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Speleogenesis based on the deglacial studies of Arthur Raistrick in the Yorkshire Dales and Arne Grønlie in Norway

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Abstract: Arthur Raistrick produced his PhD Thesis in 1925, based on study of the glaciation of the cavernous Yorkshire Dales in England, and published 16 further works on topics linked to the glaciation of the wider area. During deglaciation, the formations of ice-dammed lakes above glaciers and moraine-dammed lakes below glaciers were revealed from their overflow channels and their residual clay and silt deposits. Fifty years after the Raistrick PhD, Arne Grønlie discussed the Quaternary history of the cavernous Vefsn area in southern Nordland, Norway, and showed how ice-dammed lakes were formed there during deglaciation. Neither author, whose insights and teachings have been largely overlooked for too long, discussed the dissolutional and depositional effects that water from glacial lakes could have on underlying karstified fractures and caves. However, later research demonstrates their importance for the speleogenesis of thousands of caves in Carboniferous sedimentary limestones in Yorkshire and in Palaeozoic Caledonide meta-limestones in central Scandinavia. Indeed, as there is no convincing alternative explanation for the development of, and sedimentation in, many of these caves, their existence supports the theory of ice-dammed lake establishment during deglaciation. Belatedly, this relationship is now being recognized from surface evidence in Britain and Sweden. This paper summarizes the evolution of deglacial ice-dammed lakes in the two regions and their roles in speleogenesis. The present deglaciation in Greenland (which is geologically, glaciologically and topographically the mirror-image of late Weichselian Scandinavia) by anthropogenic global warming might well reveal, enlarge and create karst caves at sites that are presently hidden beneath an ice sheet. Modelling the Greenlandic deglaciation is in its infancy, with deglacial hydrology only now starting to be considered. It is therefore clear that the formation and growth of ice-dammed lakes around nunataks and mountain ridges as the ice surface downwastes will increase melt rates dramatically. Consequently, this extra contribution to the oceanic volume means that the rate of future eustatic sea-level rise will be faster than is indicated by most recent predictions.

Keywords: Yorkshire; southern Nordland; deglaciation; Younger Dryas; ice-dammed lakes; phreatic dissolution; Greenland.

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Introduction

This paper introduces the similar studies by Arthur Raistrick in the Yorkshire Dales of England and by Arne Grønlie in the Vefsn area of southern Nordland in Norway. They both deduced that many large and deep ice-dammed lakes (IDLs) were created during deglaciation following the Last Glacial Maximum (LGM) in Marine Isotope Stage (MIS) 2. Later research indicates that all inland areas below the summits of both landscapes became inundated with flowing meltwater in IDLs as the icesheets downwasted. This caused dissolution along karstified fractures and any existing conduits, to create or enlarge the caves that are known today. Similar deglacial processes are expected to operate during the active warming in Greenland, where melt rates will raise sea-levels higher than current forecasts predict.

Arthur Raistrick's deglacial studies

The life and work of Dr Arthur Raistrick (1896–1991; Fig.1) were celebrated at a meeting and excursions based in Grassington, Yorkshire, UK on 20–21 July 2024 (Knight, 2024). This section discusses Raistrick's papers about glaciation and deglaciation, mainly in the karstified Yorkshire Dales. Arthur Raistrick was educated at Bradford Grammar School from 1908 until 1912, leaving at the age of 16 to start work as an electrical apprentice. In 1920 he gained a scholarship at the University of Leeds, to study civil engineering for his first degree, obtained in 1923. His PhD Thesis in geology, about the glaciation of the Pennines in the northern Yorkshire Dales (Raistrick, 1925), was completed 100 years ago, also at Leeds. It is a 158-page typescript with many maps, diagrams and photographs, for a study area >3000km^2.

