Submarine landslides and tsunami threat to Scotland

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Abstract. There is strong evidence that the Storegga Slide located offshore mid-Norway caused a tsunami wave that struck the northern and eastern coasts of Scotland about 7200 years ago. Its impact physically was extensive, but socio-economically we presume it was minor. Today its consequences would be very different. Other landslides, ranging in volume from 0.2 km^3 to more than 800 km^3 have been identified on the continental margin around Scotland and need to be evaluated as to the risk the repetition that such events pose. Work is underway to map and date these events, and assess their potential triggers. The risk assessment includes evaluation of offshore seismicity and the geotechnical parameters of slope sediments. Slide frequency during the Quaternary and the environment of failure are also important factors. These marine studies are matched by studies onshore for evidence of paleotsunamis.

1. Regional Setting

Scotland sits on the northwest European passive margin, an area not usually considered affected by the more active geohazards found in many other parts of the world. Following the opening of the North Atlantic in late Mesozoic/early Paleogene time and the associated voluminous volcanic activity associated with the Iceland Plume, the traditional image of NW Europe is of an inactive area. As the Tertiary volcanics cooled and subsided the uplifted areas were subjected to rapid erosion, forming extensive basin deposits, some exploited for their hydrocarbons in the North Sea and nearby. Denudation rates fell until the Neogene when centers of uplift developed in Norway, the Faroes, Scotland, and Ireland in response to crustal stress caused by the Alpine Orogeny. The denudation rates increased further during the Quaternary when extensive ice sheets periodically developed and retreated on these uplifted areas. The eroded sediments were deposited at or just beyond the shelf break, in places advancing it 20 km in less than half a million years.

The distribution of the eroded sediment was focused on selected areas where up to 1 km of Plio-Pleistocene sediments have been mapped (Fig. 1). The distribution of the depocenters reflects the sediment transport pathways across the continental shelf, particularly where sedimentary basins provide more easily erodible surfaces compared with that of early Paleozoic and older basement. The most southerly depocenter comprising the Barra and Donegal Fans, subdivided by the Hebrides Terrace Seamount, is up to 900 m thick between 56°N and 57°N extending from the shelf break ($\sim$200 m) to more than 2000 m water depth (Fig. 1). The next depocenter, the Sula Sgeir Fan, occurs at the northeast corner of the Rockall Trough, where up to 600 m of sediments have been mapped. Like the Barra Fan these sediments comprise a large sediment wedge prograding from the shelf to the floor of the Rockall Trough. In contrast, in the between-fans area only a thin (<100 m thick)

