Geologie en Mijnbouw **77:** 225–232, 1999.



# Lateglacial climate change and coastal evolution in western Jura, Scottish Inner Hebrides

A.G. Dawson[1], D.E. Smith[1], S. Dawson[1], C.L. Brooks[2], I.D.L. Foster[1] & M.J. Tooley[3]
[1]*Centre for Quaternary Science, William Morris Building, Coventry University, Priory Street, Coventry, CV1 5FB, U.K.;* [2]*18 Bullfinch Close, Creekmoor, Poole, PH17 7UP, U.K.;* [3]*School of Geography, Kingston University, Penrhyn Road, Kingston upon Thames, Surrey KT1 2EE, U.K.*

Received October 1996; accepted in revised form 4 March 1999

*Key words:* beach ridges, Lateglacial Interstadial, shore platforms, Younger Dryas

## Abstract

The geomorphic and sedimentological evidence for former sea-level changes in the exposed coastline of western Jura shows a clear coastal response to past changes in climate. In particular the rapid and high-magnitude climate changes associated with the onset and termination of the Younger Dryas appear to have been accompanied by major changes in coastal response. In western Jura, the temperate climate of the Lateglacial Interstadial was associated with beach-ridge deposition, with the earlier part of this period being associated with larger ridges than the latter. By contrast, the cold climate during the Younger Dryas appears to have been dominated by frost processes, sea-ice development and rapid rates of coastal erosion of bedrock. Cold-climate shore erosion of bedrock appears to have ended suddenly at the close of the Younger Dryas.

## Introduction

The western coastline of the island of Jura contains some of the finest developed spreads of Lateglacial shingle ridges in the British Isles (Dawson 1982; Figure 1). Evidence for the highest level (the marine limit) reached by the Lateglacial sea immediately upon ice-sheet deglaciation is also well-preserved, and together the uplifted coastal landforms provide a record of the fall of relative sea level during the Lateglacial Interstadial as the rate of glacio-isostatic uplift outpaced the rate of glacio-eustatic sea-level rise caused by the melting of the world's ice sheets (Table 1).

Along most of the coastline the beach-ridge staircases rest upon a rock platform that terminates seaward at a cliff line above a lower uplifted coastal platform, the Main Rock Platform, generally considered to have been produced during the Younger Dryas period of cold climate (Sissons 1974, Dawson 1980, 1988, Gray 1978, 1995, Stone et al. 1996). In this paper an account is presented on the deposition of the beach-ridge staircases of western Jura during the Lateglacial Interstadial. Consideration is also given to the way in which the nature of the coastal processes changed during the succeeding Younger Dryas. This, in turn, may contribute to our understanding of the response of individual coastlines to future climate change.

## Lateglacial beach-ridge staircases

The uplifted beach ridges of western Jura were formed during regional deglaciation when relative sea level was falling rapidly due to the rate of glacio-isostatic rebound, caused by the melting of Late Devensian ice, exceeding the rate of glacio-eustatic sea-level rise (Dawson 1982). The beach ridges rest upon an uplifted rock platform up to 600 m in width, the inner edge of which occurs between 32 and 34 m OD (Dawson 1993). Glacial till locally rests upon the platform and separates it from the overlying beach ridges, and it is inferred that during the period of high Lateglacial sea level, littoral erosion of quartzite debris from the till was the principal process responsible for the production of the beach shingle. The most detailed sequence

