Sirs — This letter suggests a possible solution to the major problem that has recently arisen concerning the glaciation of the Outer Hebrides.

From the evidence of striae and roches moutonnées Geikie (1873, 1878) maintained that the Outer Hebrides were glaciated by an ice-sheet from the Scottish mainland that flowed W and NW, except for the mountains of Harris, where local ice fed into the ice-sheet. This view was supported by Jehu and Craig (1923, 1925, 1926, 1927, 1934). However, von Weymarn (1974) showed that most of eastern Lewis and Harris has been glaciated by eastward-moving ice, and Coward (1977) demonstrated eastward ice flow in South Uist from erratics. Peacock and Ross (1978) stated that their mapping in the Uists and Benbecula shows conclusively that ice flowed towards the east (or ESE). Flinn (1978) states that on the eastern side of the archipelago from just south of Stornoway to the southern tip of South Uist striae and roches moutonnées were produced by ice moving east. Even Jehu and Craig (1925, pp. 639-40) provided clear evidence of eastward carry of certain erratics in South Uist.

The above evidence of eastward flow appears inconsistent with Geikie’s interpretation. Peacock and Ross have consequently suggested ice dispersal centres on the continental shelf immediately west of the Outer Hebrides as well as over the more mountainous parts of the islands. Flinn, however, has found westward directed striae along the west coasts of North and South Uist and Benbecula and he therefore places an ice-shed along the western seaboard of these islands. His ice-shed is continued NE, off the coast of southern Harris, to end in the mountains of Harris. Thus current opinion is that during the last glaciation ice from the Scottish mainland did not cross the Outer Hebrides; instead the island chain had its own ice mass. However, this interpretation meets with several difficulties.

1. Jehu and Craig (1925, 1926) recorded erratics in South Uist and Eriskay that are probably Torridonian, as well as quartzite resembling Cambrian Quartzite, and they mentioned Torridonian sandstones and arkoses on North Uist. They also stated that boulders derived from the eastern side of North Uist, east of the Outer Isles Thrust, can often be picked up west of the thrust. It thus appears that ice from the Scottish mainland did cross this part of the Outer Hebrides.

2. Since there is clear evidence for eastward-moving ice over much of the Outer Hebrides it may be suggested that mainland ice over-ran much of the islands in a previous glaciation (e.g. Flinn 1978). Such an interpretation is unsatisfactory, however, because it does not explain why during the last glaciation the Outer Hebrides developed a major ice mass but in an earlier glaciation did not.

3. The extent of glaciers during the Loch Lomond Stadial is relevant because the limit of the Loch Lomond Advance represents a stage in the build-up of a large ice-sheet (which would have developed had not climate ameliorated). The limit of the advance in the Outer Hebrides has not been firmly established but it is clear from the
work of Jehu, Craig and von Weymarn that glaciers were entirely or almost entirely restricted to the mountains of Harris. Hence during ice-sheet accumulation one can readily envisage large glaciers building up in these mountains, ultimately merging into the mainland ice-sheet as it extended across the Outer Hebrides, but it is difficult to see how a large ice mass could have developed along the island chain farther south (which is mostly low ground with only two points attaining 600 m).

4. It is now known that the southward movement of polar water (Ruddiman et al. 1977) is intimately linked with the build-up of glaciers in Scotland (Sissons and Sutherland 1976). It is inferred that contrasting sea temperatures at the oceanic polar front (junction between polar and warmer water) were associated with vigorous interaction of contrasting air masses and that heavy precipitation resulted (Sissons 1979). During the Loch Lomond Stadial the oceanic polar front extended as far south as the latitude of SW Ireland and there was heavy snowfall over much of the Scottish Highlands. However, when the last ice-sheet existed the oceanic polar front reached much farther south (ultimately to northern Spain) and, as it did so, the zone of heavy precipitation would have moved southwards. Thus, since there is no hint of the build-up of a major ice mass on the southern islands of the Outer Hebrides during the Loch Lomond Stadial, it is very difficult to see how such a mass could have built up contemporaneously with the growth of the last Scottish ice-sheet when, as the polar front pushed south beyond SW Ireland, precipitation would have diminished over Scotland, thus making conditions increasingly unfavourable for glacier initiation.

Summarizing the above, there is firm evidence in much of the Outer Hebrides for glacier ice having flowed eastwards, yet there is also evidence suggesting that the mainland ice-sheet crossed the island chain (except for the mountains of Harris) while climatic considerations appear to preclude the build-up of an extensive ice-mass on the islands. The following hypothesis is suggested to resolve these apparent contradictions.