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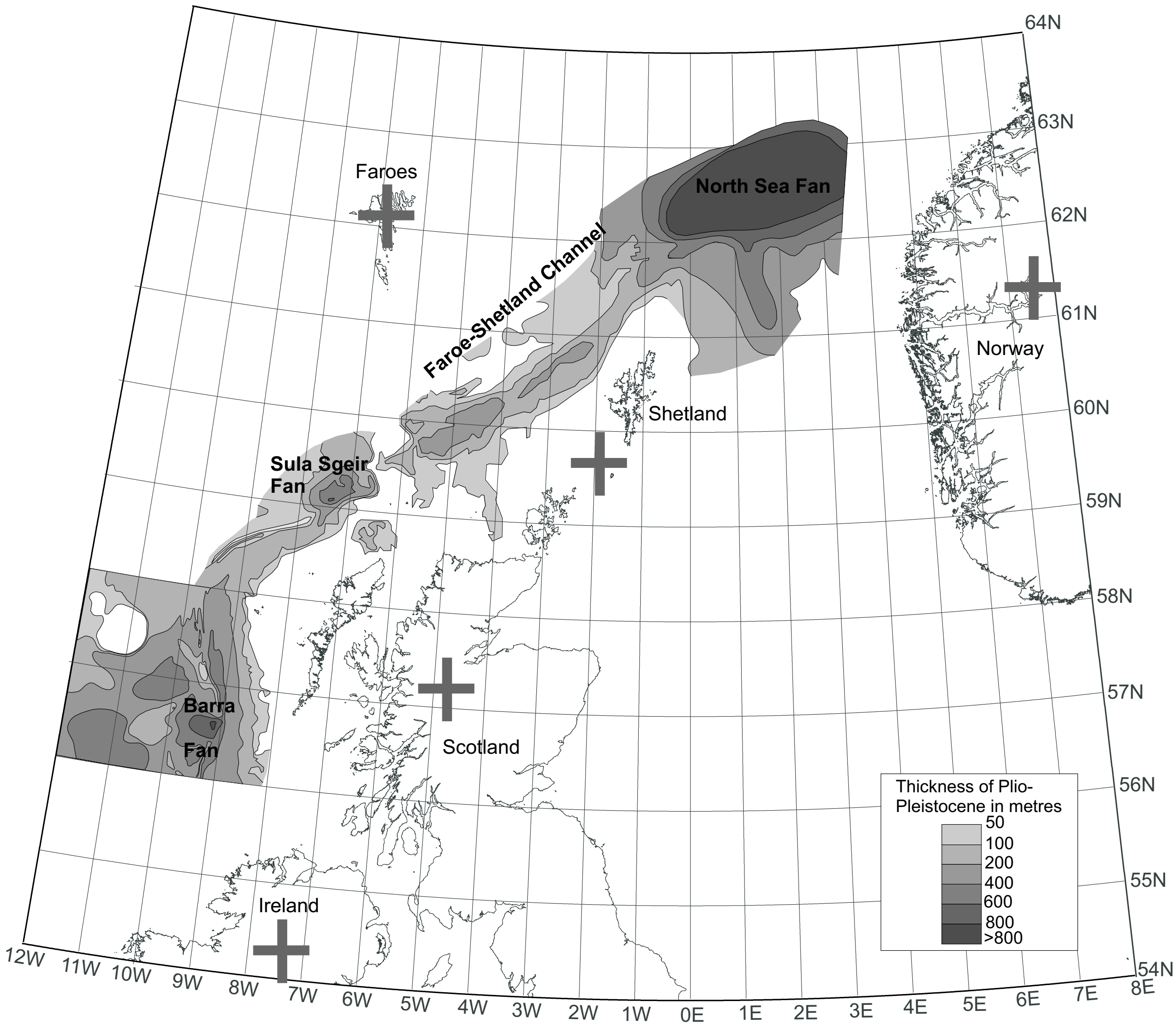

Figure 1: Map showing Plio-Pleistocene thickness along the Scottish margin; crosses mark centers of Pliocene uplift.

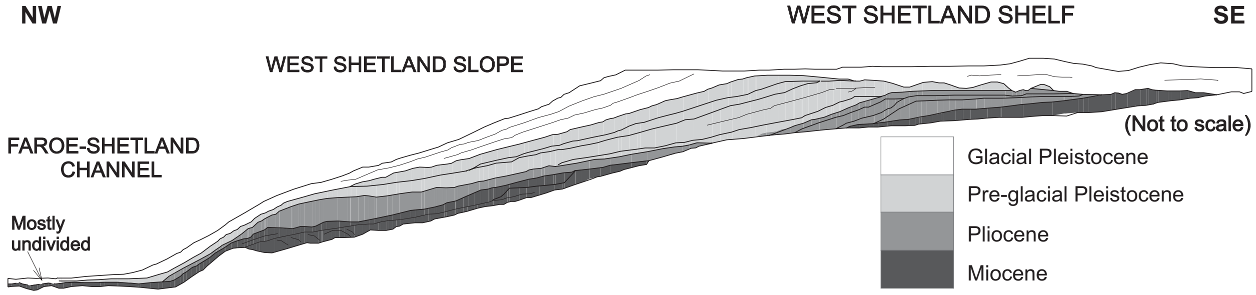

Figure 2: Schematic cross-section showing the sediment wedges build out west of Shetland.

Plio-Pleistocene sequence has accumulated. Seismic profiles suggest that in the fans a wide range of along-slope and down-slope sedimentary processes have been active, however in the inter-fan areas the sedimentary processes appear to be restricted to contourite sheets.

In the Faroe–Shetland Channel the sediment thicknesses are less and not as focused, reflecting perhaps the greater distance from mainland Scotland, and lower uplift and more limited glaciation over Shetland. Sediments locally exceed 200 m thick, extending the shelf break 20 km within the glacial Quaternary (Fig. 2). However, to the north and northeast of Shetland the North Sea Fan has the greatest thickness of Plio–Pleistocene sediments originating from Scandinavia with minor amounts from the UK. Much of the Scandinavian ice sheet flowed into the Norwegian Trench where it turned northwards to shed its load onto the North Sea Fan. This fan records the largest volume of geologically recent uncemented sediments on the European margin with 25,000 km^3 of Plio–Pleistocene sediments, locally exceeding 1200 m thick, making it comparable to the fan of a major river system.