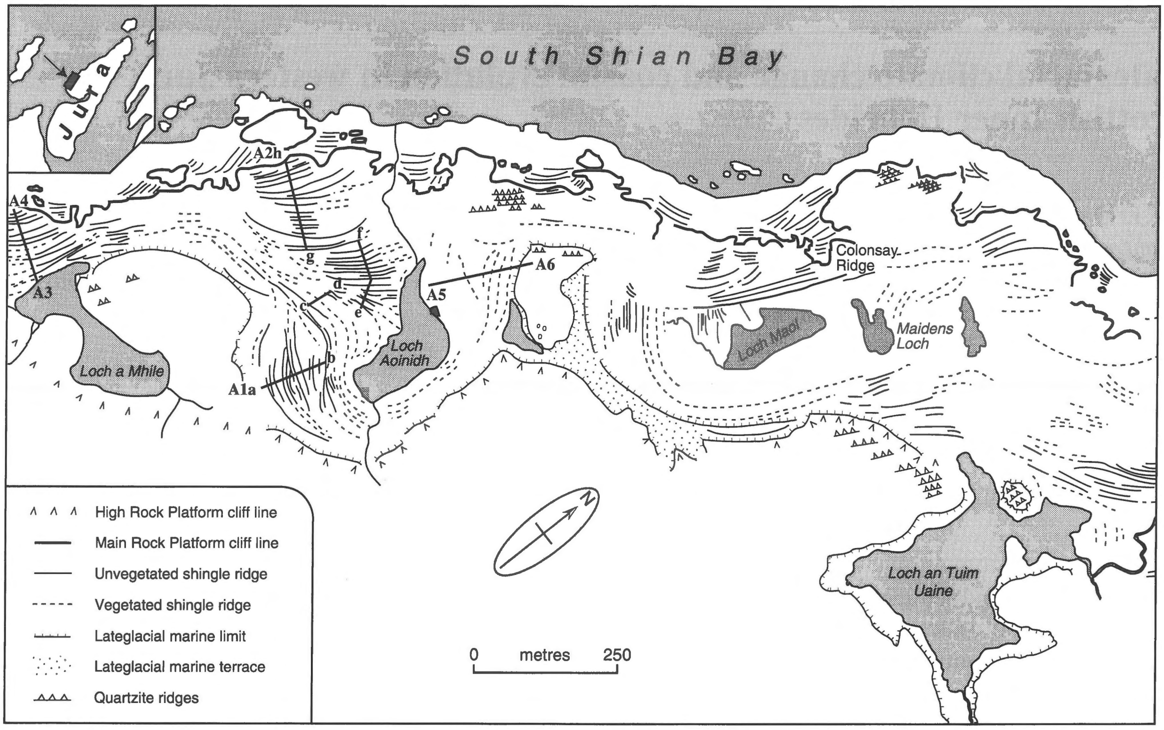


*Figure 1.* Geomorphological map of western Jura, Scottish Inner Hebrides, showing location of Loch Aoinidh beach ridges (after Dawson 1982) and of profiles in Figures 2 and 3. The unvegetated ridges occupy a palaeo-embayment fringed by the degraded cliff line of a higher rock platform.

*Table 1.* Climatostratigraphic subdivision and terminology for the Lateglacial of NW Europe (after Lowe & Gray 1980).

| Radiocarbon years BP | Climatostratigraphic Units |
|---|---|
| | Holocene Interglacial |
| 10,000 | |
| | *transition* |
| 10,500 | |
| | Younger Dryas Stadial |
| 11,000 | |
| | *transition* |
| 12,000 | |
| | Lateglacial Interstadial |
| 13,000 | |
| | *transition* |
| 14,000 | |
| | Late Weichselian/ Late Devensian/ Late Midlandian Main Glacial |

of beach ridges is at Loch Aoinidh where 55 ridges separated by swales were deposited in a relatively sheltered embayment of the Lateglacial sea (Figures 1, 2). In this area, the suites of unvegetated ridges record the progressive lowering of relative sea level throughout the Lateglacial Interstadial as it fell from c. 35 to c. 20 m OD, accompanied by changes in wave refraction patterns as the ridge system developed within the palaeo-embayment (Figure 1). By contrast, farther along the coast at Loch a Mhile, 14 ridges and swales occupy almost exactly the same altitude range in an area where the former cliff line located landward of the highest ridge is straight, and thus was more exposed to former wave action (Figures 1, 3). This contrast in the number of shingle ridges that formed within an identical altitude range in two nearby areas of contrasting wave exposure appears to demonstrate that there was significant recycling of beach shingle at Loch a Mhile during a period of falling relative sea level to produce a reduced number of composite beach ridges.

Detailed levelling of the altitudes of individual ridges and swales indicates the amplitude variations between the ridges in the Loch Aoinidh staircase as relative sea level fell from c. 35 to c. 20 m OD (Figure 4). The greatest amplitude from ridge to swale is approximately 1.6 m. The amplitudes of ridges R1 to 22 are demonstrably higher than those of ridges R23