As Geikie (1873, 1878) proposed, the last ice-sheet built up over the Scottish mainland and extended across the Outer Hebrides, merging with ice nourished on the mountains of Harris. During ice-sheet decay calving of ice-bergs was rapid in the deep water of the Minches and resulted in the separation of the mainland ice from ice on the Outer Hebrides. Calving would have been facilitated by glacio-isostatic depression and the sea would also have been deeper than at present because the thick marine accumulations that now mantle much of the sea-bed (Binns et al. 1973) had not then been laid down. To the W and NW of the Outer Hebrides calving of the ice-margin is likely to have taken place initially but here the sea-bed slopes gently away from the islands, the 100 m isobath lying 30–60 km offshore. This gentle slope, along with limited isostatic depression, means that the ice-margin would have become land-based or located in shallow water at a considerable distance from the present coastline, thus preventing rapid retreat by calving. On the east side of the islands the sea-bed descends sharply to a depth of 100 m within 3–7 km of the present coastline. Thus, the
LETTERS TO THE EDITORS

ice-shed that developed as the independent ice mass began to flow towards the east (in the E) and west (in the extreme W) was asymmetrically placed in relation to the present land area (as Flinn's evidence indicates).

The result of this reversal of ice movement in, for example, the Uists, was that clasts from west of the Outer Isles Thrust were carried east of the thrust, while many erratics from the east previously brought by the mainland ice-sheet were carried back eastwards, although some remain to testify to this earlier ice movement.

One final suggestion is offered that might provide a means of testing this hypothesis. Horizontal movement beneath an ice-shed is theoretically zero and it is very small in the vicinity of an ice-shed. Hence the erratics brought by the original (E–W) ice movement should be most abundant along the ice-shed of the independent ice mass and diminish in frequency increasingly rapidly away from it. In this context it may be significant that Jehu and Craig (1926) commented that foreign rocks are almost absent from North Uist except on the western seaboard (where Flinn places the ice-shed of the independent ice mass).

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Sirs——I have suggested that during the last major glaciation of Scotland the Outer Hebrides were glaciated by an independent ice-cap which flowed eastward into the Minch along the east side of the archipelago (Flinn 1978). Dr. Sissons (1979) objects to this model on the grounds that the climatic conditions of those times could not have given rise to an ice-cap on the Outer Hebrides by snow fall and additionally that had such an ice cap formed the ice-shed would not have formed west of the water shed as proposed by me. His objections raise some doubts in my mind about the validity of my model but I find his model more difficult to accept.

He proposes that in the last major glaciation the Scottish ice-sheet overwhelmed the Outer Hebrides in the earlier stages but later on calving in the Minch led to separation of the ice on the Outer Hebrides from that on Scotland thus leaving the former with its own independent ice-cap. I cannot understand how an ice-sheet could flow from Scotland across the Minch and then under apparently similar conditions of flow could be dissected by calving along the length of the Minch. To maintain flow from Scotland across the Outer Hebrides the upper surface of the ice-sheet would have to have been high above the present sea level in the Minch. According to equation $h = (2h_0s)^{1/3}$ (Nye 1952) the ice surface would have to have been well over one kilometre above the present sea level. This mass of ice would have been so firmly aground on even the deepest part of the Minch sea-floor that calving would have taken place no more easily there than elsewhere. Ice rising even a few tens of metres above present sea level would be aground in the deepest part of the Minch. By the time the ice had wasted down to a level at which calving could have occurred it would also have thinned so much over the Outer Hebrides that it seems unlikely it could have created the glacial features now observed. I find it less difficult to overlook Dr. Sissons' meteorological objections to the creation of an ice-cap on the Outer Hebrides by snow fall than to overlook the mechanical difficulties of calving an ice canyon along the Minch.

If an ice-cap accumulated from snow fall on the Outer Hebrides the ice-shed would tend to lie west of the water-shed. In the early stages the ice would tend to accumulate preferentially on the water-shed but the slopes are steeper to the east than to the west so that the ice would tend to drain preferentially eastward thus leading to a westward displacement of the ice-shed. The 100 m isobath lies 30-60 km to the west but a mere 10 km to the east of the water-shed.

The distribution of erratics is equally well explained by either model and so cannot be used as a test of either. I suggest that in an earlier glaciation the snow fall was much greater thus enabling the Scottish ice-cap to grow so large that it overwhelmed the smaller Outer Hebrides ice-cap.
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Let the Editors

Glaciation of the Outer Hebrides: A Reply

Sirs—Dr. Sissons’ hypothesis that the local glaciation of the Uists and Benbecula was consequent upon the break-up of the Scottish mainland ice in the Minch during the retreat from the Devensian maximum is most attractive, but difficult to reconcile with the evidence currently available.