Figure 1*: Arthur Raistrick addressing a National Park Authorities Conference in Harrogate (hosted by the Yorkshire Dales National Park) in 1975 or 1976. [Photo by John Starkey, on behalf of the then National Park Committee (fide Colin Speakman, e-mail communication).]*

His glacial studies built on 100 years of earlier local and wider geological research, as reported in >60 papers. A summary of his Thesis, with one comprehensive map (Fig.2) was published (Raistrick, 1926). Up to 1934 Raistrick produced 17 works on glacial topics. In the post-war years a further eight were published, mainly for a lay readership. His papers identified and compared the various local boulder clay ‘drift’ deposits and the ice movements (which caused some major river diversions) from the directions of moraines, drumlins and striae, and from the derivations of erratics.

Raistrick thought that most Yorkshire peaks were covered by ice at the Devensian (MIS2) glacial maximum. Importantly, he proposed that, during deglaciation, the melting glacial surface downwasted in six to eight stages into each valley, so that glaciers in main valleys held back meltwater lakes in the side valleys (Fig.2), and lakes up to 150m deep and 10km long formed later in the main valleys. Evidence for these IDLs was provided by: up to 30m of clay, laminated muds and silts in valley bottoms, deltas, terraces, some deep-cut cols where water had overflowed into another valley, and complex meltwater channel systems between previous ice edges and hillslopes. There were so many IDLs that Raistrick (1931) referred to a Yorkshire “lake district”. During a fourth stage of the deglaciation, they were contemporary with the enormous Glacial Lakes Pickering and Humber that formed in eastern England, after Scandinavian ice had reached and sealed the British coastline (Raistrick, 1933). Elevations of the upper ends of the shrinking valley glaciers and their IDLs decreased towards the east or south. Concurrently, the glacier snouts at the lower ends retreated by backwasting up the valleys towards the west or north, leaving

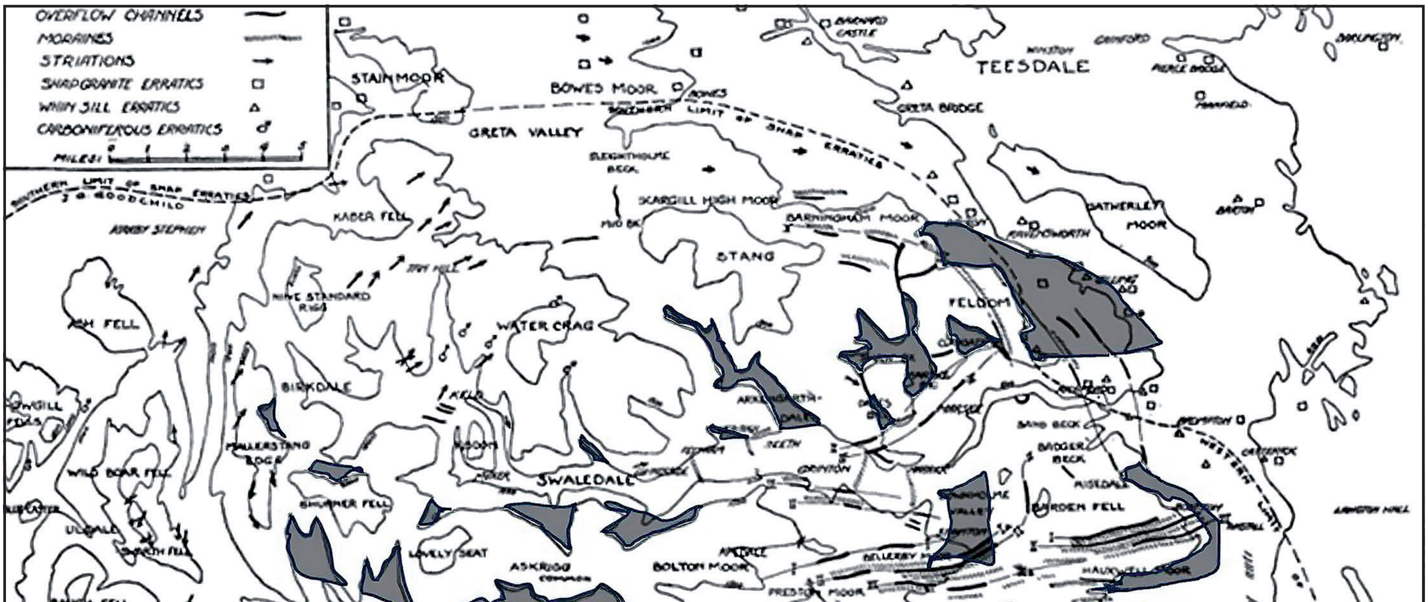

Figure 2: Map from Raistrick (1926) of his PhD study area, with some glacial lakes added from Raistrick (1925, Map IV). These lakes were held up in tributary valleys by glaciers in Swaledale, Wensleydale and the Vale of York.