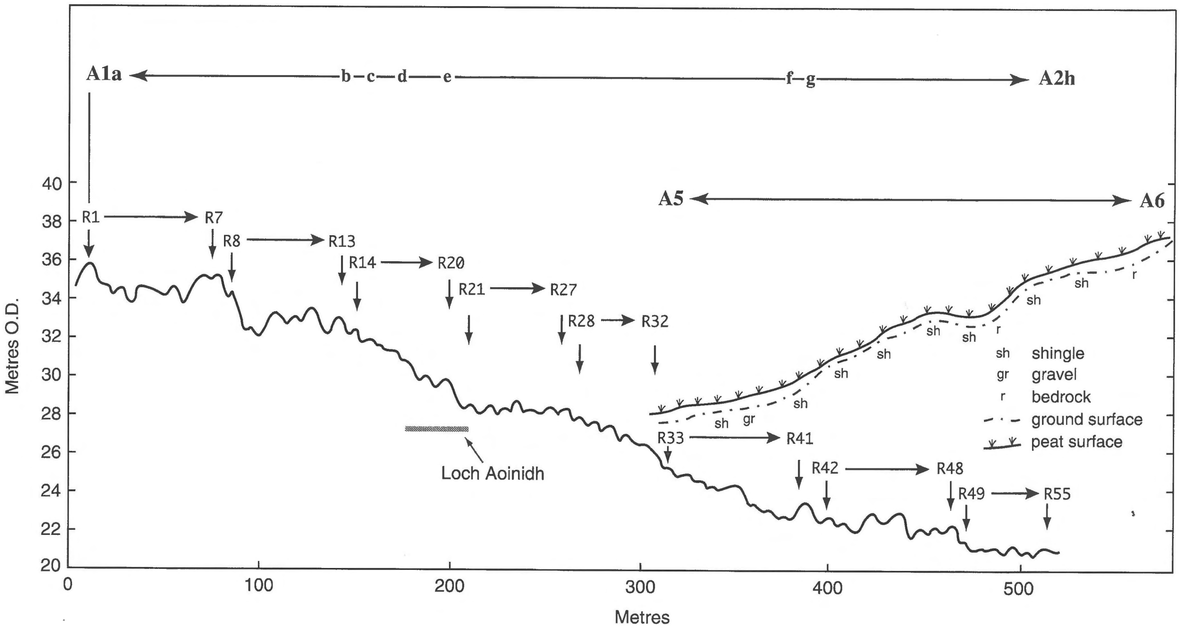


*Figure 2.* Profiles across Loch Aoinidh beach ridges (R1-55). The profiles are constructed orthogonal to the ridge orientations and consist of a series of segments (e.g. A1a to A2h, see Figure 1).

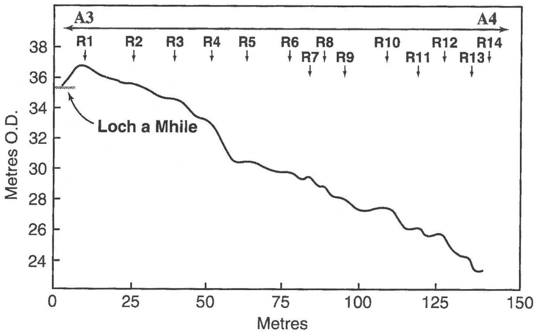


*Figure 3.* Profile across Loch a Mhile beach ridges (R1 to 14; for location see Figure 1).

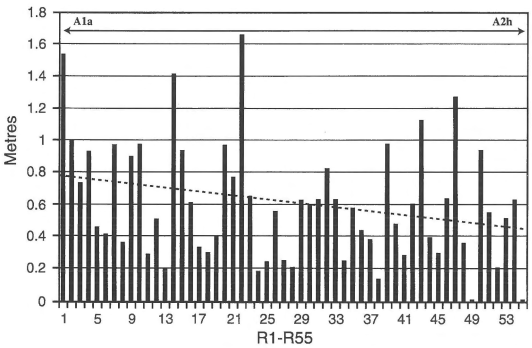


*Figure 4.* Ridge to swale amplitude variations for Loch Aoinidh area. The linear regression is significant at 0.033 (Rsq. = 8.3%, d.f. = 53). Compare Figures 1 and 2 for location of ridges R1 to 55.

to 55. Linear regression of the data shows an overall decrease in ridge to swale amplitude with time (Figure 4). The reasons for these changes are not known but are presumably related to the combined influence during the Lateglacial Interstadial of storminess and the rate of relative sea-level fall. The origins of the highest-amplitude ridges are unclear and may reflect the combined influence of storm activity, sediment supply and relative sea-level lowering.

