DISCUSSION

Discussion of glacial or non-glacial origin for the Bigganjargga tillite, Finnmark, northern Norway

M. B. Edwards comments: Of all the geological occurrences he had seen, this was the most remarkable and revealing. For him it was a spiritual place, and the journey was a pilgrimage; he used this word himself This was now the seventh time he was making this journey. Thus wrote Rosendahl (1945, p. 22; my translation from Norwegian) about the geologist Sederholm. Decades later, after dozens more publications of innumerable additional outcrops, the 'Reusch's Moraine' exposure of upper Proterozoic glacial tillite resting on a glacially striated pavement (Reusch, 1891) remains unique and significant.

Writing about this exposure, Jensen & Wulff-Pedersen (1996) concluded 'There is no evidence for glacial origin or contribution for the diamictite material' (p. 137) in the Bigganjargga tillite. This discussion explains why I disagree with their conclusions.

Jensen & Wulff-Pedersen are rightly concerned with the surface that underlies Reusch's Moraine. Instead of it being a portion of a major regional unconformity as suggested by previous workers, they maintain that it is just another bedding surface in an otherwise homogeneous succession of sandstones. There seem to be two principal reasons for their interpretation: (1) Crowell (1964) expressed the same reservations, and (2) the sandstones above and below the striated pavement 'appear identical to the observer' (p. 141).

In this context, I believe it is important to note that Dr Crowell made his several hours of observations during the course of an IGC excursion in 1960 to northern Norway. No matter how prominent the observer was (I know and admire Dr Crowell), I think it is inappropriate to ignore or reject other geologists' observations (many of which were cited by Jensen & Wulff-Pedersen) that were based on years of field and laboratory study. Perhaps the most notable documentation (not cited by Jensen & Wulff-Pedersen) is in the paper by Rosendahl (1945; Rosendahl had previously published some of these observations in his paper of 1931). His figure 5 is a photograph of the cross-bedded sandstone that underlies the diamictite. In the figure caption he states: one sees erosional cross-bedding in the sandstones in the older formation (my translation from the Norwegian). In the text, Rosendahl wrote: this surface … is truly the most well-defined division between one geological formation and the overlying one that is known on the Earth. An impressive photograph is also presented by Siedlecka & Roberts (fig. 7, 1992) that also shows the cross-bedded sandstones below the diamictite, and gradual truncation of a sandstone bed towards the east (right in the figure).

The contrast between the highly stratified, cross-bedded and rippled shallow water sandstones (of the Veinesbugten Formation) that underlie the diamictite, with the medium to thick-bedded massive sandstones that overlie it has thus been noted by many workers. Extensive modern descriptions of the former were provided by Banks *et al.* (1974) and Hobday (1974) while descriptions of the latter were provided by Bjørlykke (1967) and Edwards (1975, 1984). In this connection it should be noted that Jensen & Wulff-Pedersen's references to the Vadsø, Tanafjord and Vestertana groups comprise a progress report (Banks *et al.* 1971) and an excursion guide (Siedlecka & Roberts, 1992) instead of original publications in which the results cited were first presented (a practice which they regrettably applied for numerous other mis-citations in their paper). I conclude that the contention of Jensen & Wulff-Pedersen that the striated pavement is within the Vestertana Group is not supported by the very substantial amount of work carried out by several geologists during years of study.

A second key concern of Jensen & Wulff-Pedersen was the degree of consolidation of the substrate at the time that the surface was striated. There are a couple of points that come under this topic.

First, they erred in stating (p. 138) that a maximum of 600 m of the stratigraphy is missing at Bigganjargga. The stratigraphic relationship between the Vadsø Group and the Tanafjord Group was not resolved until later (Johnson, Levell & Siedlecki, 1978 provide a useful summary of the stratigraphy) than the three references they cited (1937–1967); a value of about 2 km missing is more in accordance with the current knowledge of the stratigraphy. The greater thickness provides more overburden for compaction and early diagenesis. A regional view of these stratigraphic relationships is presented in a dip cross-section datumed on the base of the Mortensnes Formation (Edwards & Føyn, 1981). A map of the preserved thickness of Vadsø and Tanafjord groups below the sub-Smalfjord Formation unconformity was compiled from several sources (Edwards, 1984, fig. 3).