terminal and recessional moraines that held up moraine-dammed lakes, some of which later silted-up or were drained by erosion, to form lake flats. If Raistrick was correct, the Dales limestones and the sites of their many caves were inundated by flowing meltwater in various types of IDLs during deglaciation, influencing both their speleogenesis and underground sedimentation.

Current understanding is that the Yorkshire Dales deglaciated about 18,000 calendar years ago (Vincent *et al*., 2010), after being covered completely by ice at the LGM, 27,000 years ago. Recent studies of the British Icesheet also conclude that deglaciation did occur by downwasting in many areas, including the Pennines (Clark *et al*., 2022), supporting the viability of the deglaciation process proposed by Raistrick.

There have been few previous assessments of Raistrick's contribution to understanding the glaciation of Yorkshire, and in particular to the process of deglaciation and the creation of local IDLs. Indeed, this important work and its implications for speleogenesis were largely ignored, until illustrated by a sequence showing the likely evolution of IDLs at each 60m lowering of the icesheet surface (Faulkner, 2006a; 2012a), and considered by Waltham and Lowe (2013). The deglacial formation of IDLs in a non-speleological context was also confirmed in NE Yorkshire by Bridgland *et al*. (2011). More recently, Murphy *et al*. (2015) deduced that the caves along Giggleswick Scar at the southern edge of the Yorkshire limestone outcrop were formed by dissolution beneath IDLs during the deglaciations following MIS6 and after the LGM. Lord *et al*. (2017) have also reported Pleistocene laminated sediments in the nearby Victoria Cave, suggesting deposition beneath a deglacial IDL..

Arne Grønlie's deglacial studies

Arne Grønlie (1912–2000) was born in Tromsø in northern Norway, the son of the geologist Ole Tobias Grønlie. He graduated in the late 1930s with a degree in geology at the University of Oslo and then assisted with his father's fieldwork. He became a school headmaster, teaching at Mo i Rana in Nordland, until the mid-1970s. There he was closely associated with the town's museum (Fig.3), which maintains displays about the local caves.

Mathematical formulae devised by Grønlie (1941a; 1941b; 1946; 1952) were used to compute the ages of Norwegian shorelines, the rates of isostatic uplift and the rise of eustatic sea-level during the Weichselian (MIS2) deglaciation, enabling the drawing of applicable sea-level curves. In 1975 Grønlie described the bedrock geology and landscape of the Vefsn area, at 65°30′N in southern Nordland. This included its meta-limestone (marble) and meta-dolostone outcrops, with a brief introduction to the locally well-known cave Øyfjellgrotta and the remote Stor Grublandsgrotta (Heap, 1968). His article also discussed the Quaternary geology and the effects of ice movements during the Weichselian glaciation. He showed that, during deglaciation, downwasting caused the summits to emerge as nunataks that became surrounded by many IDLs as the ice melted each summer. From these data, he devised a parabolic relationship (*"$H = 0.75t^2$"*) to give the height and time that the mountains became ice-free after the start of the Bølling Interstadial at 13,500 ^{14}C years BP (i.e. 14,700 calendar years BP). Contemporaneously, backwasting from the continental shelf led to eastward inland ice-margin retreat. He therefore also deduced the timings and locations of the marine limits during the deglacial competitions among isostatic uplift, eustatic sea-level rise and ice-margin retreat. In many areas of Vefsn, Grønlie (1975) recognized terrestrial moraines and terraces formed by IDLs some 10–30m above the levels of present lakes. His diagnostic features for lacustrine sedimentation in IDLs were: flat-bottomed valleys, stream meanders, groups of isolated tarns, deltas, lakes with uneven contours, and linear depositional (plus erosional) terraces. These are discernible on many Norwegian 1:50,000 maps, suggesting that deglacial IDLs were widespread, as later illustrated for the Main Scandinavian Watershed by Dahl *et al*. (1997, p.47).

