments, and are of an aseismic origin.

Fig. 7. The Eastern Klövberget caves occur in a huge scree accumulation (from Mörner & Sjöberg, 2011). Because the fracture pattern can still be identified in the scree masses, the entire scree must have moved in one huge mass. This is indicative of a paleoseismic origin.

METHANE VENTING TECTONICS (MVT)

Björklund (1990) was the first to suggest that methane venting might have something to do with the fractured bedrock observed both in Finland and Sweden. It was followed by general discussion of this concept (Mörner, 1993), and a comprehensive study of granitic caves in Sweden (Sjöberg, 1994a). Both authors appreciated the possibility of this mechanism, but neither was then able to present any clear observational facts. Definite evidence came with the study of the Boda Cave (Mörner, 2003) and the comprehensive presentation on Methane Venting Tectonics (Mörner, 2017b, c).

Mörner recognized at least 13 sites in Sweden, and 1-2 sites in Finland of methane venting tectonics (Mörner, 2017b, 2017c). Out of the 13 Swedish sites, 10 date from the late glacial period (with 4 from the 9663 BP event) and 3 from the Late Holocene.

Figure 8 illustrates our interpretation of methane venting tectonics triggered by the 9663 BP earthquake, and the deformational structures recorded at the site of deformation at the Boda Cave (Mörner et al., 2003; Mörner, 2017b).

North of Hudiksvall, lies the Skålboberget site (Mörner et al., 2003, p. 105-109; Sjöberg, 2009; Mörner, 2017a-c;). It refers to a 25 m high cone (with a base of about 110x170 m at an elevation of +32 m) consisting of angular blocks, and with gigantic blocks at the top (with volumes in the order of 8,000 m³). A minor cave at the base includes rounded beach boulders (Fig. 9), indicating that the cone formation occurred after the uplifting beach was at sea level at 3200 BP (Mörner, 2003, p. 105-109), because there

Fig. 8. Map of the Boda Cave surface (a) with 13 minor centres of deformation (red dots), the mode of initial expansion followed by contraction (b) and model (c) of interaction between seismic ground shaking and methane venting (from Mörner et al., 2003; Mörner, 2017b).

are no traces of marine abrasion of the cone itself. A 12 m high tsunami wave was generated in direct association with the bedrock deformation (Mörner & Dawson, 2011; Mörner, 2017c). The tsunamite layer was dated at older than $2,411 \pm 50$ cal. yrs BP. The venting of methane affected the lake environment, and most C14-dates were strongly affected by dead carbon (Mörner, 2017c), with the largest deviation being 18412 ± 378 cal. yrs BP instead of 2900 BP (the time of the event). This contamination provides a good confirmation of dead carbon from the methane venting. The methane venting tectonic took place when sea level was at +26 m, which occurred at 2900 BP (Mörner, 2017c, p. 9).

Fig. 9. The Skälboberget site represents the deformation at an explosive methane venting (from Mörner et al., 2003; Mörner, 2017b). The cone of blocks is 25 m high, and has some gigantic blocks at its top (a). The block cone contains several caves; one at the base contains rounded littoral boulders (b), indicating a deformation in Late Holocene time when sea level had fallen to +26 m at 2900 BP.

Kvarnberget refers to a site south of Stockholm, which can only be understood in terms of violent methane venting (Mörner, 2017b, c). It was first observed by Sjöberg (2009), structurally investigated in detail by Mörner (Mörner & Sjöberg, 2011) and fully presented in Mörner (2017b, c). Later field studies in 2018 (Mörner, unpublished) have further pinpointed the age determination at about 2900 ± 100 BP.

Kvarnberget is a 25 m high cone of blocks broken loose from the solid bedrock beneath. The block cone is full of minor caves. At the top there are two gigantic blocks (Fig. 10). The cone is surrounded by erosional troughs continuing in a 10–15 m deep river canyon cut in clay deposits, which ends in a huge delta (of about

400,000 m²) at the level of +15 m (Mörner, 2017c). This level (with a lot of fine structures documented in 2018) corresponds in age to about 2800–3000 BP (Mörner, unpublished).

Fig. 10. Kvarnberget, a 25 m high cone of huge blocks hosting caves (from Mörner & Sjöberg, 2011; Mörner, 2017a, b). At the top of the block cone there are some gigantic blocks (a). The cone is surrounded by depressions (b), which, via an 800 m long and 10–15 m deep canyon cut into clay deposits, end in a huge delta at +15 m. This implies that the methane venting episode took place at about 2900 BP.

SHORE CAVES

Shore caves are another type of pseudokarst. They are formed by littoral wave actions, and have little or no relation to seismotectonics. Hence our discussion is brief.

De Geer (1902) and Lindström (1902) were both pioneers in the study of shore caves. Whilst De Geer correctly understood that shore caves were predominantly formed by stones and blocks moved by the littoral wave action, Lindström advocated streaming water. Munthe (1920) gave a general account on the occurrence of “shore caves” (Swedish: *strandgrottor*) in Sweden.

