Fjords represent an important transition zone between upland valley glaciation and the glacial-marine environment. **Martyn Stoker**, **Tom Bradwell** and **Christian Wilson** explain how the study of north-west Scotland's fjords is helping to link the onshore–offshore record of Quaternary glaciation and shed new light on the glacial dynamics of the last British ice sheet.

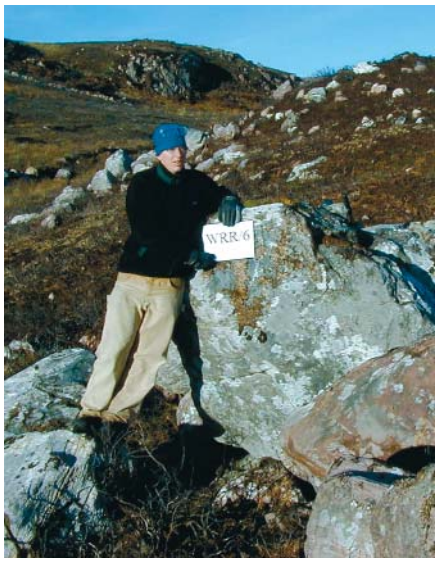
Mapping Scotland's fjords

The term 'fjord' is a generic Nordic word for a marine inlet, although it is almost always applied to the result of glacial erosion. Over the past 500 000 years, glaciers have carved and shaped the stunning fjord landscape of the west coast of Scotland. The north-west Highlands is one of the best places to view the effects of glacial erosion, from the spectacular mountain peaks and deep scalloped corries to the U-shaped valleys and sea lochs. The special nature of this unique landscape has recently been acknowledged in its designation as a 'European Geopark', an accolade also recognised by UNESCO. Less well-known, however, is the dramatic underwater landscape that forms an integral component of the region's natural heritage.

In July 2005, the BGS undertook sea-floor mapping of the Summer Isles region, west of Ullapool in the north-west Highlands. This is part of a source-to-sink initiative that is designed to develop an onshore–offshore Quaternary mapping scheme. For this survey, about 200 square kilometres of the sea floor in the Summer Isles region, including Loch Broom and Little Loch Broom, was remotely mapped using swath bathymetry and high-resolution seismic-reflection profiling. This combination of data-acquisition systems provided a sophisticated picture of the sea floor and the underlying geology. The newly acquired data were imported into a 3D-visualisation package that enabled the process of geological and geomorphological interpretation of the marine landscape to begin.

Through the source-to-sink initiative we had already identified the former pathway of a large ice stream, the Minch palaeo-ice stream, that developed on the continental shelf between north-west Scotland and the Isle of Lewis and extended 100 km offshore towards the edge of the shelf, west of the Outer Hebrides. This ice stream was one of several that were active during the late Devensian glaciation of Britain and Ireland. It helped to drain the north-west sector of the last British ice

View towards Gruinard Bay (in the mist) and An Teallach.



Boulder-strewn Wester Ross Readvance moraine near Gairloch, north-west Scotland.

sheet from soon after the peak of glaciation (about 22 000 years ago) to approximately 17 000 years ago. Our subsequent work, leading in to the fjord survey, focused on examining the dynamics of the ice sheet during deglaciation. Special emphasis was placed on moraines as a link, both temporal and spatial, between the onshore and offshore Quaternary record.

A major problem encountered by Quaternary geologists working onshore is the general absence of moraines in Scotland that relate to the last British ice sheet, as much of the evidence is either offshore or has been subsequently erased by the Loch Lomond Stadial ice cap during the Younger Dryas (about 12 900 to 11 500 years ago). However, coastal regions in the far north-west Highlands, such as Wester Ross and Sutherland, escaped glaciation during the Younger Dryas, leaving a tantalising glimpse of ice-sheet fluctuations at the end of the late Devensian glaciation. Probably the best-preserved onshore evidence of this ice-sheet margin is a series of moraines that extend from Applecross in the south to Coigach in the north, a distance of about 70 km. These moraines are typically of low relief (four to five metres high) and vary in morphology, from pronounced sharp-crested ridges to boulder-strewn hummocks. The form of the moraines, running across country for long distances with little regard for the underlying topography, is very similar to those presently seen at the margin of the Greenland ice sheet. Until now, the whole moraine system has been thought to mark the maximum extent of a regional glacial event, the Wester Ross Readvance, that occurred during the retreat phase of the last British ice sheet.

