Jens Esmark, Vassryggen and early glacial theory in Britain

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Abstract. An end moraine (Vassryggen) and associated sandur, described by Jens Esmark as early as 1824, was the first pre-Neoglacial glacigenic landform association to be recognised as such. It forms the most important element of a range of evidence used by Esmark in support of his continental-scale glaciation hypothesis. The career of Esmark, who became a foundation professor of the Royal Frederick University in Christiania (Oslo) is outlined, and his influence on the development of the glacial theory in Britain is appraised, as is the role of his associate Robert Jameson in Edinburgh. A sketch of the glacial geology of the Forsand area of southwest Norway examines Vassryggen and its allied landforms in the context of deglaciation and sea-level change at the close of the Younger Dryas stadial.

In south west Norway, some 25 km ESE of Stavanger, a magnificent glacial end moraine marks the maximum extent of a now-vanished valley glacier. This cuts across and blocks the floor of a glacial trough eroded into Precambrian gneiss. Locally it is known as Vassryggen (the lake ridge) but internationally it is also known as the Esmark Moraine, named after Jens Esmark, who, in 1824, was the first geologist to describe and interpret it as an ice-marginal geomorphological feature (Fig. 1). The lake of Haukalivatn lies at the foot of the proximal slope, while on the distal side there is a sandur - a gently sloping outwash plain. (*Note:* -et *and* -en *are suffixes that mean the in Norwegian, and context determines whether they do or do not appear on the ends of place names.*) The feature dates from the final stadial (Younger Dryas) of the Last Glacial (Weichselian) stage. There are strong historical grounds for claiming that this landform couplet, many kilometres from the nearest modern glacier, was the first ever to be recognised as having a genetic relationship to a former active glacier margin (Fig. 2).

In 1824, Esmark promulgated the concept of an extensive glaciation of mainland Europe, citing a range of field evidence that he had observed whilst travelling in the Alps, Denmark, the north German Plain and Norway. Esmark's paper is now universally regarded as a classic of the glacial literature, but sadly is not as well known as it deserves to be. The objectives here are (a) to review the historical context of Esmark's pioneering glacial geological research, (b) to examine its impact on the application of the glacial theory in Britain and (c) to assess the end moraine in the context of the last deglaciation and the modern landscape.

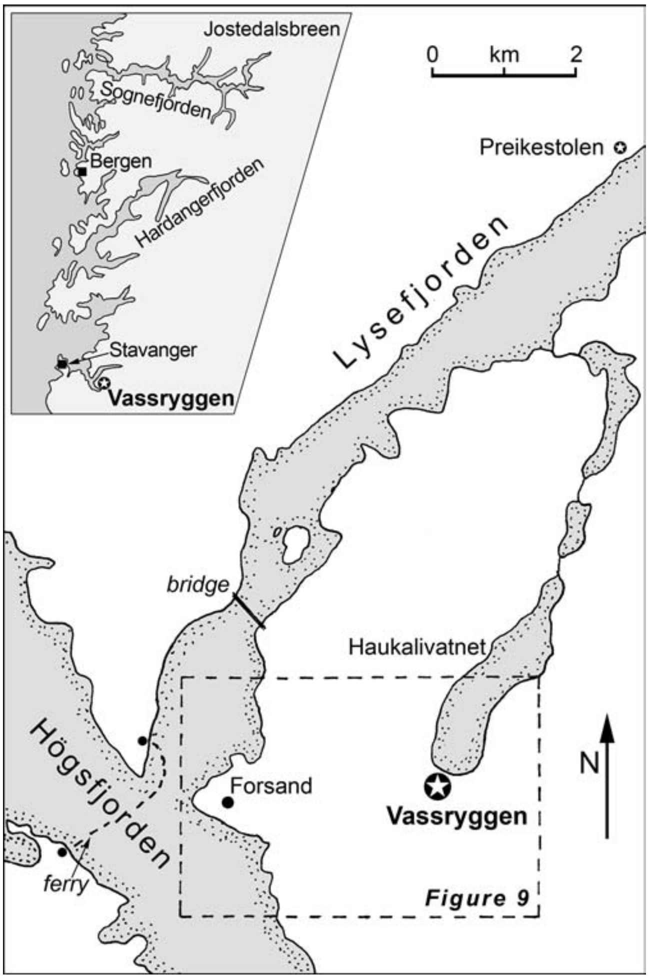


Figure 1. Location of Forsand and the Jøtunheimen area within south-west Norway.

Background

In the eighteenth century, during the Age of Enlightenment, many savants appreciated the ability of modern glaciers to transport sediment, and some realised that glacial debris found far beyond current glacier limits indicated that glaciers had once been more extensive than at present (Rudwick, 2005). As Charlesworth (1957: p623) was to observe, *The glacial theory, like many other scientific theories of note, occurred to several people at roughly the same time if not in quite identical form*. Among these was the alleged father of modern geology, James Hutton, who, in his classic treatise of 1795, suggested that Alpine glaciers had been considerably more extensive (to account for the granite erratics scattered over the limestone Juras), but omitted to apply this concept to Britain (Davies, 1968). Although Menzies (2002) claims that Hutton's promoter, John Playfair (1802), in his *Illustrations of the Huttonian Theory of the Earth*, proposed that Scotland had been glaciated, this is not the case. Interestingly, Sissons (1967: p29), in his splendid book on the evolution of Scotland's scenery, attributes to Esmark the role of catalyst in the recognition of Scottish glaciation, although Price (1983), in his detailed review of the last 30,000 years in Scotland, makes no mention of him.

From a specifically British perspective, the key event in the acceptance of the idea of glaciation in these islands was undoubtedly Louis Agassiz's journey through Britain and Ireland in 1840. Six years earlier, Agassiz had made the first of his several visits to Britain while researching his initial specialism, the study of fossil fish. During his stay he was chaperoned by William Buckland, then Reader in Geology and Mineralogy at the University of Oxford. Four years later, Buckland, accompanied by his wife, made a reciprocal visit to Agassiz in his home country of Switzerland. By that time Agassiz was devoting all of his spare time to developing a glacial theory in the context of the Alps. It is therefore not surprising that he demonstrated to Buckland the field evidence on which his crystallising glacial theory depended.