## Main Rock Platform

At a number of locations on the west coast of Jura (Figure 1) the seaward edge of a high rock platform forms the backing cliff of the Main Rock Platform (Figure 5). At several locations the unvegetated beach-ridge staircases on the high platform extend as sub-parallel ridges to the seaward cliff edge where they exhibit evidence of having been truncated by a later episode of coastal erosion. These shingle ridges extend to an altitude no lower than c. 21 m OD. Lateglacial sea-level changes below this altitude cannot be determined in this area owing to the presence of the uplifted Main Rock Platform. Since the Main Rock Platform is overlain by Holocene beach gravels and because its cliff line truncates pre-existing beach ridges deposited during the Lateglacial Interstadial,

*Figure 5.* Cliff of the Main Rock Platform, Loch a Mhile, western Jura. The base of the cliff is mantled by vegetated talus deposits and Holocene beach gravels that partly obscure the entrance to an abandoned sea cave. The cliff line, sea cave and associated (buried) platform are considered to have been produced during the cold climate of the Younger Dryas. Note that the cliff is continued landward by a higher platform that is mantled by several metres of Lateglacial beach-gravels. The gravels, that locally form unvegetated shingle ridges, are believed to have been deposited prior to the cutting of the cliff.

the most likely time interval during which the Main Rock Platform was formed was during the Younger Dryas (cf. Sissons 1974, Gray 1978, 1989, Dawson 1980, 1988, Gray & Ivanovich 1988, Stone et al. 1996). The field evidence therefore demonstrates an exceptional change in coastal response to fluctuations in climate during the Lateglacial. However, the field evidence in this area cannot show precisely the time when beach-ridge deposition was replaced by coastal erosion of rock.

Various attempts to reconstruct, using proxy climatic indicators, past environmental changes for the Lateglacial demonstrate a rapid decline in temperatures between the Lateglacial Interstadial and the Younger Dryas (Figure 6). Pollen analysis from a core sampled from Loch an Tuim Uaine reflects this deterioration in climate and the onset of the Younger Dryas quite clearly (Figures 7, 8). For example, this time interval appears to be characterised by a pronounced decline in pollen totals, particularly of tree species, and the presence of pollen characteristic of colder climatic conditions such as *Betula nana* and *Juniperus*. Increasing climatic deterioration at the Lateglacial Interstadial/Younger Dryas transition may also be reflected in pronounced increases in battered and corroded pollen and spores. However, such interpretation is tentative until further studies into the presence of corroded pollen and spores in Lateglacial deposits become available.

## Discussion

### *Air temperatures*

Recent investigations of Lateglacial palaeoclimatic changes from the Greenland ice-core records have shown quite clearly that there was a series of stepped and high-magnitude climatic deteriorations represented by falling air temperatures associated with the transition from the Lateglacial Interstadial to the Younger Dryas (Bond et al. 1993, Lowe et al. 1995, Figure 6). Estimates of changing Lateglacial air temperatures for central England based on the mutual climatic range technique show a good correspondence with the Greenland ice-core temperature record and further support the notion of a drastic lowering of air temperatures during the Younger Dryas (Lowe et al. 1995). It has long been assumed that during the Younger Dryas, the polar oceanic front was located south of the British Isles and that this southern limit of seasonal polar waters was associated with the southern limit of ice-rafted detritus (Ruddiman et al. 1973).