Figure 3*: Arne Grønlie in 1990, presenting a celebratory speech at the 25th Anniversary Celebration of the founding of the Museum in Mo i Rana. [Photograph re-used with the kind approval of the Rana Museum division of the Helgeland Museum, Mo i Rana, Norway.]*

However, early and high-level static annular IDLs that formed around warming nunataks would have left little evidence of their existence. They had low sedimentation rates with small grain-sizes from small catchments and cut no terraces as the surrounding ice lowered annually.

The simple empirical Grønlie (1975) formula incorporates reducing accumulation and the increasing velocity of valley glaciers as the icesheet became more warm-based. It was reconstructed by Faulkner (2005) for the larger area of central Scandinavia to include the Younger Dryas (YD) isobase, which measures the increasing eastward isostatic uplift above sea-level since the end of the YD Stadial, of about 1m per kilometre (Sørensen *et al*., 1987):

$$H_u = 1700 + 5(\text{YD Isobase} - 220) - 0.75 \times 10^{-4} \times (13500 - t)^2 \text{ metres,}$$

where H_u = summer upper ice-melting height, without attempting to resolve the radiocarbon plateaux problems or any cooling reversals, and t = number of ^{14}C years BP.

After covering all of the local summits during the LGM, ice ablation accelerated at the start of the Bølling Interstadial at *c*.13,500 ^{14}C years BP, when Kvigtinden, which currently has a 1700m altitude at the 220m YD isobase (Fig.4), was probably the first nunatak to emerge. Ice downwasting increased to 0.5m per year at all isobases by the start of the Holocene, creating IDLs around each exposed summit in turn. Typically, the western ice margin backwasted at 70m per year, after reaching the coast of Nordland. By 8740 ^{14}C years BP all ice had backwasted or downwasted to the 220m YD isobase. Highest sea-levels were recorded in the karstic valleys of Svenningdal and upper Vefsndal by Grønlie (1975) at 9150 and 9080 ^{14}C years BP, based upon observations of sea-level morainic terraces. The sea melted and calved the tidewater glaciers from their northern and western sides near the local deglacial marine limit at present altitudes of 131m and 133m at the 190m and 200m YD isobases. Simultaneously, ablation melted the remnant dead ice, perhaps with intraglacial lakes that were open to the sky above bedrock, on the other sides. Thus, the last ice to survive was commonly in valleys at these intermediate altitudes. The pioneering work by Grønlie (1975) in Vefsn thereby provided an understanding of the relationship between terrestrial icesheet downwasting and tidewater glacier retreat. Despite later improvements in the accuracy of place heights, radiocarbon dates and the isobase patterns, the reconstructed Grønlie formula gives many marine marginal moraine date predictions that are within 300 years of the latest published results. However, a glacier remained at Tärna in Sweden until *c*.6000 ^{14}C years BP (Earl-Gulet *et al*., 1998), but downwasting was faster along the coast, where the sea submerged large areas of isostatically depressed strandflat.