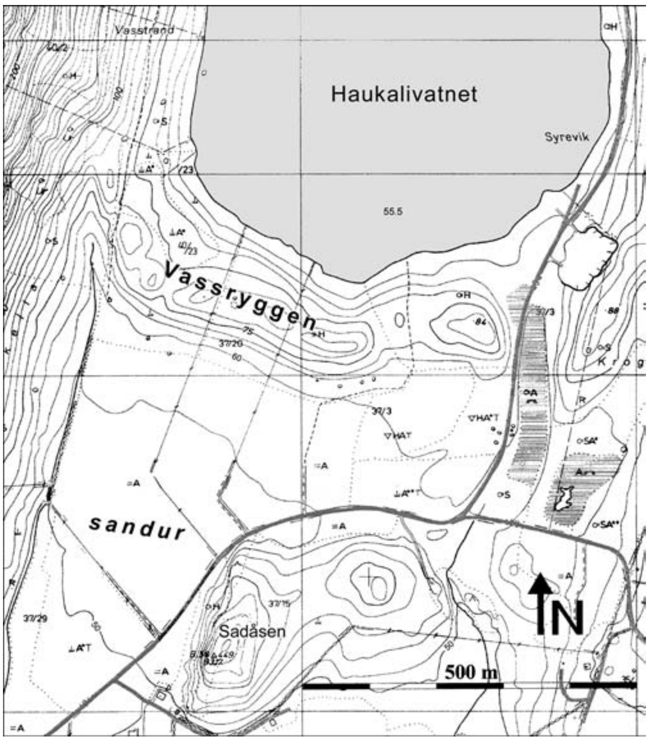


***Figure 2**. Map showing the morphology of the Vassryggen end moraine (the Esmark Moraine). Contour interval: 5m.*

Apparently Buckland expressed support for his interpretation, but also went on to describe to Agassiz some British geomorphological features that he believed were analogous to the glacial landforms they were examining in Switzerland. They resolved that they would jointly investigate this topic further when Agassiz next visited Britain (Agassiz, 1876).

In his presidential address to the Geological Society of London on 21st February 1840, Buckland (1840: p261) commented on Esmark's 1824 paper as follows - *the most important portion of this paper .... show(s) that the greater part of Norway has, at some period, been covered with ice, and that the granite blocks, so abundant in that country, have been brought to their present place by glaciers.* Just over half a year later, at the annual meeting of the British Association for the Advancement of Science, which fortuitously was held in Glasgow in the midst of a drumlin field, Agassiz presented his hypothesis that the landscapes of Britain and Ireland bore the imprint of past glacial processes (Agassiz, 1840-1). During a joint field excursion immediately after the Glasgow meeting, Buckland declared that he had been fully won over by Agassiz's reasoning (Boylan, 1998). This led to a major paradigm shift, for, as the palaeontologist Edward Forbes commented in a letter of 1841 to Louis Agassiz, *you have made all the geologists glacier-mad here, and they are turning Great Britain into an ice-house* (Agassiz, 1885). For instance, on October 16th 1841, Buckland was to write the following note in the visitor's book at the Goat Hotel, Beddgelert, in Gwynedd, north Wales - *Notice to geologists – At Pont-aber-glass-llyn, 100 yards below the bridge ... see a good example of the furrows, flutings, and striae on rounded and polished surfaces of the rock, which Agassiz refers to the action of glaciers. See many similar effects on the left, or south-west, side of the pass of Llanberis.* (Davies, 1969: p263). This entry was subsequently framed and displayed at the hotel, but, following a change in ownership, its present whereabouts is unknown. Nevertheless, despite the glacial euphoria, the general acceptance of the glacial land ice theory was to be delayed by several decades until officers of the British Geological Survey commenced serious mapping of superficial sediments and landforms.

Jens Esmark (1763-1839)

Summaries of Esmark's life have been compiled by Buckland (1840), Rózsa *et al* (2003), Rørdam (1890), Schetelig (1926), Kettner (1964) and S.A. Andersen (1980). He was born in the hamlet of Houlbjerg (Hovlbjaerg), some 30 km west of Aarhus in Denmark, the son of the local parson. Perhaps fittingly, Houlbjerg is situated in the middle of the Danish 'Younger Morainic' landscape produced by the Last Glaciation in eastern Jutland, and lies just south of a major incised sub-glacial meltwater tunnel valley. After attending the local high school in the town of

Randers, his senior studies were undertaken at the university in Copenhagen, and these included natural history, theology and medicine. For a short period, Esmark was employed at a hospital, but soon he embarked upon an in-depth training in mineralogy and geology. This involved him attending the mining school at Kongsberg (founded in 1757) in southern Norway, close to the important silver-mining area. At that time Norway was a province of Denmark. He then returned to Copenhagen University as a student in law and geometry, after which he was awarded a six-year travelling scholarship.

During 1791 and 1792 he attended the famous Bergakademie in Freiberg, Saxony, close to the Erzgebirge Mountains, where his contemporaries included Leopold von Buch and Alexander Humboldt. This academy was directed by the inspirational Saxon geologist Abraham Gottlob Werner, and not surprisingly, during his stay there he acquired the strong Wernerian (Neptunian) sympathies which he maintained for the rest of his life. Essentially, the Neptunist view was that all rocks had been precipitated from a primordial ocean. At that time a furious debate was in progress over the origin of rocks, with the main alternative being Hutton's ideas of Vulcanism which involved the internal heat of the Earth. Esmark then moved to the German mining centre of Schemnitz (Hungarian Selmec, and now Banska Stiavnica in Slovakia) for training in mineral analysis, and in 1794 toured Hungary, western Romania and southern Poland visiting mines, before spending some months in Chemnitz (Rózsa *et al* 2003). On his return to Freiberg he published an account of his journey with the title 'Short description of a mineralogical tour through Hungary, Transylvania and the Banat' (Esmark 1798, 1799). This work established him as a geologist and mineralogist of European repute (Fig. 3).

Late in 1797, Esmark settled permanently in Norway, first returning to the Kongsberg Mining School as a chief mining inspector and later (1802) as a lecturer and supervisor in mineralogy, chemistry and physics. While working at Kongsberg he travelled extensively in southern Norway and indulged in mountaineering; he made the first ascent of Snøhetta on Dovrefjell in 1798. This activity brought him face-to-face with modern glaciers and their immediate environs, an experience which was to manifest itself later in his benchmark paper of 1824. In Kongsberg, in the same year, he married Vibeke Thrane Brünnich, who hailed from Copenhagen. They had two sons, H. Morten Esmark, later a vicar and well-known mineralogist, and Lauritz M. Esmark who became Professor of Zoology at the University in Christiania.

Following pressure from the *Selskabet for Norges Vel* (Society for the good of Norway) in 1811, the Danish king agreed to support the foundation of a new Kongelige Frederiks Universitet (The Royal Frederick University). Originally, the intention was to locate the