2. Evidence of Sediment Failure

Much of the UK margin has been systematically surveyed as part of the British Geological Survey's regional mapping program. There have also been selected, more detailed, studies for various academic projects and numerous commercially funded site surveys associated with hydrocarbon exploration.

The Barra Fan shows evidence of numerous debris flows giving a chaotic acoustic appearance between regionally extensive reflectors. The latter are cut by erosive events which, when mapped out, depict several large slides. These are known collectively as the Peach Slides and together displace 1830 km^3 of sediment (Holmes *et al.*, 1998). Definitive dates for these events are not available but event 3 is less than 17,000 years BP and event 4 intersects iceberg ploughmarked seabed, suggesting a late- to post-glacial age. High resolution swath bathymetry and sidescan sonar data also show smaller superficial sediment movement with very fresh appearances, particularly within the Irish sector on the Donegal Fan (Fig. 3). These Holocene failed sediments are predominantly at the shelf margin.

Farther north, the Sula Sgeir Fan shows downslope sediment movement

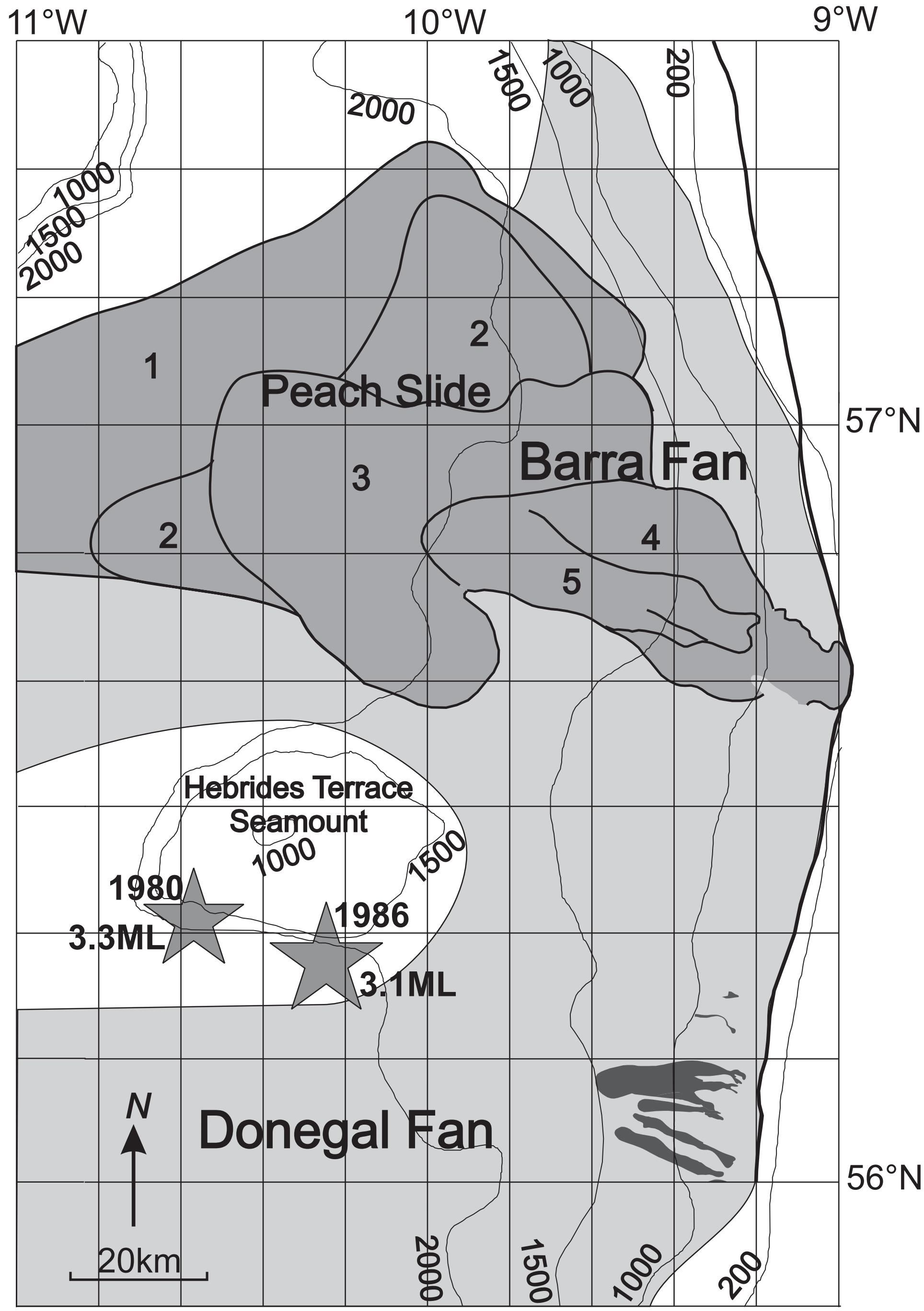

Figure 3: Map of the Barra and Donegal fans. Light grey—area of Plio-Pleistocene debris deposits, mid-grey—Peach Slide events, dark grey—recent events, stars—locations of seismic events with magnitudes.

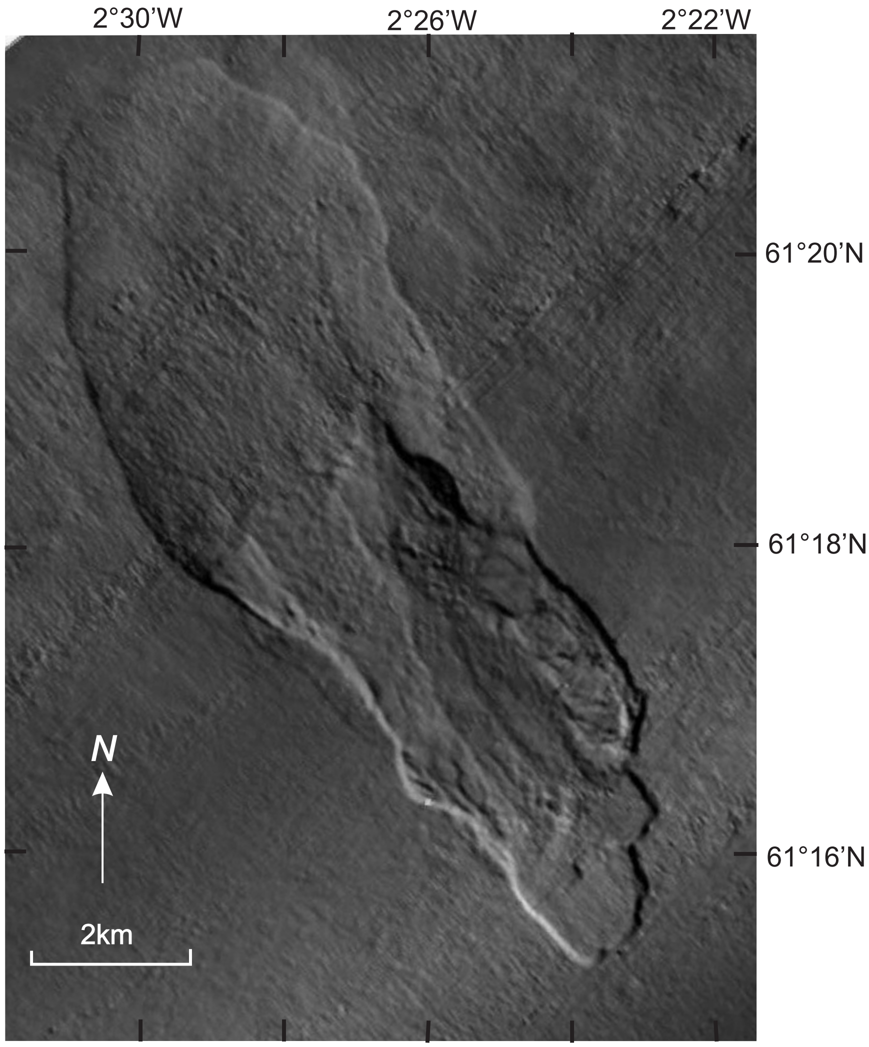

Figure 4: Seabed image showing downslope debris flows and base of slope fans.

in several forms. GLORIA surveys identified three bottle-neck slides, 1–2 km wide, 10 km long (Kenyon, 1987). These were originally interpreted as post-glacial as their headwalls appeared to have cut iceberg ploughmarks. However, more recent surveys show they are older and are just the most recent of numerous events extending back to when shelf-wide glaciation began.