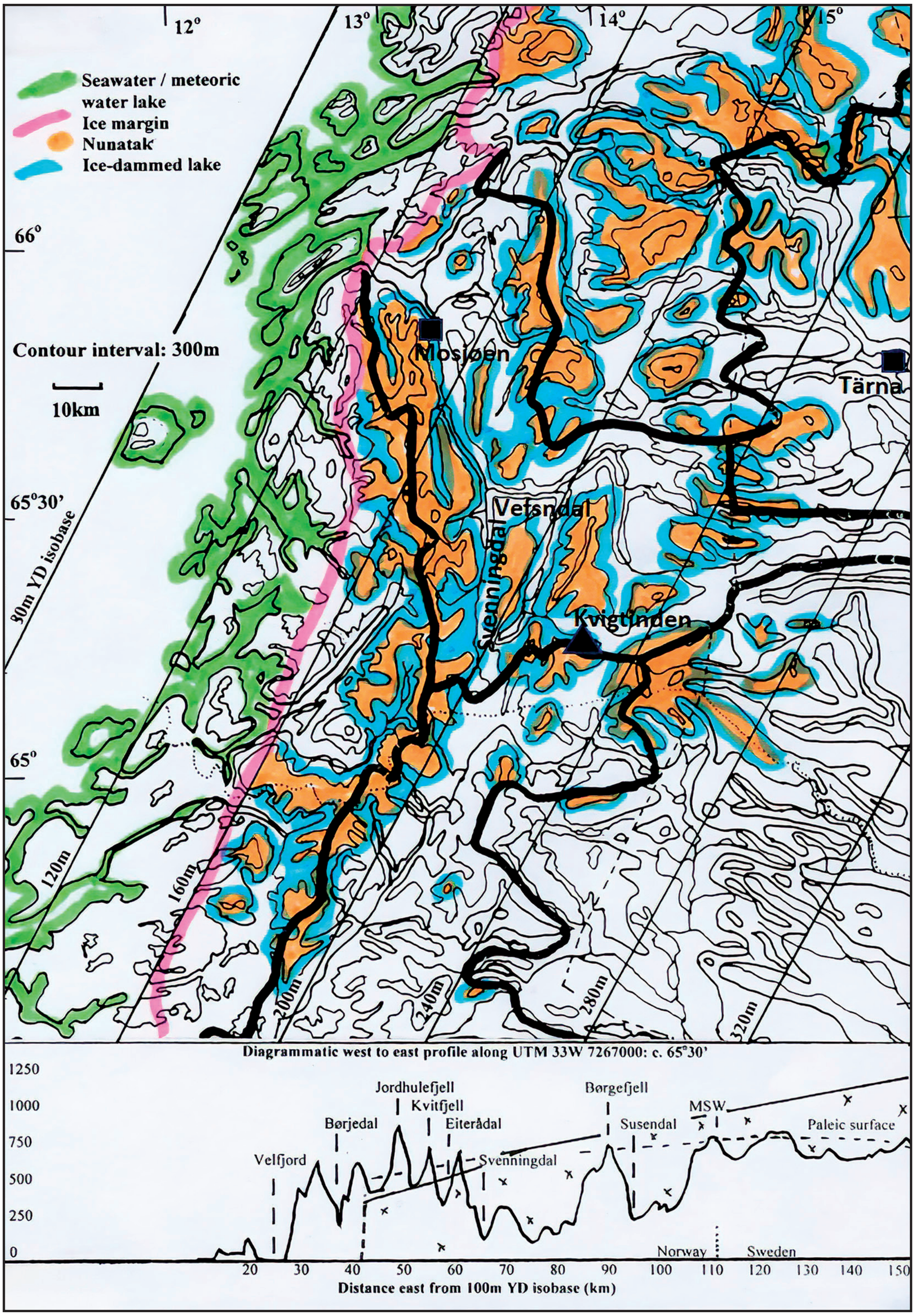

***Figure** 4:*
The deglaciation of central Scandinavia at 10,100 ¹⁴C years BP, showing YD isobases and major watersheds.
Assumed IDLs are plotted in blue; deglaciated land is shown brown.
Inland areas shown uncoloured remained glaciated.

See also the Key: image top left.

[From Faulkner, 2005.]