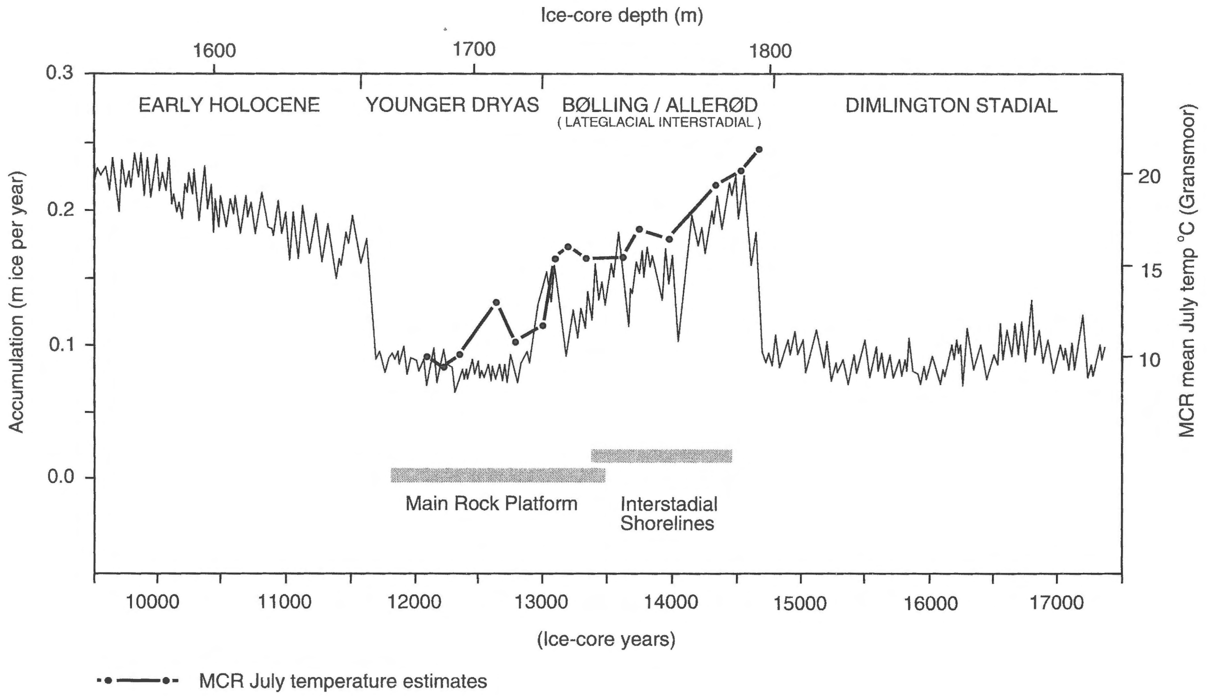


*Figure 6.* Graph of inferred temperature changes for the Lateglacial based on Greenland ice-core research (GRIP), and reconstructed trend of temperature for central England based on the Mutual Climatic Range (MCR) technique (after Lowe et al. 1995). Black lines indicate principal episodes of Lateglacial shoreline formation.

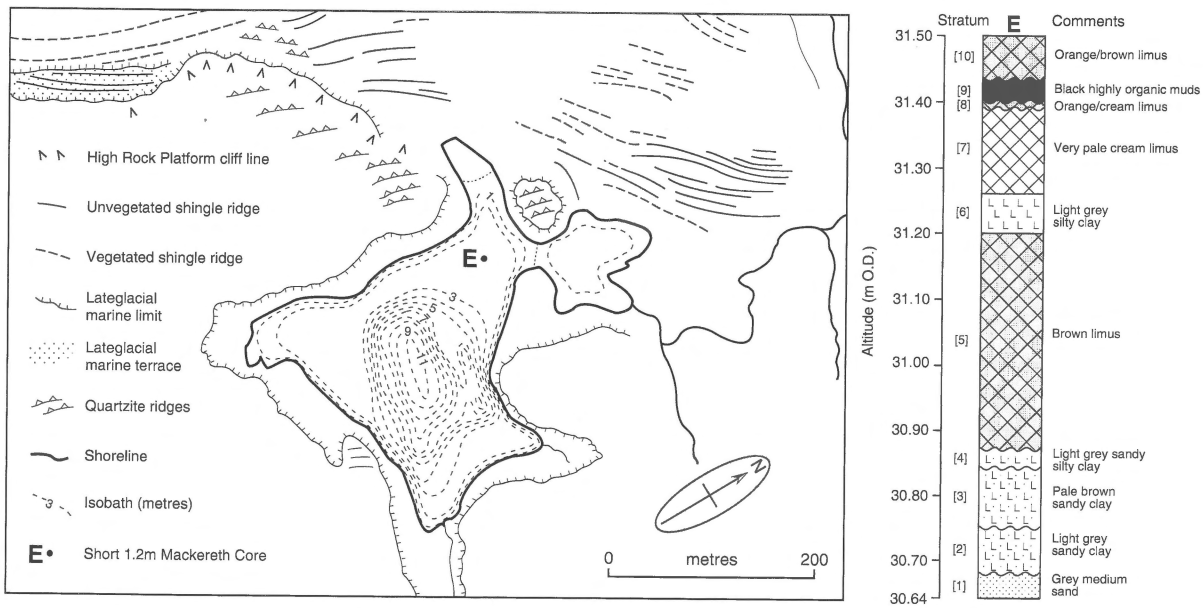


*Figure 7.* Lateglacial beach ridges and lake sediment stratigraphy, Loch Tuim Uaine (see Figure 1).