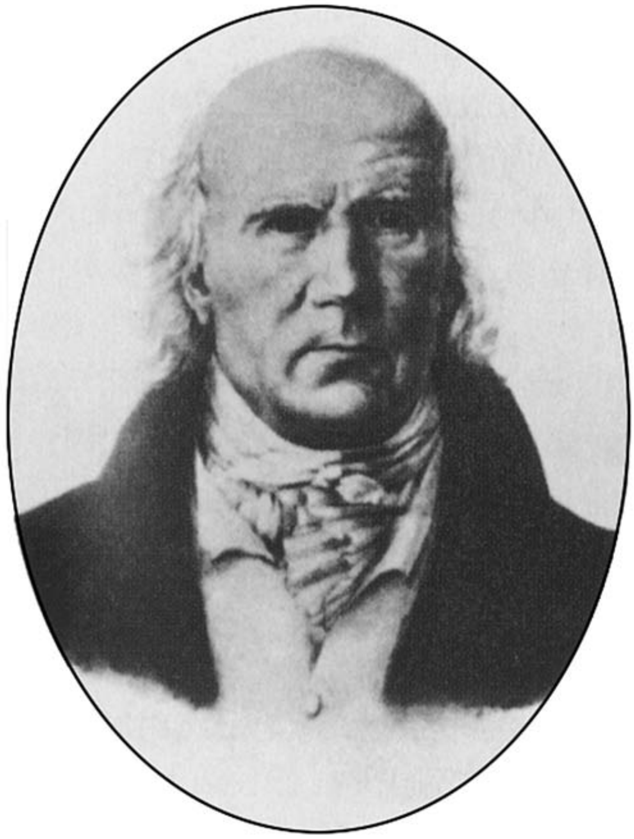
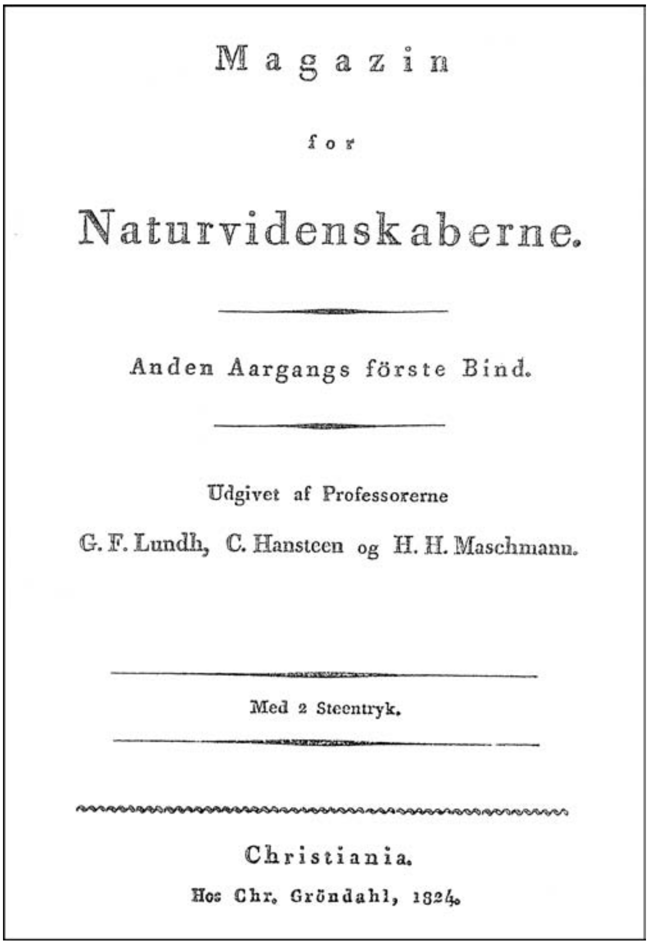


***Figure 3**. Portrait of Jens Esmark (from Schiffuer, 1935: p19)*

new institution in Kongsberg, but soon this was changed in favour of Christiania. From the beginning (1813), it was planned that the new university would include applied subjects within its curriculum, and to support this objective, the mining school was transferred from Kongsberg (Popperwell, 1972). So, when in 1814 a Chair of Bergverkvitenskap (Mining Science) was created in the new Faculty of Philosophy, Esmark was elected to occupy it. Despite the inclusion of sciences, Latin remained the official language of the university until 1845 (it was renamed University of Oslo as late as 1939).

Internationally, 1814 was a critical and politically complex year in the aftermath of the Napoleonic wars in Europe. At the Treaty of Kiel, Denmark, as an ally of France, was obliged to cede its province of Norway to Sweden, following 400 years of sovereignty (ironically, the former Norwegian territories of Færoe Islands, Greenland and Iceland were overlooked, and these remained as part of Denmark). Latent Norwegian nationalism was triggered by this change, and as a consequence a new constitution was declared at Eidsvoll, and a parliament (known as the Storting) established. Effectively Norway was an independent nation for a few months, until the will of the victorious powers was able to assert itself. Following union, the Swedish crown showed sensible pragmatism and permitted effective Norwegian home rule, and then in return, the Storting voted in favour of a combined


Magazin

for

Naturvidenskaberne.

Anden Aargangs förste Bind.

Udgivet af Professorerne

G. F. Lundh, C. Hansteen og H. H. Maschmann.

Med 2 Steentryk.

Christiania.

Hos Chr. Gröndahl, 1824.

***Figure 4**. Title page of the second year issue of the Magazin for Naturvidenskarberne (1824).*

kingdom. Ironically, the national language remained Danish and it could be argued that technically Esmark became a Swedish citizen (Norwegian misgivings being acknowledged!).

Esmark remained in this post at the university until he died early in 1839 after an illness which had lasted several years. From 1816 to 1838 he was responsible for maintaining a series of meteorological observations which are the oldest pertaining to the capital (Christiania became Kristiania in 1897, and finally Oslo in 1925). He also published a book (in Danish and German editions) concerning a geological circular journey in 1827 (anticlockwise) from the capital up to central Norway and into Værdal, during which he paid special attention to establishing the heights and plotting a relief profile (Esmark, 1829a, 1829b). According to William Buckland, he was an excellent chess player.

Esmark was probably one of the founding foreign members of the Wernerian Natural History Society in Edinburgh (he was a member at least by 1811). This link was to become significant for British glacial geological history. In the summer of 1815, he made a scientific study visit to England, and read a short mineralogical paper before the Geological Society of London on June 18th, (Esmark, 1816). He was elected as only the third Foreign Member of the society. A good indication of his international eminence at that time can be gauged from the fact that in the society's list of foreign members he was senior to such distinguished geologists as Georges Cuvier, his mentor Abraham Werner, and Alexander von Humboldt.

Esmark's classic paper of 1824

It should first be emphasised that this paper by Esmark dates from well *before* Agassiz became involved with modern and ancient glaciation in his native Switzerland, and sixteen years prior to his pivotal visit to Britain. The paper appeared in the Christiania-published journal *Magazin for Naturvidenskaberne*, then in its second year (Fig. 4). This new journal's content resembled the Memoirs of the Wernerian Natural History Society, and the issue containing Esmark's paper included another (in Danish) by the English seafarer Captain Scoresby on the rediscovery of parts of eastern Greenland, and a report on an English scientific expedition to the polar seas. The only extant copies in Britain are at the British Library and in the library of the Royal Society of London.

Esmark's paper (also written in Danish) is not wholly devoted to his glacial hypothesis, and the first half concerns a discourse on the formation of the Earth with Wernerian undertones (Fig. 5). It is in the second part where he argues that his adopted country, Norway, had once been covered by *immense masses of ice* which reached *down to sea level*.

The evidence from the Norwegian landscape, which he considered gave support to his glacial hypothesis, included:-

(a) Scattered boulder-sized blocks, often of a different composition to the rock beneath, some even occurring on mountain summits.