The “tunnel-cave” (Sjöberg, 1986a) is a special type of shore cave abraded along a single sub-vertical fracture (Fig. 3). The caves have a typical well-rounded cross-section. In a number of papers, Sjöberg addressed the occurrence and formation of these caves (Sjöberg, 1981, 1982, 1983a, b, 1984, 1985, 1986b, c, 1987a, 1991, 1994b). He found that the formation of these caves needed fractures that were directed toward the sea (with a long relative fetch) and the prevailing winds. Furthermore, the volume of abraded rock was, at the time of formation, depending on sufficient access of abrading material in the form of washed till.

In northern Sweden, the rate of uplift is still very fast: up to 10 mm/yr with an exponentially increasing rate back in time (Mörner, 1979). This means that

littoral erosion can only have had a short duration of activity at a single elevation when passing through the shore zone. Nevertheless, Sjöberg (1982, 1983b, 1984, 1987a, 1991, 1994b) reported numerous tunnel caves hanging in the hillsides inland, far above present sea level (Fig. 4). They seem to date from the Littorina Sea period of the Baltic and to represent minor retardations in the relative sea level rise, due to the effect of eustatic oscillations (Mörner et al., 2008). At Lidberget, south of Umeå, there are at least five good examples of littoral caves (Sjöberg, 1982, 1991). They are concentrated at 90–110 m above sea level, and are associated with an extensive fracture system (Mörner et al., 2008, Fig. 26), formerly filled with dykes of dolerite (Sjöberg, 1983b).

Some caves and abraded depressions may have got their primary erosion by water-flow under high hydrostatic pressure along fractures and bedrock irregularities in subglacial position (Mörner, 2003, p. 238).

CAVE EXAMPLES

After the above theoretical review of Swedish pseudokarst caves, we now turn to a representative “gallery” of some of the cave structures actually recorded.

The Boda Cave

The Boda Cave at Iggesund represents a former bedrock hill deformed into a seemingly chaotic field of angular blocks (Fig. 11). The sub-surface contains a system of cave passages of a total length of 2,633 m. The cave system was skilfully mapped by Alf Sidén. His map (Fig. 12) agrees perfectly well with our air photography (Fig. 11) as further discussed in Mörner et al. (2003). Though the surface may look chaotic (Fig. 11), a closer analysis reveals that much of the surface remains more or less in place (as seen in glacial striae and rock veins). This indicates that the deformation took place in two steps; first a nearly “explosive” extensional deformation, and second a falling-back contraction as illustrated in Fig. 13. This mechanism (Mörner et al., 2003) also seems to apply to most of the other bedrock block caves in Sweden.

Fig. 11. The Boda cave as seen from the air: a hilltop transformed into a large field of huge, angular blocks from the underlying crystalline bedrock (from Mörner et al., 2003).

Fig. 12. Map of the sub-surface caves and passages of a total length of 2633 m (from Mörner et al., 2003). The caves have been followed 25 m down, but the roots of the cave seem to go down 100–150 m.

Fig. 13. Mode of deformation as recorded in two cross-profiles (from Mörner et al., 2003). It shows the interaction of an extension force deforming the old bedrock surface into blocks moved upwards and outwards, followed by a contraction force with blocks falling back

The cave system goes down 25 m below the surface. The root fractures of the cave system seem to reach at least 100–150 m below the surface, however, judging from our deep drillings. The surface gives an impressive view of huge angular blocks where one side is a smoothly polished bedrock surface from the pre-deformational glacial surface (Fig. 14). This, too, is a characteristic criterion of Swedish bedrock block caves. Figure 15 shows a bedrock disc trapped in an open fracture, vividly illustrating the mode of deformation: extensional fracture opening and throwing out of the disc, followed by a subsequent contraction trapping the disc when it fell back.

From the violence of deformation recorded at the Boda Cave, one might suspect that it was formed close to the epicentre of a high-magnitude earthquake. This is not the case, however. The epicentre lies 12.5 km to the NE. Therefore, methane venting tectonics is likely to have been an additional or primary process (Fig. 8), as further discussed in Mörner et al. (2003) and Mörner (2017b).

Alf's Gryt

Alf's Gryt is another bedrock cave formed by the 9963 BP paleoseismic event (Mörner et al., 2003). The sub-surface cave includes deltaic deposits of sandy silt with grits, sucked into the cave when extensional

Fig. 14. The surface of the Boda cave area (from Mörner et al., 2003; Mörner, 2017c); partly a chaotic block field (below) and partly huge blocks fractured loose from the bedrock and “vibrated” more or less in position (above).

Fig. 15. A bedrock disk stuck right in its falling-back motion by a contraction fracture (from Mörner et al., 2003). This provides firm evidence of an extensional opening followed by contraction. To throw a piece of rock up into the air can only be achieved by a violent seismic event.

forces lifted and fractured the roof (Fig. 16). Violent methane venting tectonics may have been the driving force (Mörner, 2017c).

Mehedeby

Site Mehedeby (Sjöberg, 1994a) refers to a bedrock hill totally fractured into huge angular blocks (Fig. 17). This can only have been achieved at a major earthquake. An age of about 10,000 varve years BP was assigned (Mörner, 2003, 2017c, d).