Along the west Shetland margin there is abundant geomorphological evidence of numerous debris flows with base of slope fans. However, they all appear to be glacigenic and are located downslope of where ice sheets extended beyond the shelf break (Fig. 4). Toward the northern end of the Faroe–Shetland Channel, seabed surveys show clear evidence of a recent landslide (Fig. 5). This feature, the Afen Slide, 3 km wide, 13 km long, has been tentatively dated to mid-Holocene. Detailed studies show that it is a multi-phase feature with possible retrogressive failure upslope. There has also been some sidewall failure. The total volume of displaced sediment

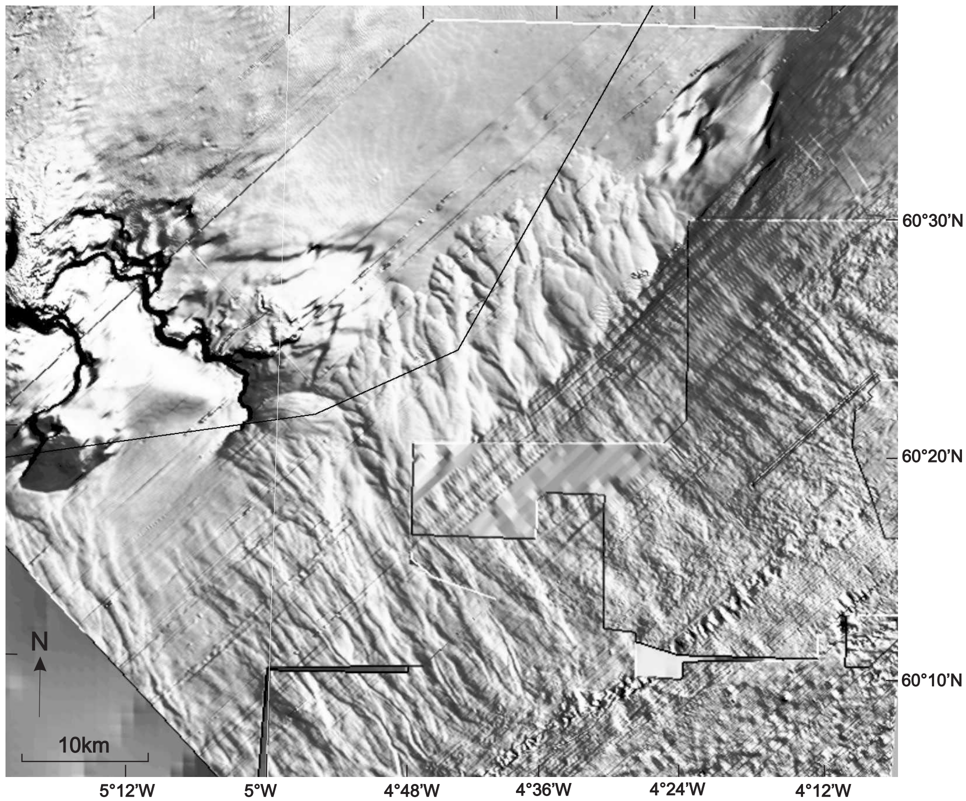

Figure 5: Seabed image of the Afen Slide.

involved in this feature is about 0.4 km^3. Recent work has identified another slide of virtually the same dimensions buried about 50 m below the present seabed, seismo-stratigraphically several 100,000 years old. To the north, another buried slide, the Miller Slide, has a headwall up to 100 m high and a debris flow extending more than 100 km out into the Faroe–Shetland Channel (Fig. 6). This may have displaced more than 200 km^3 of slope sediments. Seismo-stratigraphic correlation suggests an O^{18} stage 9 or 11 age to this feature. This slide is located close to the edge of the North Sea Fan, within which there is abundant evidence for large buried events (King *et al.*, 1996; Evans *et al.*, 1996). They include syndepositional debris flows associated with glacial processes and landslides that have transported large blocks of sediment (Fig. 7). Most of these features are within the Norwegian sector of the northern North Sea and the modern seabed-failure analogue is the 7200 year BP Storegga Slide located on the northern flank of the North Sea Fan.

3. Triggers

The rapid sedimentation in selected loci along the UK margin has created thick sequences of under-consolidated sediments. Excess pore-pressures within the sediment pile are presumed to occur due to this rapid loading.