(b) A widespread sediment cover consisting of poorly-sorted admixture of large-sized material in a finer matrix, which was inconsistent with attribution to fluvial action, i.e. boulder clay or till.

(c) Steep-sided flat bottomed valleys (U-shaped cross profiles). He wrote - *Ice or glaciers, by their immense expanding powers must beyond doubt have produced this change in their original form from this circumstance, that they were continually sliding downwards from the higher mountains to the lower districts and by progressive motion carried with them the masses of stone which they had torn from the mountains.*

(d) Fluted, smoothed and scoured bedrock surfaces, including conglomerates which appeared to have been *cut across by a sharp knife.*

(e) A ridge (Vassryggen), which completely crosses a U-shaped valley from one side to the other. Here he made his most dramatic landform insight since he interpreted this as an end moraine produced by a

II.

Bidrag til vor Jordklodes Historie,

af

Professor J. Esmark.

Vidi ego, qvod fuerat qvondam solidissima tellus
Esse fretum. Vidi factas ex æqvore terras
Et procul a pelago conchæ jacuere marinæ.
Ovidii Metamorph.: lib. XV.

Gaae vi med vore Betragtninger og Undersögelser om vor Jordklode saa langt tilbage, indtil vi komme til den Tid, da Skaberen böd: "Bliv," finde vi Alt indhyllet i et tyk Mörke. Der har dog ikke manglet paa vittige Hoveder, som have dannet sig Theorier om Verdens Skabelse, ja man har saadanne allerede af flere græske Philosopher. Disse havde tvende væsentlig forskjellige Meninger, i det Nogle troede at Jorden var opstaaet ved Ild, Andre derimod ved Vand. *Anaxarches fra Lampsacus* har erkjendt, at Fjeldene i hans Land have staaet under Vand, hvilken Mening og *Aristoteles*, *Eratostenes*, *Strabo* og *Plutark* have antaget. I de nyere Tider

Figure 5*. First page of Esmark's paper in the Magazine for Naturvidenskarberne 1824.*

glacier which had subsequently vanished. In the original he referred to this as a *gletcher vold* (glacial rampart) and regarded it as *his strongest proof* that glaciers had been much more extensive in the past.

(f) A plain distal to the ridge (i.e. an outwash plain or sandur).

But he was not quite finished. Next he utilised current geomorphological and sedimentological methodologies to infer the nature of former geological processes by making comparisons with modern depositional environments, the so-called actualistic approach. Esmark clearly realised that the depositional environments of modern Norwegian glaciers displayed striking parallels with the much older landform assemblage that he had identified near Stavanger. He drew independent support from Mr O. Tank, a young mineralogist who accompanied him during the examination of Vassryggen and later the modern ice margins between Londfjord and Lomb. He reported that when Tank encountered the modern glacier environments for the first time he did not require any prompting before immediately making a genetic connection between the two. Sadly, progress in British glacial geology during the first half of the twentieth century was often retarded by an absence of such an actualistic approach.

Esmark's paper in English translation

Remarkably, within two years, a complete English translation of Esmark's paper was published in Edinburgh (Esmark, 1826) (Fig. 6). However, the unidentified translator indulged in some fanciful language such that the original title *Bidrag til vor jordklodes historie,* that translates as *Contribution to the history of our Earth,* became *Remarks tending to explain the geological history of the Earth.*

The rationale of undertaking the translation is of special relevance to the historical development of the glacial theory in Britain. It arose through the initiative of Robert Jameson (1774-1854), who occupied the chair of Regius Professor of Natural History in the University of Edinburgh from 1804 to 1854 (Fig. 7). Jameson, like Esmark, had attended classes given by Abraham Werner at the Freiberg Mining Academy. In his case it was from 1800 only to 1802, when the death of his father forced his return to Scotland. During his time at Freiberg he was converted *into Neptunism's most devoted and ardent disciple* (Davis, 1969: p147). On March 3rd 1808 he formed the Wernerian Natural History Society of Edinburgh, just two months after

Remarks tending to explain the Geological History of the Earth. By Professor ESMARK.*

If we carry back our investigations with regard to the structure of the earth to its original formation, we find all involved in thick darkness. There have not been wanting, however, ingenious men, who have formed theories on this subject; we find some of these even among the Greek philosophers. Among these, two opposite opinions especially prevailed; some considered fire as the chief agent in this process; others water. Anaxarchus from Lampascus averred, that in his country the mountains had stood under water. Aristotle, Eratosthenes, Strabo, and Plutarch, supported his opinion. In later times, nobody doubts this fact, as we find petrified animals on the highest mountains. In America, such have been found in the Andes, at the height of 12,000 Rhenish feet above the level of the sea †. At first it was believed that these petrifactions were remains of the general deluge; but a more accurate investigation discovered, that they could not all be derived from this source; for, as we find on the highest mountains, and inclosed in the bowels of the earth, petrifactions of animals in every stage of their growth, and arranged in classes such as we still find alive in the sea, it may be readily inferred, that the duration of the flood was not sufficient to produce that amazing multitude of organic forms, the remains of which are now to be found in the bosom of the earth, but that these places must have once been the bottom of the sea.

* It being our intention to lay before our readers, as occasion may offer, statements of the opinions on the formation of the Earth entertained by distinguished writers, we now communicate the ideas on this subject by Esmark, from the Christiania Journal.

† Colonel Gerard found many *ammonites* at a height of 16,200 feet above the sea, in the Himalya range of mountains.

Figure 6*. First page of Esmark's translated paper in the Edinburgh New Philosophical Journal in 1826.*

the founding of the Geological Society of London, and thereafter was re-elected annually as president for the rest of his life! Geikie (1909: p5) described Edinburgh as *the headquarters of the Neptunists in this country with a policy of active propaganda of Wernerian doctrines.* Esmark, as we have seen, was an early member of the Society, and this almost certainly arose through his friendship with Jameson and their shared Neptunist views derived from their common Freiburg heritage. The oral proceedings of the Wernerian Natural History Society are recorded as an appendix (History of the Society) in the last pages of each memoir. These reveal that during the February and March meetings of 1826, Jameson had read out instalments of Esmark's paper. It is reasonable to assume that the second instalment, presented during the March 11th session, featured Esmark's glacial geological hypothesis. Unfortunately, there is no report of Jameson's personal views at that time, although it is highly likely that he favoured the hypothesis, since otherwise he would have been unlikely to promote its reading.

From 1819 to 1824, Jameson was the founder, and initially co-editor with David Brewster, of the *The Edinburgh Philosophical Journal*. Following a disagreement with Brewster, he started, as sole editor, *The **New** Edinburgh Philosophical Journal*, a post which he held for the following 30 years, with a specific policy of *exhibiting a view of the progressive improvements and discoveries in the sciences and the arts*. This publication is frequently referred to as *Jameson's Journal* such was his domination of it.