Later studies

The motivation for Faulkner (2005; 2006b) to consider the evolution of IDLs was to explain the existence of >1000 karst caves in the >1000 individual meta-limestone outcrops in central Scandinavia. This is an area of 40,000km^2 that extends from the Norwegian coast to the Caledonide thrust front in Sweden and, in Norway, from Grong northward to Mo i Rana. He deduced that they were initiated by phreatic dissolution and mechanical erosion of the non-porous marble at up to 1mm per year, when open fractures, created during deglacial isostatic uplift, were inundated by flowing aggressive meltwater with little dissolved calcite beneath IDLs. Maps generated using the reconstructed Grønlie formula showed the assumed evolution and merging of IDLs from 12,000–8700 ^{14}C years BP, at roughly 300 ^{14}C year intervals. They illustrated the recession of the decaying icesheet and its synchronous thinning as its margin lost its sharp, approximately linear, definition under the increasing influence of topography.

The maps (e.g., Fig.4) showed that most of the land became inundated by lowering IDLs that could exceed 10km^2 in area and 100m in depth for periods of up to 2000 calendar years. The only exceptions were the actual peaks and the coastal slopes, where the water ran directly to the sea. The integrated deglacial hydrology included precipitation from a higher catchment area flowing via an IDL through a karst system back into the IDL. If the lower ice remained cold-based, the water flowed out over a spillway col, or as a supraglacial stream, or as a lateral meltwater channel beside a valley glacier. Where the ice became warm-based, the IDL increased greatly in volume as a subglacial reservoir and water could flow out into an englacial (Röthlisberger) conduit.

If the warm base continued to the ice margin, the IDL could also drain away along a Nye tunnel channel in the bedrock as a subglacial waterway at the valley bottom, perhaps reducing further karstic dissolution. Proglacial, moraine-dammed, lakes could also form below a retreating glacial snout. Lundqvist (1972) defined an IDL as water dependant on damming by dynamically active ice. Five local IDL types were recognized, which were labelled: Nunatak, Westward-flowing, Backward-flowing, Eastward-flowing and Ice margin. Evidence that Backward-flowing IDLs could collapse at jökulhlaups was demonstrated by rock-strewn gullies below cols only on the western side of the N−S aligned mountain ridge of the karstic Jordhulefjell. Later and more detailed studies of the relationships among IDLs, cave formation in central Scandinavia and relative sea-levels were by Faulkner (2008; 2009a; 2010; 2011a; 2011b; 2012b; 2018; 2019 and 2020). Local sea-level curves based on those for Trondheim by Svendsen and Mangerud (1987: Fig.11) were constructed and used to resolve the competitions among eustatic sea-level rise, isostatic uplift and ice margin retreat in places adjacent to IDLs. Similar processes applied to cave development in most of the other glaciated Caledonide marble terranes in North America, Ireland and Scotland (Faulkner, 2009b). The prime influences on their cave dimensions were the thicknesses of the successive Quaternary icesheets and the positions of the caves relative to deglacial IDLs and to interglacial local catchment areas.

These studies support the >100-year-old hypothesis that deep extensive glacial lakes were dammed in the Scandinavian mountains during ice-sheet retreat (e.g. Högbom, 1897). This had been disputed during the last 70 years by some opinions that the ice retreated into the high mountains, whilst some valleys remained filled with stagnant dead ice and small water bodies, including by Lundqvist (1972). However, Blomdin *et al.* (2021) used LiDAR to identify >36,000 landforms associated with the evolution of high-level IDLs during the deglaciation of the Weichselian Fenno-Scandinavian Icesheet in Jämtland, as discussed by Faulkner (2021). This is just one inland mountainous Swedish county along the Norwegian border that also contains marble caves. Additionally, Regnell *et al*. (2023) reported >4500 relict shorelines, deltas and meltwater channels related to 30 IDLs that formed during the deglacial history of central Jämtland, just southeast of southern Nordland, as also discussed by Faulkner (2024). Thus, the role of ice-dammed lakes in causing phreatic karstic dissolution to explain the creation of most of the marble caves of central Scandinavia during the deglaciation of the Scandinavian Icesheet has been further supported by this detailed inland geomorphological evidence.