Second, their interpretation of the imprints (depressions) is questionable. Their photographs of the imprints (figs. 8 and 9) clearly show that the imprints are much wider than the striations. If the substrate had been unconsolidated when the striations formed, then the striations would have been the same width as the clasts in the diamictite, and would have had the appearance of much wider grooves. The difference in size indicates that the relatively wide imprints formed as a result of post-depositional compaction of the sediments. Jensen &

Wulff-Pedersen also described imprints on the striated pavement west of the diamictite that they claim rule out a post-depositional pressure solution mechanism (they do not consider compaction as a possible mechanism for imprint formation). I do not agree with this because this area of the pavement is overlain by a lag conglomerate whose pebbles could also have created imprints. To the contrary, the preservation of striations up to 10 m to the west of the diamictite suggests that the substrate layers were not unconsolidated. (This also argues against the substrate having been frozen, unconsolidated sand at the time of erosion). A degree of consolidation is also consistent with occurrence of numerous sandstone clasts in the diamictite.

Rounded grain shapes from the clasts and matrix of the diamictite were used by Jensen & Wulff-Pedersen to question the glacial origin of the diamictite. But studies of diamictite textures from the Smalfjord and Mortensnes formations consistently show a close relationship in composition between the diamictite and the local substrate (Edwards, 1984). Such an inherited texture is the norm where glaciers flow over a readily eroded and comminuted substrate. Thus, the rounded sand grains in the matrix were derived from glacial disaggregation of the eroded sandstones. The observation of quartz overgrowths in both the substrate sandstones and the diamictite matrix suggests that most of the cementation occurred following deposition of the diamictite (Barrow *in* Strahan, 1897, pp. 145–6). Thus the strata of the Vadsø Group were variably consolidated and cemented at the time of this erosional phase. Such variability is commonly seen in oil and gas wells in sedimentary basins. Thus the presence of rounded sand grains in the diamictite does not argue against a glacial origin.

Several other points deserve additional discussion. Jensen & Wulff-Pedersen suggest (p. 141) that I mistook a protrusion of diamictite into an overlying sandstone bed for a clast of diamictite. This is not consistent with my documentation that shows the clast to be in the intertidal zone of 1971. The outcrop may have changed since my observation of 25 years ago.

Jensen & Wulff-Pedersen suggest that sandy plugs in the upper part of the diamictite represent rigid plugs within debris flow (p. 143). Sandy inclusions are preserved in subglacial and supraglacial diamictites (see for example Edwards, 1986), and can hardly be considered diagnostic of a debris flow origin.

Jensen & Wulff-Pedersen disagree that the northeast part of the diamictite represents the termination of the diamictite. The reason for suspecting a termination in this direction is the clear onlap and pinch-out of sandstone beds at this end of the outcrop (fig. 11 in Edwards, 1975), inviting comparison with the opposite end of the outcrop.

In 1944 I had the privilege of revisiting Reusch's Moraine on an IGCP field trip to examine the Terminal Proterozoic system of Finnmark, lead by Anna Siedlecka. The features that I interpreted as inclined beds of flow till (Edwards, 1975, fig. 10) were alternatively interpreted as surfaces of shear in a basal till (Grant Young, pers. comm.). The orientation of these features is consistent with glacial flow toward the northwest.

Toward the end of their article, Jensen & Wulff-Pedersen (p. 143) make two related provocative statements: '…the geological evidence at the Bigganjargga site is not adequate to constrain the history of this material' and 'Why are fragments locally derived in diamictites regarded as deposited from regional glaciations?' To the first I reply that there is no need to limit our understanding of the site exclusive of its context, any more than we would expect a geologist studying a sample of Pleistocene glacial diamict to argue that the sample in itself contains no conclusive evidence for glaciation and therefore there is no reason to interpret the sample in a glacial context. Regarding the second statement, locally derived fragments are typical of many Pleistocene glacial tills. Closer reading of the literature on glaciated soft-rock terrains such as North America and the North Sea would provide them with a better appreciation for this.