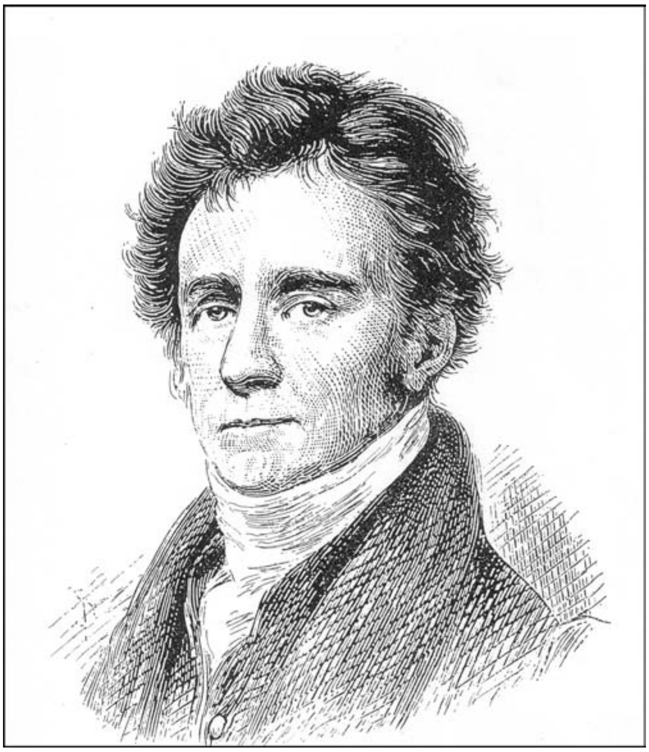


***Figure** 7. Portrait of Robert Jameson (from a miniature).*

Jameson regarded himself as *conductor* rather than editor of the journal, and during his tenure he published a wide range of manuscripts. Some of these related to cold environments; in the quarterly issue (October-December 1826) which contained Esmark's paper, there was one on Arctic seas and allied ice. He developed a policy of using his journal to keep British geologists abreast of scientific developments by instigating a *Scientific Intelligence* section that consisted of summaries of new findings.

Jameson's role in the concept of Scottish glaciation

Gordon Herries Davies has chronicled how Jameson was probably the first person to publicly declare that glacial processes had contributed to the character of the British landscape (Davies, 1969). As a student at Edinburgh University, the celebrated Scottish glaciologist J. D. Forbes (1809-1868), attended a natural history course given by Jameson in 1827-28. This had a syllabus covering zoology, botany, palaeontology, geology, mineralogy, the philosophy of zoology and practical work both in the museum and the field. Lectures were given five days a week for a period of five months and the emphasis was on mineralogy and geology. Secord (1991) describes the course as *one of the leading natural history courses in the world*. Crucially, Forbes's lecture notes from Jameson's lecture 12 on 27th November 1827 survive, and these state - *Moraine is the name for stones, fragments and deposits by the motion of the glacier on its borders which have accumulated in great masses. In Norway and in Scotland such appearances are observed which are considered proofs of formerly existent glaciers* (Cunningham, 1990: p15).

In the previous session, 1826-27, among the over 200 attendees taking this course was a seventeen year old second-year undergraduate called Charles Darwin, who attended as an extracurricular activity. He records that Jameson came across as an *old brown dry stick* and further added with respect to the lectures (probably at a particularly cynical moment) *The sole effect they produced on me was the determination never as long as I lived to read a book on geology, or in way any to study the science* (Barlow, 1958: p52-3; Browne, 1995). Nevertheless, despite his unflattering impression of Jameson, Darwin assiduously attended the course and thereby gained a thorough grounding in the basics of geology. He personally owned the course text-book which, unsurprisingly, was Jameson's latest book (Jameson, 1821), and his copy survives in the Darwin archive of Cambridge University Library. The many hand-written annotations it contains reveal that he must have studied it carefully (Herbert, 2005). Jameson in 1826 was undoubtedly fired by the implications of Esmark's glacial theory, and his teaching of the elements of glacial geology and their significance with respect to Scotland reflected this. It is very plausible that Darwin witnessed Jameson's first glacial exposition, but apparently its implications did not register with him at the time, and it was not until

1842 that he adopted much of the newly defined glacial theory.

Four years after leaving Edinburgh, in 1831, Darwin spent at least a week in North Wales with Adam Sedgwick, in order to become better acquainted in field geology. This venture had been arranged by his Cambridge tutor J. S. Henslow who, although a Professor of Botany, was originally a Professor of Mineralogy at Cambridge. Years later Darwin recalled that they totally missed seeing the abundant evidence of glaciation - *on this tour I had a striking instance how easy it is to overlook phenomena, however conspicuous, before they have been observed by anyone .... neither of us saw a trace of the wonderful glacial phenomena all around us, we did not notice the plainly scored rocks, the perched boulders, the lateral and terminal moraines.*

Another astonishing paper included in the first part of Jameson's journal in 1827 was by G Bohr (1773-1832) a teacher from Bergen. It is unknown whether this had been specially translated into English but was almost certainly derived from Bohr (1820). It records actualistic observations made on a journey to Jostedalen, on the eastern side of the Josterdalsbreen ice cap (the largest in Europe) in southern Norway. Among others, the now well-known glaciers of Berset, Nigaard and Lodal are described. It is very clear from the narrative that Bohr appreciated that these glaciers were subject to size variations and referred to the *encroachments of the glaciers and of the mischief occasioned by them* (Bohr, 1827: p257). Further, he notes that a peasant called Claus Elvekragen had earlier recalled seeing the roof of a house buried in a moraine. From today's perspective, this observation suggests that, during the culmination of the Late Neoglacial Little Ice Age around 1750AD, an advancing glacier must have almost completely enveloped a building. The term *moraine* is noted as being a Swiss word for *masses of gravel, and sand and stone*. Bohr notes Esmark's work on establishing the heights of various Norwegian summits, and it is clear that he must have visited Jostedal and was familiar with its glaciers.

The delayed impact of Esmark's hypothesis

Despite the availability of an English translation of Esmark's paper, and an extended French summary (Esmark, 1827), it appears to have had little impact on the British geological community. The reasons behind the delayed acceptance of the glacial theory have attracted the attention of science historians. Rudwick (1969), in a review arising from the publication of an English translation of Agassiz's *Studies on Glaciers* monograph of 1840, points out that the diluvial theory, which invoked a universal deluge linked to the Mosaic testimony, was very persuasive. He argued that this was especially so when viewed in the context of a clearly anomalous recent Earth history. Support was strengthened by an awareness of the tsunami generated by the 1755 Lisbon earthquake and its coastal impact. Further, there was considerable conceptual difficulty in reconciling the huge areas of northern and central Europe (hypothetically affected by glaciation) with the comparatively limited areas occupied by modern glaciers. Even Professor B. M. Keilhau (1797-1858), a younger geological colleague of Esmark at the University of Christiania, advocated the flood hypothesis until 1840, even though he had experience of the Jotunheimen glaciated region, north Norway and Svalbard (Keilhau, 1831; Andersen, 2000). Keilhau joined the Wernerian Natural History Society in 1836, and became the seventh member from Norway. In opposing such deeply embedded conventional wisdom, Esmark's perception is truly remarkable. Although Rudwick cites Esmark's paper, he did not convey the full nature of its content, and in particular made no mention of what Esmark regarded as the strongest proof - the end moraine of Vassryggen.