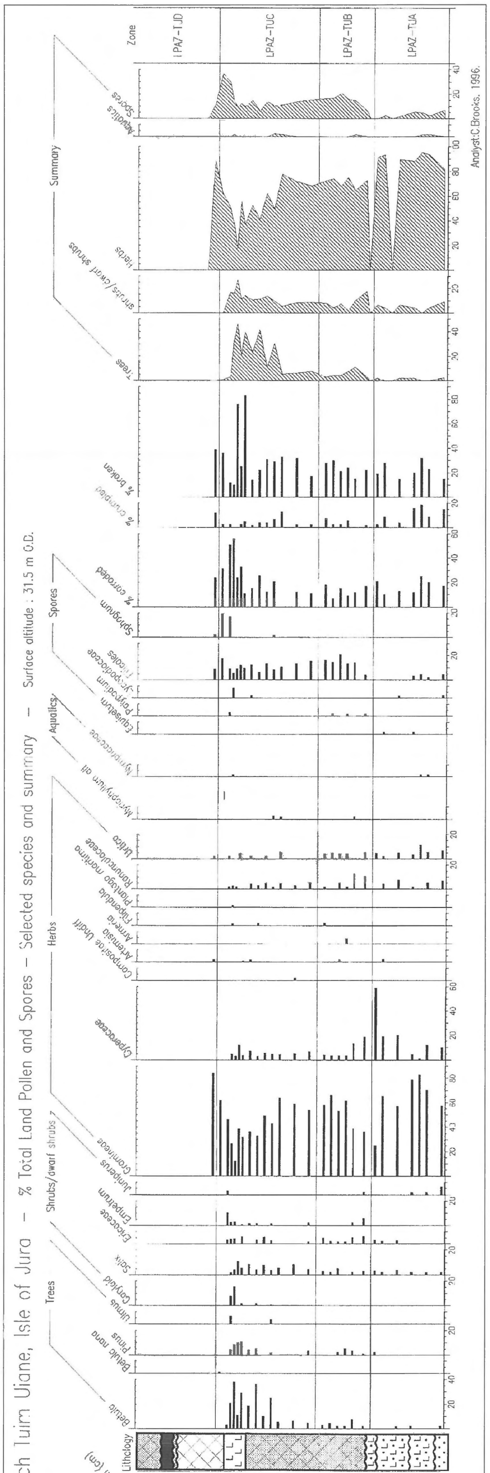


*Figure 8.* Pollen diagram and local pollen assemblage-zones for Core E, Loch Tuim Uaine (see Figure 7). NB: No data present between 0–20 cm depth. Note also that the inferred Younger Dryas stratigraphic horizon occurs between c. 25 and 30 cm depth.

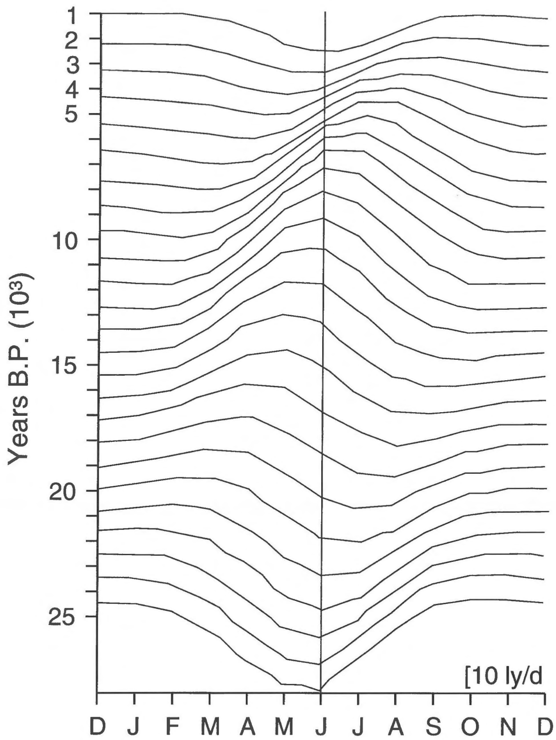


*Figure 9.* Insolation signatures from 25000 till 1000 years BP showing long-term monthly deviations from the average annual insolation value for 60°N. Note the way in which there are long-term seasonal drifts of individual insolation minima and maxima (after Berger 1979). Insolation is recorded in Langleys (1 ly = 1 cal $cm^{-2}$) per day. Note that the insolation values are theoretical values for the outer edge of the Earth's atmosphere and that these are calibrated by astronomical theory. Note also that present-day summer values are low since this is when the Earth is farthest from the Sun.

Recent stable-isotope research using foraminifera has enabled reconstructions of summer ocean-surface temperatures for this time-period (Weinelt et al. 1995, Duplessy et al. 1996). These studies have derived estimates for August sea-surface temperatures for the North Atlantic during the Younger Dryas, showing values for western Scotland of between c. 7 and 10°C.

Reconstructions of former air temperatures for Scotland suggest mean July values at sea level of c. 7 to 10°C and mean January temperatures in the order of –20°C (Ballantyne & Harris 1994). Such severe palaeoenvironmental conditions contrast with air and ocean temperatures during the Lateglacial Interstadial that are believed to have been similar to those of the present. Such pronounced lowering of annual air temperatures should also be considered from the perspective of reconstructed Milankovitch cycles of monthly insolation variations (Berger 1979), which show that during both the Lateglacial Interstadial and the Younger Dryas, there was a reversal of perihelion and aphelion (Figure 9). This resulted in the occurrence of winters at times in the Earth's orbital cycle when the Earth was farthest from the Sun (the opposite of the present), and of summers at times when it was closest to the Sun. These changed orbital parameters would have accentuated seasonal contrasts in insolation such that the Younger Dryas (and also the preceding interstadial), was characterised by long cold winters and short warm summers.