In conclusion, the available evidence strongly supports the existence of a glacially-scoured palaeovalley at the present site of Varangerfjord (Bjørlykke, 1967). The Bigganjargga exposure is the smallest one of several outcrops. The other outcrops do not display a dramatic striated pavement, but they do show critical stratigraphic relationships between the Vadsø and Vestertana groups (for examples at Mortensnes: Siedlecka & Roberts, 1992, p. 18; and at Skjåholmen, Mortensnes and Vieranjarga: Edwards, 1984, pp. 5–13), and critical facies relationships within the Vestertana Group (Bjørlykke, 1967; Edwards, 1975, 1984) that cannot be ignored when interpreting the Bigganjargga exposure. The striated pavement at Bigganjargga is part of the regional erosional unconformity at the base of the Vestertana Group. If Jensen & Wulff-Pedersen maintain that the Bigganjargga diamictite is within the Vadsø Group, then they ultimately will be expected to offer their own interpretation of where the regional unconformity is located stratigraphically and geographically between the diamictite and the Nyborg Formation (undeniably Vestertana Group) outcrops in inner Varangerfjord.

P. A. Jensen & E. Wulff-Pedersen reply: The principal basis for our interpretation of the Bigganjargga diamictite lies in the numerous pieces of evidence for a non-consolidated basement. We will therefore first comment on Edwards' discussion of this topic. Edwards find our interpretation of the imprints on the sandstone substrate underlying the Bigganjargga tillite to be questionable. He claims that if the substrate had been unconsolidated when the striations formed, then the striations would have been the same width as the clasts in the diamictite. Firstly, both clasts, imprints and grooves come in different sizes; we have only in one case been able to refer a striation to a particular clast (or imprint of clast). Secondly, the fact that debris flows are literally 'floating' on the substrate due to the hydrostatic pressure at the base of the flow, the clasts are expected to erode more deeply into the substrate when the flow ceases. This can be seen in figure 9 in Jensen & Wulff-Pedersen (1996) when a striation end in an imprint. Clearly, we cannot agree with Edwards' claim that imprints should necessarily be of the same width as the striations. We also consider it impossible to make discontinuous striations that end in imprints by any sort of compaction processes or later pressure solution mechanisms. We have considered compaction processes as a possible mechanism for imprint formation on page 142 in the original paper. We fail to see why striations on a non-consolidated substrate, now 10 m to the west of the diamictite, could not have been preserved as long as both cross-beds and ripple marks are preserved in the same sequence. The fact that both the diamictite and the substrate show similar diagenesis can only be used as support for both being of the same age and consolidated at the same time.

The debris flow origin is further strengthened by the fact that the diamictite incorporates sandy material identical to the underlying basement. In addition, the Bigganjargga diamictite is characterized by random oriented fragments, some vertical to bedding, and clear flow structures, indicating movement from the northeast, consistent with both striations and imprints. These features are typical for debris flow. In our opinion, the case for the Bigganjargga diamictite as a debris flow formed on an unconsolidated basement is as good as they come.

Edwards criticizes our use of references. Edwards himself relies heavily on some very old references, that are far from today's standards, as support for the glacial interpretation. The reason we used Siedlecka & Roberts (1992) as source for the regional stratigraphy is because this work is an up-to-date overview of the stratigraphy in a regional sense.

We do not reject earlier workers observations. We just don't agree with their interpretations. The problem with most earlier works is that they do not discuss the origin of the diamictites, but simply state that they are glacial. Rosendahl (1945) clearly observed a spectacular erosional unconformity at the base of the diamictite, as will anyone who interpret the diamictite as a tillite. However, this is a highly theory-laden observation based more on what the interpretation implies than on what is actually observed. There is, however, little doubt that there is an erosional unconformity beneath the diamictite. This is hardly surprising since the diamictite has eroded into the basement and even incorporated some of the basement material into the diamictite. However, the unconformity is not possible to identify outside the diamictite lens. The unconformity is no more spectacular than the many unconformities in the underlying sandstone basement due to cross-bedding. Hence, it could be argued that the unconformity is just another bed surface in the succession.