Unfortunately, Esmark's paper has on occasion escaped the attention of some major historians of glacial geology and glaciology. Inexplicably, Esmark is not mentioned at all in the authoritative two-part Norwegian tome on glacial matters published by the Norwegian Polar Institute (Hoel & Werenskiold, 1962; and Hoel & Norvik, 1962). James Geikie, who was long associated with Edinburgh and glacial geology, appears never to have discussed or cited it in his voluminous writings. Yet he was a friend of Helland, who was the first Norwegian geologist to investigate and publish on Vassryggen after Esmark (Helland, 1875), and cites this latter paper in his book *Prehistoric Europe* (Geikie, 1881). Even more surprisingly, North (1943) is silent in his very detailed review of the glacial theory marking the centenary of Agassiz's 1840 visit to Britain, despite the paper's subtitle *notes on manuscripts and publications relating to its origin, development and its introduction into Britain*. Chorley *et al*. (1964), in the first volume of their masterful history of global geomorphology, appear to be unaware of the contents of Esmark's paper, and make no specific reference to him in their chapter reviewing the development of the glacial theory. Yet, in their informative index, there is an entry for *Esmarch* (Esmarck). This simply records that this worker is noted to have expressed the view that the Norwegian glaciers were once much more extensive. Paradoxically, in their main text they include a quotation from Sir Roderick Murchison's paper of 1835-1836. This reveals that even though Murchison remained unconvinced, he was clearly aware of 'Esmarck's' interpretations and attendant implications (p205). Probably this citation accounts for the index entry. Hansen (1970) focussed on the role of Agassiz and Lyell, apparently unaware of the existence of Esmark's paper and the activities of Jameson. Bill Sarjeant (1980: v2, p968-9), in his massive multi-volume history, has a brief entry on 'Esmarch' as a mineralogist, but sadly omits any mention of his landmark glacial paper.

The reawakening

Following the founding of the British Glaciological Society in 1946, the *Journal of Glaciology* was launched, and it soon commenced a series of articles on the theme of *Early discoverers.* The fourth of these, *Esmark on glaciation*, was communicated by Kaare Strøm, the distinguished Norwegian Professor of Geography and Limnology in the University of Oslo. This paper consisted of an extract from the Esmark translation of 1826 of that part relating to the glaciation of Norway. Apart from tinkering with the spelling of some geographical names, he somewhat disappointingly makes virtually no comment on the significance of the text (Strøm, 1950). Changing geographical names remains a continuing problem in Norway, in part because of the existence of two official languages, Riksmål and Nynorsk, with their range of dialects and spelling reforms.

Finally *Boreas*, which is an international Quaternary research journal, later initiated a series called *Boreas Pioneers* with a similar objective to the Early discoverers just mentioned. From a Norwegian standpoint, Bjørn Andersen (1992) contributed a comprehensive analysis and review of the significance of Esmark's paper. Both Andersen and Borns (1994) in their attractive textbook and Andersen (2000) in his popular book on *The Ice Age in Norway* briefly cover the work of Esmark, and Vassryggen in particular. Unfortunately, as of 2005, this latter book was not available in any British library.

The glacial geology of the Forsand area

Vassryggen end moraine lies in Forsand Kommune (district). In the earlier literature Forsand is spelt Fossand. Forsand is an extended village stretching from the coast inland along the featureless valley floor towards the end moraine. It lies at the eastern margin of the mouth of Lysefjorden, a magnificent classic glacial trough flooded by the sea (Ahlmann, 1919; Andersen, 2000). At one very accessible overlook called Preikestolen (the priest's pulpit), the fjord wall drops vertically for 600m (Fig. 8). The bathymetry of the fjord was investigated by Kaare Strøm, who established that the maximum water depth is 457m (Strøm, 1936). Towards the lower end of the main Lysefjord trough, at a low elevation on the east shore, a narrow valley diverges to run roughly parallel with the master feature. Southwards this widens into a valley occupied by the lake known as Haukalivatnet. The north slope of the Vassryggen end moraine forms the southern shore of this lake, which now drains out to the north, against the direction of former ice flow.

Following Esmark, four Norwegian geologists have contributed to a growing understanding of the area's glacial history. First, Helland (1875) discussed the genesis of moraines and terraces bordering the lower ends of lakes, since landform associations of this character are widespread in southern Norway. He highlighted Esmark's description and added that the moraine crest is 35m above the lake. He inferred a local relative sea level some 35m above that of the present at the time of formation.

Second, Reusch (1901), with the aid of a sketch map, briefly commented on the occurrence of the sandars extending between Vassryggen and the eastern segment of the Lysefjorden end moraine at Forsand (Fossan) and appreciated that they were contemporary.

Third, Hansen (1913) in a long paper on the theme of the Ice Age in the Sørlandet region, recognised that an end moraine and raised shoreline system that had been named Ra (ra is an old Norwegian term for ridge) was extensive; he incorporated the observations of Esmark, Helland and Reusch in his discussion.

Finally, Andersen (1954), on the basis of geomorphological mapping of ice-marginal morainic features, was able to accurately reconstruct the dimensions of the last (Younger Dryas) Lysefjord glacier. He demonstrated that it was an outlet glacier extending from an inland ice source for about 30 km to the sea, with a maximum ice thickness of 1300m and a surface slope towards its terminus of 75 m/km. Inland, the gradient was reduced to 20 m/km. At the mouth of Lysefjorden, beyond the confining valley walls, the glacier terminus was seen to have expanded to form a lobate foot extending into Høgsfjorden. Today, the main frontal end moraine remains submerged below sea level at a depth between 10 and 15 m, but its lateral margins are emergent as two separate arcuate ridges on each side of the fjord mouth.