The Summer Isles region is located within the northern area of the Wester Ross Readvance. The sea-floor images reveal the juxtaposition of shallow marine banks, less than 15 to 20 m below present-day sea level, and deeply incised fjord troughs, up to 180 m deep, with steep sides, flat bottoms and undulating axial profiles. The troughs represent the offshore continuation of the modern sea lochs. The shallow banks have a distinct ribbed appearance that reflects the preservation of a suite of at least 15 sea-floor moraines, 5 to 15 m high and 50 to 125 m wide. These moraines chart the decay of the ice sheet as it receded from the adjacent continental shelf, through the fjord system, and back towards the mountains of the north-west Highlands.

By integrating the onshore mapping data with the newly acquired sea-floor imagery, we have established for the first time:

- the continuity and integrity of the ice-margin moraine system in the Wester Ross region, through linkage of the sea-floor moraines with the Wester Ross Readvance moraines on land
- that the Wester Ross Readvance event, rather than being a simple ice-sheet readvance, was characterised by an oscillating ice-sheet margin undergoing overall, but punctuated, glacier retreat within the fjords, following the breakdown of The Minch palaeo-ice stream

This work continues with the development of an onshore–offshore Quaternary map that captures the glacial geomorphology, terrestrial and submarine, of the Summer Isles region, together with an event stratigraphy. This will have consequences for assessing the link between ice-sheet dynamics and climate change in north-west Scotland, towards the end of the last glaciation, (about 15 000 years ago).

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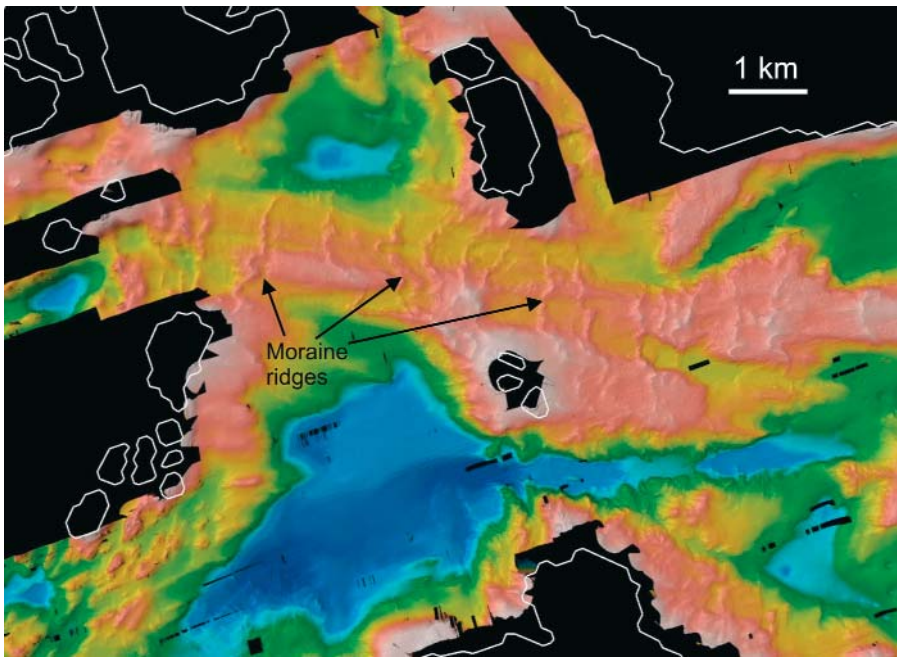

Colour-shaded perspective of the sea floor around the Summer Isles. Shallow, moraine-covered banks are white/pink; deep fjord troughs are blue/dark blue.