It is necessary to invoke a large-scale unconformity beneath the diamictite if the striations are interpreted as glacial and the Bigganjargga diamictite is correlated with other diamictites. The removal of 600 m or 2 km of the stratigraphy is therefore to a large extent an *ad hoc* hypothesis, necessary in order to explain glacial striations in an apparently continuous sedimentary sequence and for regional correlation. However, if the diamictite is non-glacial, correlation with other diamictites is not necessarily correct. Hence, the need to remove 2 km of the stratigraphy may therefore be a product of miscorrelations. We do not dispute the existence of an erosional unconformity between the Vestertana and the Vadsø groups. However, we do not think it is present at Bigganjargga.

We agree with Edwards that neither rounded grain shapes or sandy plugs can be considered diagnostic of a debris flow. However, they are both consistent with our interpretation of the diamictite as a locally derived debris flow.

Edwards claims that locally derived fragments are typical for many Pleistocene glacial tills. However, the local nature of fragments is symptomatic for the Neoproterozoic diamictites in Finnmark and northern Troms county. On a local scale, diamictites nearly always show fragments derived from nearby sources. Source rocks to fragments can usually be found within a radius of a few kilometres. Basement rocks identical to the gneissic and granitic blocks contained in the Bigganjargga diamictite, can be found in outcrop at Karlebotn, a few kilometres away from the diamictite. It is reasonable to assume that these rocks underlie the Bigganjargga site as well. The dark sandstone fragments show similarities with part of the 'older sandstone series' (Vadsø Group) described by Holtedahl (1918) from the north side of the Varangerfjord. According to Føyn (1937), part of the diamictite in the Smalfjord Formation in the Tana area consists in some cases exclusively of dolomite; erratics as well as matrix. Fragments in diamictites in the Repparfjord–Komagfjord tectonic window in western Finnmark consist of rocks derived from the Proterozoic basement exposed in that window (Pharaoh, 1985). In a diamictite outcrop in the southern part of this window the author has observed a diamictite outcrop where the fragment material is exclusively derived from the underlying, early Proterozoic arkosic sandstone, although four other basement lithologies are exposed within a radius of less than 1 km. Similarly, Holmsen (1956) describes what he calls a 'greenstone moraine', near Masi, which lies directly on a greenstone substrate. Less than 1 km west of this locality, Holmsen (1956) reports a diamictite, resting on a quartzite substrate, where fragment material consists almost exclusively of quartzite. These features indicate that the sources for the clast material are almost point-like in nature. This is more in agreement with an alluvial fan–debris flow origin of the diamictites than regional glaciations. A non-glacial environment may also better explain the pronounced chemical weathering with kaolinite and illite formation, in the basement rocks beneath the Neoproterozoic succession, and also the reported occurrences of evaporite deposits in several levels within the Neoproterozoic succession.

Acknowledgements. MBE acknowledges: Harold Reading initiated and supervised Oxford University's extensive work in North Norway. I am indebted to him for his suggestion of and support for my thesis work in this region. Sven Føyn generously shared with me his unique knowledge of this region, based upon years of field study and research. In addition to the literature cited in this discussion, extensive field work and the resulting insights acquired by Nigel Banks, David Hobday, Howard Johnson, Signe-Line Røe, Anna Siedecka, Stanislaw Siedlecki, Paul Taylor and numerous field assistants form the foundation for my present understanding of the inner Varangerfjord region. I further thank Anna Siedlecka for her critique of a draft of this discussion.

References

BANKS, N. L., EDWARDS, M. B., GEDDES, W. P., HOBDAY, D. K. & READING, H. G. 1971. Late Precambrian and Cambro-Ordovician sedimentation in east Finnmark. In *The Caledonian Geology of northern Norway* (eds D. Roberts and M. Gustavson), pp. 197–236. *Norges Geologiske Undersøkelse* **269**.

BANKS, N. L., HOBDAY, D. K., READING, H. G. & TAYLOR, P. N. 1974. Stratigraphy of the late Precambrian 'Older Sandstone Series' of the Varangerfjord area, Finnmark. *Norges Geologiske Undersølkelse* **303**, 1–16.