*Cold-climate coastal processes*

The prevailing ocean and atmosphere temperature regimes of the Younger Dryas occurred at a time when ice cover over northern Britain and most of Scandinavia resulted in the occurrence of permanent anticyclonic circulation over NW Europe, and the steering of North Atlantic depressions to the north and south of the British Isles. Under these circumstances, it is likely that the extremely low winter temperatures may have resulted in the development of sea ice in inshore areas of western Scotland. Furthermore, the extreme annual temperature range in conjunction with the inferred extremely low winter values may have promoted vigorous frost action on coastal cliffs during the Younger Dryas. In addition, the presence during winter of ice frozen to the base of coastal cliffs (an ice foot), together with cycles of freezing and thawing of bedrock within a vertical zone exposed to semi-diurnal wetting and drying may have promoted the shattering of bedrock and its removal by sea-ice processes (Sissons 1974, Dionne 1979, Dawson et al. 1987).

A well-developed shore platform and cliff (the Main Line) of presumed Younger Dryas age, are a prominent feature along much of the coastline of NW Norway (Rasmussen 1981). It is therefore concluded that since such a platform and cliff appear to have been produced in a variety of areas of NW Europe where the rate of relative sea-level change has varied greatly (Rasmussen 1981, Gray 1974, 1978, Dawson 1980, 1988, 1989), the rate of relative sea-level change during the Younger Dryas could not have been a critical factor in platform evolution. The principal factors responsible for the production of the Main Rock Platform in western Scotland were probably mostly related to the nature of the climatic deterioration that took place at this time, rather than to the rate of change in relative sea level in particular areas.

The occurrence at many locations of vegetated talus deposits that mantle the cliff of the Main Rock Platform and the partial burial of these deposits by younger Holocene marine sediments appear to indicate that frost shattering on the coastal cliffs was suddenly terminated. This termination and the inferred amelioration in climate may be represented in the Greenland ice-core record where a high-magnitude climate warming has been inferred to have taken place over a matter of decades at the end of the Younger Dryas (Bond et al. 1993).

## Conclusions

The geomorphological evidence of raised shoreline features in western Jura appears to indicate that the Lateglacial Interstadial that followed regional deglaciation and preceded the Younger Dryas, was characterised by temperate coastal processes similar to those of the present. There is no unequivocal evidence that sea ice and an ice foot were important agents of coastal evolution during this time-period in the Scottish Hebrides. The temperate coastal processes of the interstadial appear to have been suddenly ended as a result of a high-magnitude climatic deterioration associated with the onset of the Younger Dryas. The drastic lowering of air and ocean temperatures was accompanied by frost shattering of rock on coastal cliffs and it is inferred that these changes in climate may also have been associated with the formation of seasonal sea ice in inshore coastal waters and the development of an ice foot at the base of many coastal cliffs. These processes, acting in conjunction with enhanced seasonality caused by a reversal of perihelion and aphelion contributed significantly to the production of a well-developed coastal platform and cliff. The sudden climatic amelioration associated with the termination of the Younger Dryas, had a pronounced effect on the coastal zone where frost shattering of bedrock suddenly ceased. It is concluded that the production of the platform and cliff was principally related to changes in the coastal processes linked to changes in climate rather than to changes in relative sea level. At present, the intertidal zone in western Jura is characterised by relict quartzite-rock platform surfaces of Younger Dryas age. Thus, the effect of modern storms is to cause the translation and dissipation of wave energy across a fossil rock platform surface. The high sea levels predicted by the Intergovernmental Panel on Climate Change (IPCC) for the next century would, therefore, have a negligible effect on this coastal zone particularly since the area is characterised by continued glacio-isostatic uplift (cf. Shennan et al. this issue).

## Acknowledgements

This paper was partly supported by research under European Union Contract 'Climate Change and Coastal Evolution in Europe' (EV5V-CT94-0445). Thanks are also given to Erica Milwain and Steve Turnbull for cartographic assistance and to Gillian West for typing the manuscript.

