Reply to “Marble caves and self-declared paradigms”

The three respondents (Lauritzen *et al*., 2009) are thanked for their interest in, and comments on, the article (Faulkner, 2009a), and especially for their generous introductory remarks. Stein-Erik is well-known for his U-series dating of stalagmites from caves in Norway and around the world, Ulv for his courageous exploration of arduous Norwegian caves in his youth, and Terje has recently completed a treatise about caves in Gråtådal, a valley in northern Norway that has some geological affinities with some valleys in South Nordland.

Commenting on their paragraphs 2–4, the diagram by Lauritzen (1986: Fig. 5) could be generalised by expanding the areal size of the ice-dammed lake (IDL) that supplies the recharge at the ice contact, and by showing that the outflow from the base of the cave may be back into the lake and / or into englacial Röthlisberger conduits within the ice as well as possibly into Nye conduits under the ice sheet. It could then usefully apply to many more (if not most) deglacial situations rather than just to the Kvithola example cited (see also Faulkner, 2007: Fig. 5). A crucial reference that was not cited is that by Lauritzen (1990), who believes that four high-altitude large relict phreatic caves in northern Norway may survive from the (mainly pre-glacial) Tertiary period and were enlarged below valley bottoms during several fluvial interglacial episodes, before glacial erosion deepened the valleys and the caves became abandoned. Instead, it seems more likely that (e.g.) the 40 m-diameter of Svarthamarhola was achieved primarily by phreatic dissolution beneath a succession of IDLs formed during glacial and stadial deglaciations. Similarly, the diving reports of continuing phreatic enlargement in the Holocene probably refer to caves in valley bottoms (as at Glomdal and Plurdal) that are likely to be partly removed by future glacial incision, rather than to be left hanging, because valley entrenchment rates are in the range 15–55 m per full glacial cycle (Lauritzen, 1990). Although the extent of the respondents’ disagreement is poorly specified, I suspect that this different interpretation is key to their position. The interesting work by Solbakk (2006) unfortunately does not recognise either that high-level IDLs that lowered each year were unlikely to deposit sediments or to cut observable terraces in valley sides or that they could last long enough to enlarge conduits to explorable sizes. Consequently, although he deduces that some caves in Gråtådal have formed over a few glacial cycles, he justifies this with arguments based on phreatic passage enlargement as part of an unclear ‘subglacial drainage route’.

It is uncertain in the fifth paragraph if the respondents claim to know about significantly more relict vadose cave passages in South Nordland. Or are they just confirming the existence of the many geometrically complex cave systems there that were primarily formed phreatically? My suggestion that *most* (but not *all*) caves (recorded down to a length of 5 m) developed in the last glacial cycle applies to all non-arctic Caledonide terranes *except* Northern Scandinavia, where insufficient morphological analysis has been published to decide this. Regarding what happened during the remaining 99% of the time, the 1% represents the roughly 1000 year deglacial periods, when most marble outcrops were submerged by active IDLs and passages could grow by chemical and mechanical erosion up to about 2m diameter, as did Kvithola (Lauritzen, 1986), agreeing with Lauritzen (1990, p35), who remarked that phreatic cave passage growth is ‘almost instantaneous’ in geological timescales. Roughly 10% of the time is represented by roughly 10,000 year interglacial periods, such as the present Holocene, when most caves develop by ‘mainly vadose’ processes, with phreatic dissolution only along low-level sumped conduits (e.g. Faulkner, 2007). The bulk of each glacial cycle is commonly occupied by three or four cold stadial periods (separated by warmer interstadials that are cooler than interglacials) that get progressively colder, with more extensive continental ice sheets, until the final glacial maximum is reached before a rapid deglaciation ushers in the next interglacial. Under cold-based ice and during periglacial and permafrost conditions, there is no flow of water to cause passage enlargement, but ice wedging may widen existing fractures in the marble, promoting later cave formation. At glacial maxima, subglacial lakes may form in warm-based valleys and submerge fractures and conduits. However, the evidence from Antarctica is that these do not flow continuously. Any water in contact with limestone would therefore saturate with calcite and be incapable of enlarging conduits in available timescales, as also discussed by Lauritzen (1986). What is commonly unknown at present is the extent of deglaciation during interstadial periods. Most reports describe at least the mountains of Scandinavia as remaining covered by an ice sheet throughout much of the last glaciation and the same may be true for the inland North American ice sheet. In Britain, the ice sheets were smaller and more dynamic, and there may have been several smaller and shorter deglaciations during each full glacial cycle, making the dissolution and sedimentation of cave passages more complex. However, in Scandinavia and New England (Faulkner, 2009b), the only opportunities for cave enlargement appear to be phreatic during deglaciation, and mainly vadose (including phreatic along sumps) during interglacials, possibly supplemented by similar processes during interstadials at high altitude caves if the ice sheet surface lowered sufficiently.

The article was offered to *NSS News* to coincide with the UIS 15th Congress at Kerrville, Texas, because it tries to discuss speleogenesis in the marble outcrops of all the Caledonide terranes for an audience unfamiliar with this hitherto largely ignored subject, with possible additional application to northern sedimentary limestones. It was not parochially limited to Norway. The title was deliberately designed to be intriguing and to provoke discussion. The new paradigm offered referred particularly to Central Scandinavia, whilst the article itself made it clear that extra processes must apply in Northern Scandinavia, an important point that the respondents have partly overlooked. For example, the active caves in Gråtådal are recharged in summer from perennial glaciers, a situation that does not occur in the Caledonides outside Northern Scandinavia. This explains their much larger mean size, because of vigorous vadose entrenchment throughout most of the Holocene (Faulkner, 2009c).

It is re-assuring that no reaction was made to the prime conclusion of the article, that the main control on the extent of karstification in Caledonide marble terranes is the thickness of the local ice sheet at glacial maxima. The three respondents are also encouraged to continue their research into the speleogenesis of Caledonide marbles. Although every cave is unique, they all, ultimately, depend on the laws of physics for their existence, and it is reasonable to expect that caves formed in similar lithologies that have experienced similar geological histories will share some simple common speleogenetic processes. Just to describe caves as 'polygenetic' does not take us much further forward. There is a danger that, by concentrating on just a few of the longer caves, researchers may 'not see the wood for the trees' and so miss the bigger picture: the short caves also provide much relevant information. There is an urgent need to analyse all the known caves >5 m long in *Northern Scandinavia* and to synthesise their speleogenesis so that common and additional processes can be derived and compared with those in the other Caledonide terranes. An essential component of this analysis will be to derive local deglacial sequences at appropriate topographic scales. In this way, the reasons suggested in the article for the much greater maximum lengths and depths of these marble caves, when compared with those in the rest of the Caledonides, should be further examined and extended. This would then address the morphological contrast issue raised quite legitimately in the fifth paragraph, but which this author regrettably feels he has little chance of advancing further himself. I would therefore like to urge Lauritzen, Holbye and Solbakk to attend to that task, to be less secretive about the work that they have apparently been doing in South Nordland, and to place their raw data and full results (including any Norwegian cave databases they have constructed) promptly in accessible places for all speleologists to share, with summaries in *Norsk Grotteblad*, the magazine of the Norwegian Speleological Society.

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