BJØRLYKKE, K. O. 1967. The Eocambrian 'Reusch Moraine' at Bigganjargga and the geology around Varangerfjord; Northern Norway. *Norges Geologiske Undersøkelse* **251**, 18–44.

CROWELL, J. C. 1964. Climatic significance of sedimentary deposits containing dispersed megaclasts. In *Problems in Palaeoclimatology* (ed. A. E. M. Nairn), pp. 86–99. London: John Wiley & Sons.

EDWARDS, M. B. 1975. Glacial retreat sedimentation in the Smalfjord Formation, late Precambrian, north Norway. *Sedimentology* **22**, 75–94.

EDWARDS, M. B. 1984. Sedimentology of the Upper Proterozoic glacial record, Vestertana Group, Finnmark, North Norway. *Norges Geologiske Undersøkelse* **394**, 1–76.

EDWARDS, M. B. 1986. Glacial environments. In *Sedimentary Environments and Facies* (ed. H. G. Reading), pp. 445–70. Blackwell Scientific Publications.

EDWARDS, M. B. & FØYN, S. 1981. Late Precambrian tillites in Finnmark, North Norway. In *Earth's pre-Pleistocene Glacial Record* (eds M. J. Hambrey and W. B. Harland), pp. 606–10. Cambridge University Press.

FØYN, S. 1937. The Eo-Cambrian series of the Tana district, Northern Norway. *Norsk Geologisk Tidskrift* **17**, 65–164.

HOBDAY, D. K. 1974. Interaction between fluvial and marine processes in the lower part of the late Precambrian Vadsø Group, Finnmark. *Norges Geologiske Undersøkelse* **303**, 39–56.

HOLMSEN, P. 1956. Hyolithus-sonens basal lag i Vest-Finnmark. *Norges Geologiske Undersøkelse* **195**, 65–72.

HOLTEDAHL, O. 1918. Bidrag til Finnmarkens geologi. *Norges Geologsike Undersøkelse* **84**, 311 pp.

JENSEN, P. A. & WULFF-PEDERSEN, E. 1996. Glacial or non-glacial origin for the Bigganjargga tillite, Finnmark, northern Norway. *Geological Magazine* **133**, 137–45.

JOHNSON, H. D., LEVELL, B. K. & SIEDLECKI, S. 1978. Late Precambrian sedimentary rocks in East Finnmark, North Norway, and their relationship to the Trollfjord-Komagelv fault. *Journal of the Geological Society, London* **135**, 517–34.

PHARAOH, T. C., 1985. The stratigraphy and sedimentology of autochthonous metasediments in the Repparfjord-Komagfjord tectonic window, west Finnmark. In *The Caledonide Orogen – Scandinavia and related areas* (eds D. G. Gee and B. A. Sturt), pp. 347–57. Wiley.

REUSCH, H. 1891. Glacial straie and boulder-clay in Norwegian Lapponie from a period much older than the last ice age (in Norwegian with an English summary). *Norges Geologsike Undersøkelse* **1**, 78–85 and 97–100.

ROSENDAHL, H. 1931. Bidrag til Varangernesets geologi. *Norsk Geologisk Tidsskrift* **12**, 487–506.

ROSENDAHL, H. 1945. Prækambrium–Eokambrium I Finnmark. *Norsk Geologisk Tidsskrift* **25**, 327–49.

SIEDLECKA, A. & ROBERTS, D. 1992. The bedrock geology of the Varanger Peninsula, Finnmark North Norway: an excursion guide. *Norges Geologiske Undersøkelse Special Publication* **5**, 1–45.

STRAHAN, A. 1897. On glacial phenomena of Palæozoic age in the Varanger Fiord. *Proceedings, Geological Society of London* **53**, 137–46.

EDWARDS, M. B., 5430 Dumfries, Houston, Texas 77096, USA

JENSEN, P. A., Institute of Biology & Geology, University of Tromsø, N-9037 Tromsø, Norway

WULFF-PEDERSEN, E., Mineralogical–Geological Museum, University of Oslo, Sarsgate 1, N-0562 Oslo, Norway