Gillberga Gryt

Gillberga Gryt refers to a fracture and block cave about 100 m long. It is described in detail by Sjöberg

Fig. 16. Alf's Gryt; a cave formed at the 9663 BP paleoseismic event (from Mörner et al., 2003; Mörner, 2017b). A bedrock area of about 60×70 m was fractured into blocks, which were moved anti-gravitationally upwards (top profile and lower right). This forced sediments to become sucked into the cave and deposited in a deltaic manner (lower left).

(1994a), with some additional notes in Mörner (2003, 2017c, d). It was formed at a paleoseismic event at 10160 varve years BP. Fig. 18 gives a view of the block deformation. Explosive methane venting seems – totally or partly – to have been involved (Mörner, 2017c).

Fig. 17. Mehedeby (from Mörner, 2003; Mörner & Sjöberg, 2011). The bedrock is cut up into large blocks with the fracture pattern still visible. Caves occur underneath and between the blocks.

Fig. 18. Gillberga Gryt (Sjöberg, 1994a; Mörner, 2003) deformed by an earthquake at about 10160 BP. The deformation produced a heap of big blocks with quite large caves underneath.

Trollberget

This site was investigated quite recently (Mörner 2017b, c). It consists of huge angular blocks broken loose from a previous smooth bedrock surface, well

striated and polished by glacial motions (Fig. 19). No doubt, it represents a severe deformation in postglacial time, maybe at around 10200 varve years BP. It seems to be a quite clear case of explosive methane venting tectonics (Mörner, 2017c).

Fig. 19. Trollberget (from Mörner, 2017c); a site of quite violent bedrock deformation hosting several sub-surface caves. The old glacially polished bedrock surface is well visible on the loose blocks, providing solid evidence that the deformation must have taken place in postglacial time.

Pukeberg

This is quite an interesting site (Sjöberg, 1994a; Mörner & Sjöberg, 2011). The cave and its surrounding area were recently investigated in detail (Mörner, 2017e). It seems obvious that it was formed by a combination of earthquake forces and methane venting tectonics (Mörner, 2017c). The age of deformation is estimated at about 10300 varve years BP.

The Pukeberg cave lies inside a hill that was solid and glacially well polished at deglaciation, but is now totally deformed into huge blocks and open fractures (Fig. 20).

The mode of deformation is well recorded in Fig. 21. An initial opening of fractures allowed a well-rounded erratic block of 60 cm diameter to fall into the cave below. A subsequent partial contraction of the fault fractures now no longer allows a block of that size to pass.

Other sites

The bedrock block caves illustrated above just represent a selection of available sites. Several other sites are discussed in Sjöberg (1994a). Torekulla Kyrka and Trollegater, for example, are block caves of very similar type to those of Boda (Fig. 11), Gillberga (Fig. 18) and Trollberget (Fig. 19).

Fig. 20. Pukeberg (from Mörner, 2017e); a glacially formed solid bedrock hill is now strongly faulted and fractured with individual blocks moved laterally.

Fig. 21. The mode of deformation at Pukeberg (Sjöberg, 1994a; Mörner, 2017e); extension opened the fractures so that a 60 cm round erratic block could fall down into the cave below, followed by contraction so that the fractures above the cave are now far narrower than the size of the erratic block.

COMPARISONS

Block and fracture caves of a seismotectonic origin have been described in Finland (Mörner, 2010). In recent years there have been several reports on paleoseismic fracturing of the crystalline bedrock in northwest Russia (e.g., Rodkin et al., 2012; Shvarev & Rodkin, 2017; Gorbatoev et al., 2017; Nikolaeva et al., 2018). Cooper & Mylroie (2015a, b) described “*large fractures, and upon failure, large talus blocks, assisting pseudokarst cave development*” from the

northeast of USA. An international comparison of potential records of methane venting tectonics (MVT) is given in Mörner (2017b, c).

CONCLUSIONS

After the preceding reviews of Swedish cave history and the evolution of paleoseismic understanding, we can now sum up some of the main conclusions with respect to the origin of fracture caves and block caves in Sweden:

- Sweden has an excellent database of speleological objects (SSF, 2018). The vast majority of sites (1919 or 66.8%) refer to fracture caves and block caves.
- The fracture caves and block caves (also known as boulder caves, bedrock caves or granite caves) have taken some time to be understood. With the thesis by Sjöberg (1994a), a seismotectonic origin became the most logical explanation. With the Boda Cave Project it became indisputable (Mörner et al., 2003).
- Methane venting tectonics has recently been proposed as the causal process of some heaps and cones of angular boulders (Mörner, 2003; 2017b, c). The most surprising thing with some of those block caves and block concentrations is that they took place in Late Holocene time, with four events occurring at about 3000 BP.
- We trust we have now successfully joined the concept of fracture caves and block caves in Sweden with the concept of a high paleoseismic activity in deglacial time as well as in Holocene time into a unified theory, where we claim that the majority of those caves were formed by seismotectonic processes and sometimes by methane venting tectonics.

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