## References

Ballantyne, C.K. & C. Harris 1994 The periglaciation of Great Britain. Cambridge University Press, 330 pp

Berger, A.L. 1979 Insolation signatures of Quaternary climatic changes – Il Nuovo Cimento 2C-1: 63–87

Bond, G., W.S. Broecker, S. Johnsen, J. McManus, J. Labeyrue & G. Bonani 1993 Correlations between climatic records from North Atlantic sediments and Greenland ice – Nature 365: 143–147

Dawson, A.G. 1980 Shore erosion by frost: an example from the Scottish Lateglacial. In: Lowe, J.J., J.M. Gray & J.E. Robinson (eds) Studies in the Lateglacial of North-West Europe. Pergamon, Oxford: 45–53

Dawson, A.G. 1982 Lateglacial sea-level changes and ice-limits in Islay, Jura and Scarba, Scottish Inner Hebrides – Scot. J. Geol. 18: 253–265

Dawson, A.G. 1988 The Main Rock Platform (Main Lateglacial Shoreline) in Ardnamurchan and Moidart, western Scotland – Scot. J. Geol. 24: 163–174

Dawson, A.G. 1989 Distribution and development of the Main Rock Platform: reply – Scot. J. Geol. 25: 233–238

Dawson, A.G. 1993 West Coast of Jura. In: Gordon, J.E. & D.G. Sutherland (eds) Quaternary of Scotland. Chapman and Hall: 382–389

Dawson, A.G., J.A. Matthews & R.A. Shakesby 1987 Rock platform erosion on periglacial shores: a modern analogue for Pleistocene rock platforms in Britain. In: Boardman, J. (ed.) Periglacial processes and landforms in Britain and Ireland. Cambridge University Press, 296 pp

Dionne, J.C. 1979 Ice action in the lacustrine environment. A review with particular reference to Subarctic Quebec, Canada – Earth Sci. Rev. 15: 185–212

Duplessy, J.C., L.D. Labeyrie & M. Paterne 1996 North Atlantic sea surface conditions during the Younger Dryas cold event. In: Andrews, J.T., W.E.N. Austin, H. Bergsten & A.E. Jennings (eds.) Late Quaternary Palaeoceanography of the North Atlantic Margins. The Geological Society, London, 376 pp

Gray, J.M. 1974 The Main Rock Platform of the Firth of Lorn, western Scotland – Trans. Inst. Br. Geogr. 61: 81–99

Gray, J.M. 1978 Low-level shore platforms in the south west Scottish Highlands: altitude, age and correlation – Trans. Inst. Brit. Geogr. New Series 3: 151–64

Gray, J.M. 1989 Distribution and development of the Main Rock Platform, western Scotland: comment – Scot. J. Geol. 25: 227–231

Gray, J.M. 1995 Influence of Southern Upland ice on glacio-isostatic rebound in Scotland – Boreas 24: 30–36

Gray, J.M. & M. Ivanovich 1988 Age of the Main Rock Platform, western Scotland – Palaeogeogr. Palaeoecol. Palaeoclim. 68: 337–345

Lowe, J.J. & J.M. Gray 1980 The stratigraphic subdivision of the Lateglacial of NW Europe: A Discussion. In: Lowe, J.J., J.M. Gray & J.E. Robinson (eds) Studies in the Lateglacial of North-West Europe. Pergamon Press: 157–176

Lowe, J.J., G.R. Coope, D.D. Harkness, C. Sheldrick & M.J.C. Walker 1995 Direct comparison of UK temperatures and Greenland snow accumulation rates, 15000–12000 yr ago – J. Quat. Sci. 10–2: 175–180

Rasmussen, A. 1981 The deglaciation of the coastal area NW of Svartisen, Northern Norway – Nor. Geol. Unders. 369: 1–31

Ruddiman, W.F., L.K. Glover & A. McIntyre 1973 Time-transgressive deglacial retreat of polar waters from the North Atlantic – Quat. Res. 3: 117–130

Shennan, I., M. Tooley, F. Green, J. Innes, K. Kennington, J. Lloyd & M. Rutherford (this issue) Sea level, climate change and coastal evolution in Morar, northwest Scotland

Sissons, J.B. 1974 Lateglacial marine erosion in Scotland – Boreas 3: 41–8

Stone, J., K. Lambeck, L.K. Fifield, J.M. Evans & R.G. Cresswell 1996 A Lateglacial age for the Main Rock Platform, western Scotland – Geology 24–8: 707–710

Weinelt, M., M. Sarnthein, E. Jansen, H. Erlenkeuser & H. Schultz 1995 Younger Dryas Cold Spell and a Holocene-style Circulation in the Nordic Seas. In: Troelstra, S.R. (ed.) The Younger Dryas. North-Holland, Amsterdam: 109–116