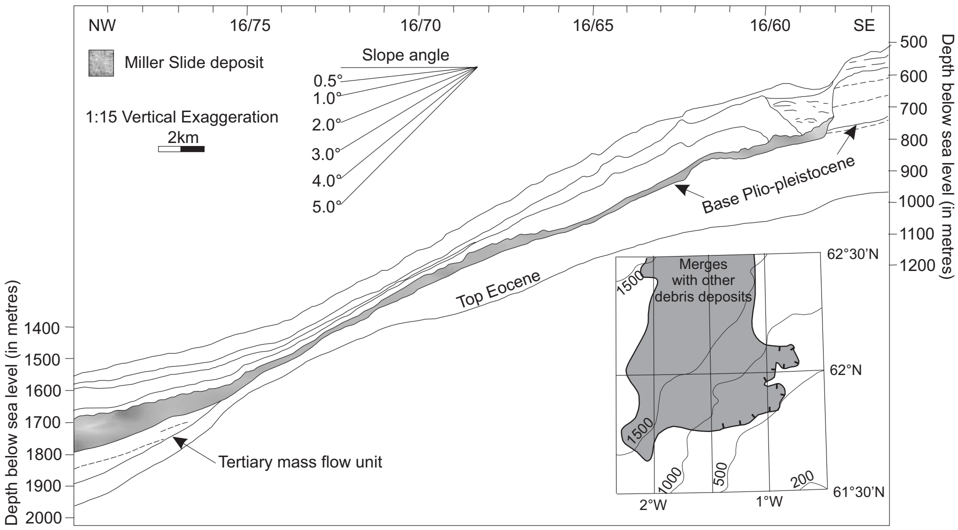

Figure 6: The Miller Slide northwest of Shetland—interpreted seismic section and location map

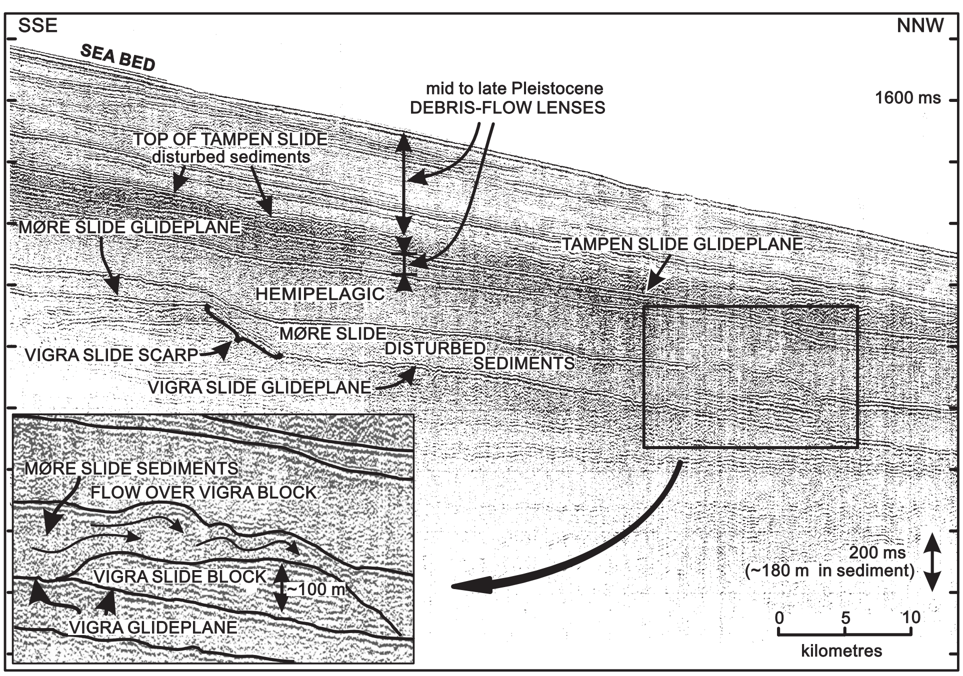

Figure 7: Seismic section from the North Sea Fan showing displaced blocks (adapted from Evans *et al.*, 1996).

Gas may also contribute to the excess pore-pressure due to the breakdown of in-situ organic matter and leakage from underlying hydrocarbon reservoirs. Acoustic gas blanking has been noted with some of the slide features. However, many of the sites occur within the methane hydrate stability zone and so, except in areas of high gas flux, free gas may not occur. Other than some evidence within the Storegga complex, bottom simulating reflectors and other acoustic evidence for hydrates are absent. As the NW European margin has been subjected to large eustatic and isostatic tectonic movements during the Quaternary, significant pressure changes (and thermal fluctuations) may have sublimated much of any hydrate present.