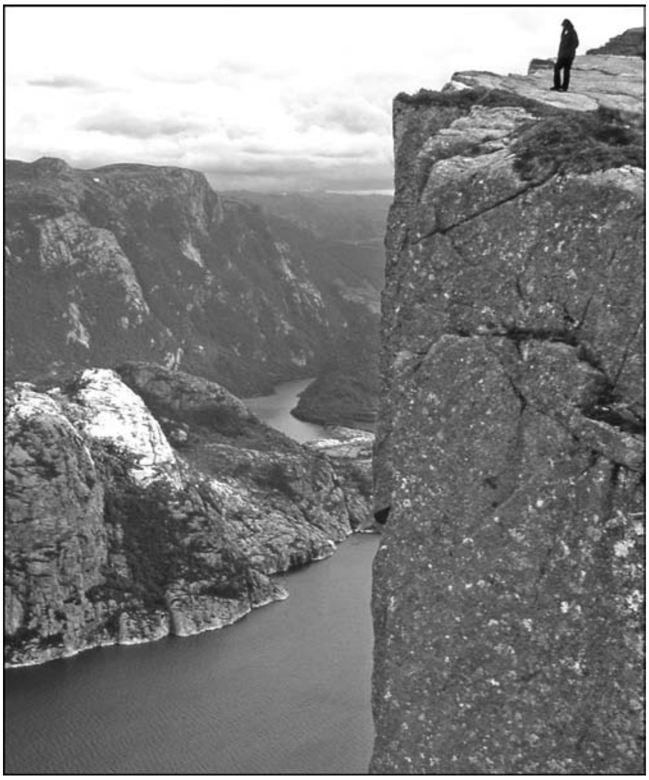


***Figure 8**. The view south past Preiteskolen, the rock ledge 600m above Lysefjorden, with the first lake just visible in the glaciated trough that continues to Haukalivatn.*

Andersen's model shows how a distributary of the Lysefjord glacier entered the sub-trough now occupied by Haukalivatnet lying at 53-54m above sea level, to form Vassryggen at its southern terminus. Unlike the main trunk glacier, this branch ended above the contemporary sea level, and rather than forming a calving ice margin, it produced a typical sub-aerial end moraine with a sandur extending from the glacier margin towards the sea which at that time was some 40m above that of present. Although partially covered in forest today, the Vassryggen ridge is about 800m long forming a prominent arcuate landform rising to 20-30m above its surroundings (Fig. 9). The proximal slope is steep and descends below the lake level to a maximum depth of 30m. In contrast, the distal slope is shallower and abruptly terminates at the head of the southward-sloping palaeosandur surface known locally as Fossanmoen (Fig. 10). The sandur splits around the till-plastered bedrock hill of Sadåsen (Figs. 2 and 9).

In composition, the moraine surface is typical of glacial ridges in the Norwegian mountains, consisting of a bimodal mixture of mainly sub-rounded large cobble and boulder-sized clasts, set within a sandy gravely matrix. Close to the eastern end of Vassryggen, there is a breach in the ridge where a glacial meltwater river discharged. Since this channel is incised a little into the sandur surface extending across the valley floor, it is likely that it was active for a short period after the ice had withdrawn from the maximum limit. Interestingly, Esmark was clearly aware of the significance of this feature.

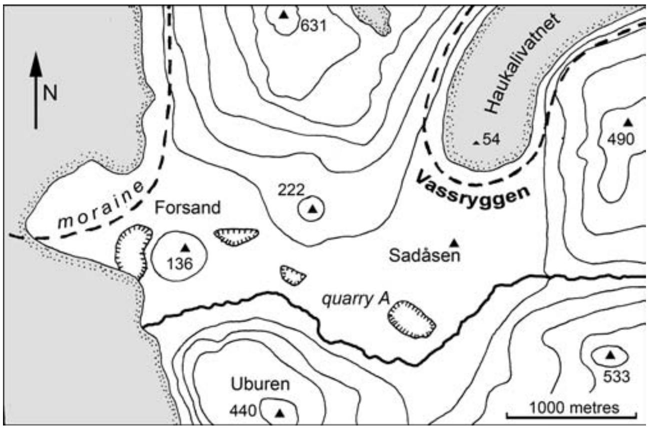


***Figure 9**. Forsand area with Vassryggen and the Younger Dryas ice limit after Andersen. (Base map from Statens Kartverk M711 Series Sheet 1212 1 Høle. 1:50,000, 1991)*

Recently in connection with a ground water study, seismic data, ground penetrating radar and boreholes have substantially augmented the Quaternary geological data base of the area immediately around Vassryggen (Eckholdt & Wahl, 2002). Two water abstraction wells sunk close to the intake of the former meltwater breach in the end moraine attained depths of 26m and 32m. These reveal a variable succession of sand, sandy gravels, gravels and till. The geophysical measurements suggest that the bedrock beneath the sandur is overlain by 40-50m of sediment infill.

During the readvance maximum, the eastern side of the lobate foot of the trunk Lysefjord glacier built an end moraine that blocked the former exit of the east-west trending Forsand valley, thereby obliging the

***Figure 10**. Vassryggen, from the distal side looking north from the hill of Sadåsen, with part of the lake of Haukalivatn visible beyond the moraine ridge.*

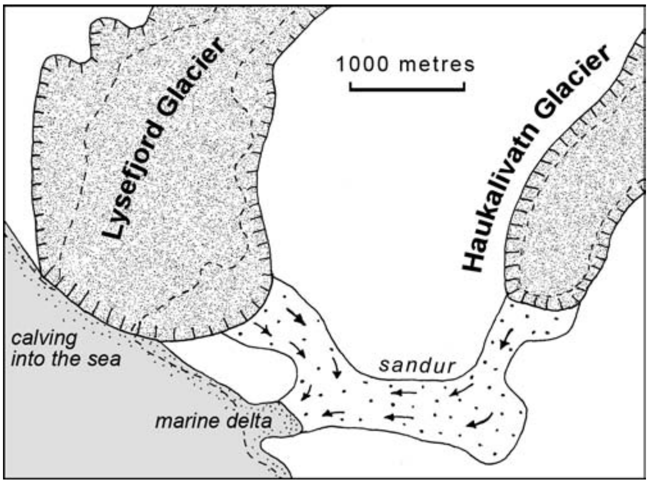


***Figure 11**. Palaeogeographical reconstruction of the Forsand area when the Vassrygg moraine was being formed at the Younger Dryas maximum, 12,700 - 11,400 cal yr BP.*

meltwater issuing from it to build a sandur sloping to the south east. This meltwater merged with another westward directed flow originating from Vassryggen, and the combined river went around the southern side of the bedrock hill of Åslund (136m). In the process, an extending delta was created where it entered the sea (Fig. 11). Post-glacially the modern Forsandåna (Fossanåna) river system has incised into the delta-sandar surface as it adjusted its bed in response to an overall lowering of sea level due to isostatic uplift.

These sandur and allied deltaic sediments are economically important sources of aggregate and sand. A factory on the shore at Forsand processes the sand to produce a dry ready-mix mortar that is transported by ship.