During IGS work in the Outer Hebrides in 1977 and 1978, the writer was able to confirm the presence of pebbles of red sandstone and arkoses of Torridonian aspect in the western storm beaches of the islands from N. Uist southwards as well as white quartzite similar to that of the basal Cambrian of the Scottish mainland. As reported by Jehu and Craig (1923), these are especially prominent in Barra and Vatersay, where well-rounded pebbles of reddish sandstone also occur locally in the till along the west coasts of these islands. Whether these pebbles have been derived entirely from the Torridonian of the Scottish mainland (and inner Hebrides), or whether they have been reworked in part from conglomerates in the Mesozoic strata now known to occur extensively in the Minches and which could be present elsewhere around the Hebrides, is impossible to decide at present. It is however worth reiterating the fundamental problem that the Tertiary basaltic lavas of Skye and the fossiliferous Mesozoic beds in the Minches have made little contribution to the erratics of the Outer Hebrides, a fact which is apparently at variance with the widespread presence of pebbles of Torridonian aspect. These details were not known to Geikie and remain a stumbling block for any hypothesis suggesting an extension of Scottish mainland ice across the islands.

As regards features of ice-movement, the eastward or south-eastward passage of ice from ice centres immediately west of the Uists and Benbecula reported by Peacock and Ross (1978) has now been confirmed along the east coasts of Barra and Vatersay, but in the western parts of these latter islands the direction of ice-movement is ambiguous and at some localities the quarried faces suggest a westerly flow. Vatersay seems to have been at the southerly end of an elongated ice dome, with the ice-shed extending northwards along or just to the west of the west coast of South Uist and Benbecula into the extreme western part of North Uist. The westerly indications of ice-movement reported from S. Uist and Benbecula by Flinn (1979) are recorded from a coastal strip where quarried faces give an ambiguous sense of transport, according to IGS records. However, the difference in the position of the ice shed as reconstructed from Flinn’s observations and those of the IGS is minimal, as far as this discussion is concerned.

Rock which has been obviously glaciated extends to a height of 500 metres about Hecla and Beinn Mhor in South Uist, but above 350 metres plucked surfaces and striae, which below this level show an easterly ice flow, have been chiefly obscured or destroyed by frost shattering. In Barra, Heaval (383 m O.D.) was submerged by eastward flowing ice. It seems likely therefore that the ice in this area was at least 400
metres thick during the easterly flow, but whether or not this easterly flow extended to the summits of the highest hills, though likely, remains to be confirmed. Relatively thin ice would be in accord with Sissons’ hypothesis, but would not in itself invalidate the suggestion that the Outer Hebrides were glaciated only by local ice during the Devensian.

At the north end of Lewis, Von Weymarn (1974) noted that the raised beach with Torridonian pebbles first described from Galson by Baden Powell and Elton (1937) in places overlies till which also contains Torridonian erratics and is itself partly overlain by till of the Hebridean local glaciation. Moreover, the coast beyond the sharply-defined limit of the local glaciation has been subjected to intense periglacial activity whereas that within the limit has been little affected. The inferred advance of the local ice in this area was thus probably a major event, which could with some justification be correlated with the Devensian maximum (cf. Von Weymarn 1979). It is therefore of considerable interest that a raised gravel beach of identical appearance and similar height to that in Lewis occurs a few metres above O.D. at Cliad in Barra. Pebbles of hard reddish Torridonian sandstone are abundant in the beach, which is overlain by up to 6 metres of till in which such pebbles are present but sparse. Whether or not this raised beach can be directly correlated with that in Lewis is open to question, but as the sequence of deposits (raised beach gravel overlain by local till) is similar it does suggest the probability that the southern parts of the Outer Hebrides were entirely deglaciated before the onset of the local glaciation. There is little doubt that the raised beach on Barra owes its preservation to its situation adjacent to the ice-shed and its destruction elsewhere by the passage of ice could have given rise to some of the invariably well-rounded pebbles of Torridonian type in the tills and present-day storm beaches in these southerly islands.

From the above discussion the writer is of the opinion that the balance of evidence is in accord with the hypothesis that the Outer Hebrides supported an independent ice-sheet at the Devensian maximum, and at this stage ice from the Scottish mainland, if present at all, was just able to reach the extreme north of Lewis. There is no evidence to show that mainland ice reached the more southerly islands at a time post-dating the Barra raised beach, though Jehu and Craig (1923) noted NE-SW oriented striae in Berneray and Mingulay. Excepting for the major problem of the absence of Skye erratics on the Outer Hebrides referred to above, the distribution of material possibly transported from the mainland can be best explained on the basis of a much more extensive coverage of Scottish ice at a time pre-dating both the raised beach and, by implication, the late Devensian maximum as defined by Mitchell et al. (1973). Pending further evidence there appears to be little support for Sissons’ hypothesis (though it is not necessarily wholly invalid) and the problem of how an independent ice-sheet could develop in the Outer Hebrides remains unresolved.
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