The future deglaciation in Greenland

Global warming is irreversible in decadal timescales, despite limited efforts to reduce the use of fossils fuels. P_{CO_2} and global mean temperature have already risen by >50ppm and by *c.* 1.5°C above their pre-industrial levels. Decadal rising trends of P_{CO_2}, temperature and sea level approximate to straight-line graphs, so that mean temperature rises will reach +2°C by 2045 and +3°C by 2085. It is therefore quite clear that the Earth's climate will tend towards that during the Eemian Interglacial at MIS5e, when the global temperature was 3°C higher, the Greenland icesheet about 60% smaller, and sea-level consequently several metres higher. The present climate is already causing significant problems, with civilisation regularly being impacted by heat waves, fires, droughts, floods and storms. Regrettably, the scale and magnitude of these crises will now increase inevitably year by year. Another threat yet to manifest itself fully is the impact that rising sea-levels and more powerful storms will have on low-lying islands and on coastal cities, especially those with underground transport systems. If all ice on Greenland melted, eustatic sea-level would rise by 7m.

Interestingly, Greenland presently resembles a geological, glaciological and topographical mirror image of Scandinavia during its Weichselian deglaciation at the beginning of the Holocene Interglacial, as is illustrated partly in Figure 4. Indeed, many Greenlandic IDLs can be observed using *Google Earth*, especially around nunataks on the mountainous east side, although the relict caves in Caledonide limestones at Centrumsø in northeastern Greenland (Moseley *et al*., 2020) are already deglaciated. However, modelling the forthcoming deglaciation in Greenland is in its infancy, with deglacial hydrology only now being considered (but only to account for the evolution of supraglacial lakes). It is also clear, in comparison with the Weichselian deglaciation of Scandinavia, that the formation and growth of IDLs around nunataks and mountain ridges as the ice surface downwastes will increase melt rates dramatically. IDLs contribute to deglacial melting and sea-level rise by overflowing as supraglacial streams, melting englacial conduits as Röthlisberger channels, and creating larger and deeper subglacial reservoirs, which can also collapse at jökulhlaups, as can IDLs themselves. The final flows are along bedrock Nye channels as subglacial waterways, perhaps via subglacial lakes. The stagnant lowering ice finally disappears at ice-walled lakes at intermediate altitudes, where it meets the retreating ice margin that backwastes from the coast (Grønlie, 1975). Because these deglacial mechanisms are still not modelled for Greenland, the predictable effect of this extra ice melt contribution to the rate of sea-level rise needs to be added to previous forecasts.

Although the subglacial geology of Greenland remains largely unknown (Ebbing *et al.,* 2025), it is quite possible that deglaciation will reveal more limestone outcrops that might already contain karst caves, or will create new fractures, which would enlarge further by dissolution beneath IDLs. The present mostly arid and unglaciated Peary Land in northern Greenland, which contains the nearest-known carbonates to the North Pole, might also contain unexplored relict pre-Quaternary karst caves.

Conclusions

There have been few previous assessments of the contributions of Arthur Raistrick and Arne Grønlie to understanding the deglaciations of the karstic Yorkshire Dales in England and of the Vefsn area in Norway. Independently, they envisaged almost identical processes to explain the deglacial landforms and the creation of local ice-dammed lakes, but without realizing the significance for speleogenesis and underground clastic sedimentation. Furthermore, their important works have, so far, been largely ignored by Quaternary scientists and geomorphologists. With the renewed interest in the deglaciations of the Devensian and Weichselian icesheets in Britain and Scandinavia after the Last Glacial Maximum, there is now an opportunity for their findings to be reviewed using modern analytical and dating techniques. In England, the production of ice-dammed lakes during the deglaciation of the Yorkshire Dales should be correlated with the much-better-studied creation of the enormous ice-dammed lakes inland of the Yorkshire coast. In Scandinavia, the study of ice-dammed lakes in Jämtland in Sweden should be extended to the Norwegian coast and the whole international border area. With this knowledge, the timescales and processes of the speleogenesis and sedimentation of the karst caves in both regions should be better understood and placed firmly within the sequence of Quaternary glaciations. The understandings gained from this work would also help in forecasting the effects of the upcoming deglaciation in Greenland and the future rate of sea-level rise, so that the worst impacts of global warming can be foreseen and at least partially mitigated.

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