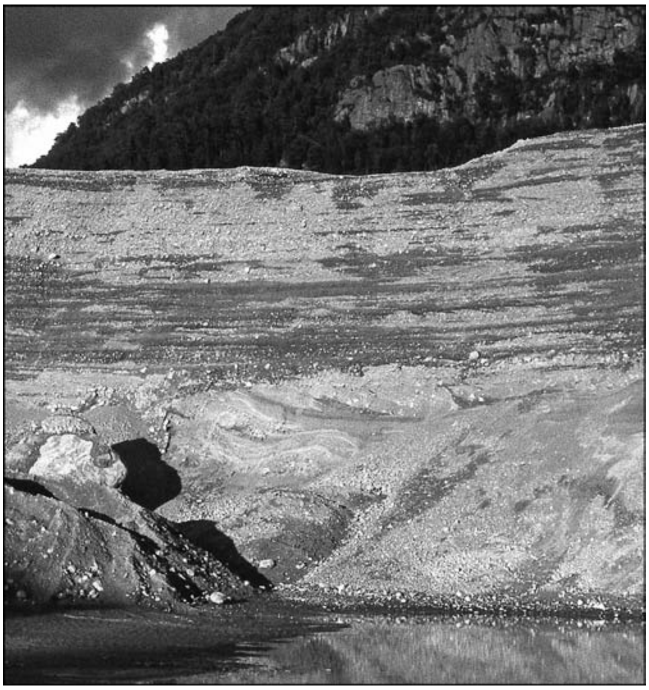


***Figure 12**. Section through the sandur deposits in Quarry A, showing the characteristic horizontal stratification.*

Where quarrying has occurred, sections reveal an earlier lower valley infill consisting of till and outwash sediments with giant erratics, which probably date from the main Weichselian deglaciation. The upper fill consists of the Younger Dryas sandur and delta deposits above a paraconformity that separates the two sequences. Typically they consist of sandy gravels, 3-6m thick, dominated by near-horizontal stratification (Fig. 12). On the coast just east of Forsand, huge volumes of sediment have been quarried, exposing the once-buried bedrock. A prominent horizontal line on the hillside marks the former upper surface of the aggradation, related to the marine limit in Høgsfjorden at the time of deposition. Several abandoned quarries line the east side of the road leading from Forsand towards Vassryggen. In the second of these, the main succession was seen to be characterised by large scale cross-bedded sets, signifying the progressive extension of a delta into the sea. On top of these, up to 5m of horizontal strata represented the extension of the sandur deposits across the former delta, the unusual thickness possibly due to a rising sea level at the time of aggradation (Andersen, pers. com. 2006; Rose *et al*, 1977: Lohne *et al*, 2004).

Regional context of Vassryggen

Andersen (1954) mapped the pattern of deglaciation in the Ryfylke region of Rogaland County, southwest Norway (including Forsand), and identified two concentric end moraine systems produced by distinct glacier readvances during the wastage of the main Norwegian ice sheet. These systems he attributed to what he termed the Lysefjord and the Trollgaren Stadials. The outer of the glacial limits attributed to the Lysefjord Stadial incorporated Vassryggen. Later, Andersen was able to demonstrate that eastwards this limit could be traced into the Younger Dryas Ra moraines of Sørlandet and Oslo fjord. Ultimately, landforms associated with the Younger Dryas ice margins could be traced throughout Fennoscandia. These landforms are interpreted as signifying a glacial re-advance induced by the dramatic climatic deterioration during the Younger Dryas (known as the Loch Lomond Stadial in Britain) with an absolute age of 12.8 - 11.6 ka BP. A Younger Dryas readvance of at least 40 km to the Herdla moraine can be demonstrated in the area north of Bergen (Mangerud, 2000).

It is important to appreciate that the Younger Dryas glacial readvance was superimposed on an overall pattern of ice retreat from the Last Glacial Maximum ice border that lay off-shore in southwest Norway. Hence, outside the Younger Dryas maximum limit, the landscape contains abundant evidence of both erosional and depositional glacial processes. It is often difficult to differentiate these slightly older features from the slightly younger landforms and deposits, since they were formed by the same processes. Also it has to be recognised that glacial erosional forms in bedrock represent the end products of repeated Quaternary glaciations.

Conclusions

The glacial depositional landforms in the Forsand area are of special significance in the development of ideas concerning global climatic change. Jens Esmark was clearly a scientist of exceptional merit, since he had the perception to identify and interpret a range of evidence occurring across much of northern Europe in terms of a now-vanished phase of extensive glaciation. Specifically at Vassryggen, some distance from modern glaciers, he had the ability to see that this end moraine landform was essentially identical to those which had been produced by modern glaciers. Unfortunately, his contemporaries were mostly unable to comprehend the importance of his hypothesis, although Robert Jameson did appreciate that it provided an innovative explanation for features in Scotland that had previously been attributed to a deluge. Even though Jameson was not himself a specialist worker in the field, he attempted to bring Esmark's hypothesis to a wider audience by having it translated into English and by featuring it in his lecture course. Of equal importance was his pioneering attempt to apply the hypothesis to the interpretation of Scotland's scenery.

These days, the public at large is almost daily being reminded by the media that much of the modern world's glacial ice is potentially unstable due to feedback processes arising from anthropogenic atmospheric pollution. Doomsday scenarios predict imminent catastrophic glacier collapse and awful effects on coastlines and their populations. It is appropriate to recall the lessons from the investigation of recent Earth history, particularly the Younger Dryas climatic deterioration. This was both preceded and followed by abrupt climate change, as is clearly apparent in the isotope stratigraphy of the Greenland ice-sheet (Fig. 13). Rapid global change is not a new phenomenon, although the Younger Dryas shifts were only experienced by small human populations unlike those confronting any imminent future change.

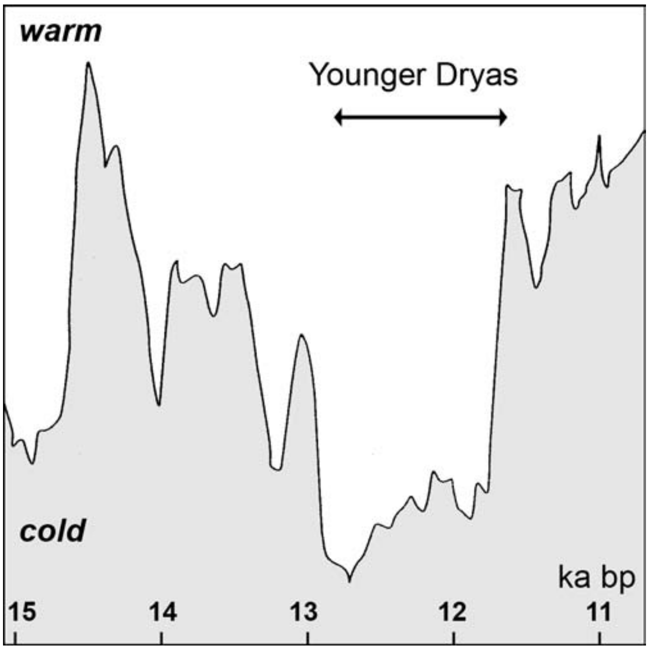


Figure 13*. The signal of the Younger Dryas climatic deterioration, as expressed by oxygen isotope variations in a central Greenland ice core (after Grootes and Stuiver, 1997). The time scale is in thousands of years before present ("present" is 1950AD); 11,600 years ago, the temperature increased by about 8ºC within no more than a few decades.*

From the perspective of both prehistoric rapid climatic change and the conceptual development of the glacial theory, it is suggested that the Forsand glacial geology warrants listing as a candidate for World Heritage Site status. This would have the merit of bringing the pioneering work of Esmark and his key site to the attention of a much greater lay and professional audience than hitherto. It would also help to ensure that any future quarry developments would be in areas that would not jeopardise this largely pristine landscape.

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