Seismicity is normally low along a passive margin. However, the northern end of the North Sea is one of the more active areas of NW Europe. There have been 90 events of magnitude >3 M_L in the last 30 years out of 1500 recorded by stations in the UK and Norway (2 events $>$ magnitude 5 M_L). West of the UK, monitoring has been more limited, but two events of magnitude >3 M_L were detected in the 1980s close to the Peach Slide (Fig. 3). Activity in the Faroe–Shetland Channel has been monitored over the last 5 years without detection (current detection threshold 2 to 2.5 M_L). However, the location of the Afen Slide, above a significant tectonic lineament, the Victory Transfer Zone, mimics the co-location of the Storegga Slide above the Jan Mayen Fracture Zone and the Trænadjupet Slide above the Bivrost Lineament offshore Norway (Laberg and Vorren, 2000). It should be noted that modern seismic activity may be lower than that in the early Holocene when the postglacial crustal rebound rate was greater. Neotectonism is evident at glacial centers in Scotland (Ringrose, 1989) and Northern Ireland (Knight, 2000) with surface displacement since deglaciation.

4. Threats to Scotland

All these slides on the continental margin are located more than 70 km from the coastline, therefore only the largest sea perturbations are likely to impact the coast. The western and northern coastlines of Scotland are sparsely populated, however a few key economic sites are potentially vulnerable. Perhaps of greater impact, although originating from much smaller events, would be submarine landslides in the sea lochs of western Scotland. The steeper sides, greater late- to post-glacial sedimentation rates, and elevated seismicity due to post-glacial crustal rebound make these areas worthy of further study.

The Afen Slide of mid-Holocene age is located above a similar feature indicating repetition. The most recent Peach Slide is the latest of two postdating 17 ka. The North Sea Fan has had repeated failure. Together this indicates that the threat of new landslides is ever present. The larger events such as the Peach and Miller slides, if displaced singularly, might have caused a tsunami. They are as large as some other slides that have been associated with tsunamis over distances as great as that between the slide and the present day coastlines. However, due to their suspected age it is extremely unlikely that any geological evidence exists to confirm this. Along the eastern

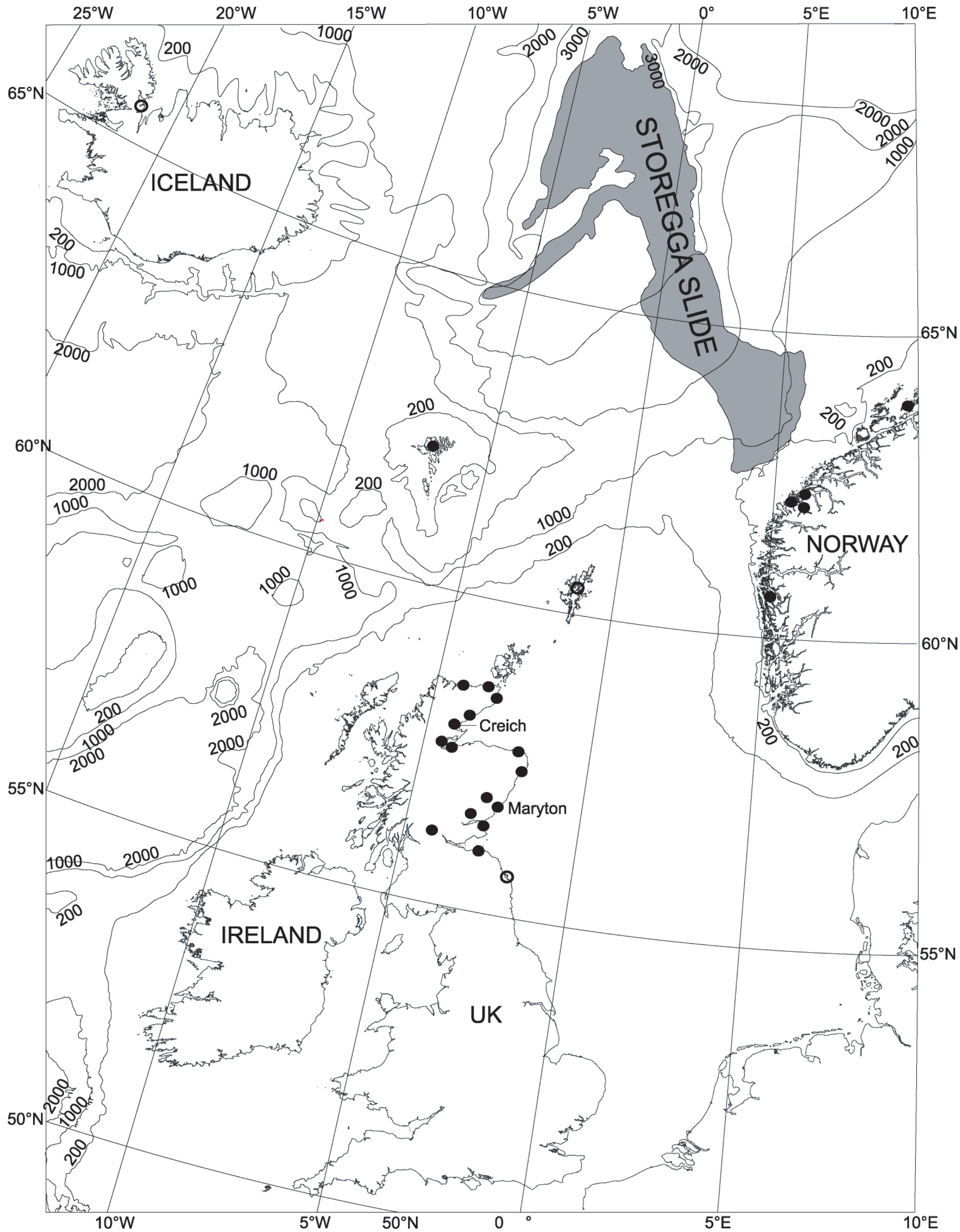

Figure 8: Map of tsunami deposits attributed to the Storegga Slide. Solid dots—sites dated to about 7200 yBP, open dots—sites undated.

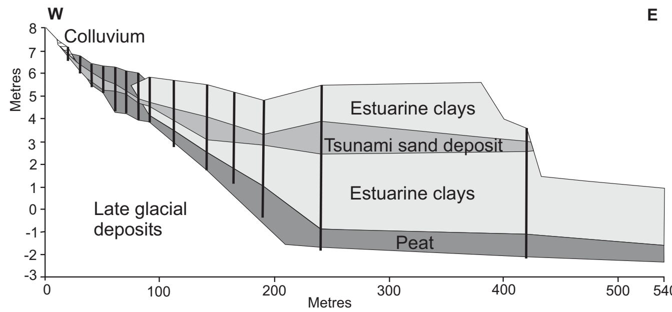

Figure 9: Profile at Creich, east coast of Scotland, illustrating the litho-transgressive nature of the Storegga tsunami deposit. For location see Fig. 8.

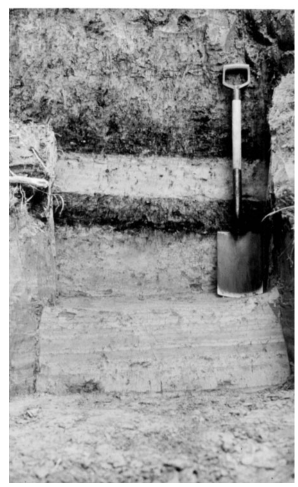

Figure 10: Photograph of tsunami sand layer (behind shaft of spade) within peat deposits at Maryton, east coast of Scotland. For location see Fig. 8.

and northern coasts of Scotland, though, there is evidence for a tsunami associated with the Storegga Slide of 7200 yBP (Dawson *et al.*, 1987).

The landslide's impact on Scotland was to cause a tsunami that struck the north and eastern coasts extending as far south as Lindesfarne in northern England (Fig. 8). Based on the sedimentological evidence, the waves would locally have extended several hundred meters inland of the former coastline with a run-up of 1–2 m in open areas and much greater in enclosed bays or lochs (Long *et al.*, 1989). These figures are based on sediments laid down (Fig. 9) and subsequently preserved, therefore representing minimum run-up values. The tsunami sediments (Fig. 10) typically comprise marine sands but also contain debris from the coastal marshes, etc. Detailed examination of this debris indicates that the event happened in the autumn (Dawson and Smith, 2000), matching similar evidence in Norway (Bondevik, 1997) where recent high precision dating gives an age of 7262 ± 47 yBP (Bondevik, personal communication, 2001). We have to presume the human impact was small due to the low population levels 7200 years ago, yet the deposit has been found at sites of early human habitation. However, we should presume that if it occurred today the consequences would be economically catastrophic. The frequency of tsunamis can be considered extremely low but not non-existent and needs to be considered in long-term planning for Scotland.

5. Current Work

Continued mapping for landslides offshore and tsunami deposits onshore continues under a range of oil company, European, and national funded programs.

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