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Landform assemblages and sedimentary processes along the Norwegian Channel Ice Stream

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Several regional and detailed bathymetric datasets together with 2D and 3D seismic data are compiled to investigate the landform assemblages and sedimentary processes along the former path of the Norwegian Channel Ice Stream (NCIS). At the broad scale, the glacial geomorphology and sedimentary architecture reveals three different zones along the ice-stream path, characterized by: (1) glacial erosion in the onset zone and inner shelf area, (2) sediment transport through the main trunk of the ice stream across the mid-shelf, and (3) a zone of deposition towards the outer continental shelf edge. Along the first 400 km of the ice stream bed (outer Oslofjord–Skagerrak–Stavanger) a major overdeepening is associated with suites of crag-and-tail features at the transition from the crystalline bedrock to the sedimentary bedrock, together with evidence of glaciotectonic thrusting in the form of hill-hole pairs. Here we interpret extensive erosion of both sedimentary rocks and Quaternary sediments. This zone is succeeded by an approximately 400 km long zone, through which most of the sediments eroded from the inner shelf were transported, rather than being deposited. We infer that sediment was transported subglacially and is likely to have been advected downstream by soft sediment deformation. The thickness of till of inferred Weichselian age generally varies from 0 and 50 m and this zone is characterized by mega-scale glacial lineations (MSGLs) which we interpret to be formed in a dynamic sedimentary system dominated by high sediment fluxes, but with some localized sediment accretion associated with lineations. Towards the shelf break, the North Sea Fan extends to the deep Norwegian Sea, and reflects massive sedimentation of glacigenic debris onto the continental slope. Numerous glacigenic debris flows accumulated and constructed a unit up to 400 m thick during the Last Glacial Maximum. The presence of these three zones (erosion, transport, deposition) is consistent with observations from other palaeo-ice streams and their significance arises from their potential to feedback and impact on ice stream dynamics.

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1. Introduction

The flow of continental ice sheets is partitioned between large areas of relatively low velocity (<50 m a^{-1}) and narrower 'arteries' of much higher velocity (>100 m a^{-1}), with tributaries that extend well into the ice sheet interior (Bamber et al., 2000). These rapidly-flowing zones are known as ice streams and they are viewed as an important control on ice sheet mass balance and stability (Hughes, 1977; Bentley, 1987; Stokes and Clark, 2001; Bennett, 2003). Given their significance, much work has been devoted to investigating the subglacial processes that facilitate their rapid flow, and recent advances in geophysics have enabled workers to image the bed of active ice streams (Smith, 1997a,b; King et al., 2007, 2009; Smith et al., 2007; Smith and Murray, 2009; Jezek et al., 2011; Ashmore et al., 2014). A key conclusion from these studies is that the ice-bed interface is highly dynamic, with sediment being eroded and transported over short (sub-decadal) time-scales, and in association with the evolution of subglacial bedforms, such as mega-scale glacial lineations (MSGLs: King et al., 2009). However, the precise mechanism(s) of flow remain difficult to ascertain, e.g., basal sliding over the till versus deformation and advection of sediment to various depths (Alley et al., 1986; Engelhardt and Kamb, 1998; Tulaczyk et al., 2000). Moreover, borehole and geophysical investigations of active ice streams are typically limited to just a few sites, making it difficult to investigate sedimentary processes along the entire ice stream bed. In contrast, numerous workers have recognized the potential to glean insights about subglacial processes beneath ice streams by investigating well-preserved palaeo-ice stream beds, either proximal to modern-day ice sheets in Greenland (Evans et al., 2009; Ó Cofaigh et al., 2013; Dowdeswell et al., 2014) and Antarctica (Livingstone et al., 2012; Graham et al., 2009; Ó

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Cofaigh et al., 2002, 2005), or from the beds of the last mid-latitude ice sheets (Andreassen et al., 2004; Ottesen et al., 2005, 2008; Rydningen et al., 2013; Margold et al., 2015).

Palaeo-ice stream beds are easily recognizable by a distinctive glacial geomorphological imprint, compared to slow-flowing regions outside of the ice stream, especially in areas where till is thick enough to be moulded into subglacial bedforms (Dyke and Morris, 1988; Stokes and Clark, 1999, 2001). Characteristic landforms on these 'soft-bedded' ice stream beds include highly elongate mega-scale glacial lineations (MSGLs) (Clark, 1993; Spagnolo et al., 2014) and ice stream shear margin moraines (Dyke and Morris, 1988; Stokes and Clark, 2002). Along continental shelves that fringed palaeo-ice sheets, ice streams also carved large cross-shelf troughs (Shaw et al., 2006; Rydningen et al., 2013; Batchelor and Dowdeswell, 2015), often associated with grounding zone wedges that mark their terminus position (Dowdeswell and Fugelli, 2012; Evans and Hogan, in press), and trough-mouth fans that attest to large volumes of sediment transport (Vorren and Laberg, 1997; King et al., 1996; Nygård et al., 2007). In areas devoid of till cover, 'hard-bedded' ice streams are more difficult to identify, but recent work suggests that mega-lineated terrain (including rock drumlins and bedrock mega-grooves) is produced by enhanced abrasion and quarrying of bedrock (Roberts and Long, 2005; Bradwell et al., 2008; Eyles, 2012; Krabbendam et al., 2016). Thus, these landform assemblages offer potential to understand sedimentary processes and flow mechanisms beneath ice streams over much larger spatial scales than is possible from geophysical investigation of modern ice streams.

One of the best-preserved and largest palaeo-ice streams yet reported was located in the Norwegian Channel (NC), the Norwegian Channel Ice Stream (NCIS), which represents one of the most important ice and sediment discharge routes from the former Fennoscandian Ice Sheet. Its trough extends for >800 km from near its source area in southern Norway and Sweden, and is >100 km wide at the edge of the continental shelf (Fig. 1). In this paper, we describe the landform assemblages along the entire length of this palaeo-ice stream system and its marginal areas. Our data sources benefit from over four decades of hydrocarbon exploration and we also take advantage of several new datasets to explore the sedimentary processes, with a particular focus on the identification of zones of erosion, transport and deposition at the local Last Glacial Maximum.

2. Geological background and previous work on the Norwegian Channel Ice Stream

The Norwegian Channel Ice Stream (NCIS) was first postulated by Helland (1885), largely based on the presence of bedrock clasts in clays from the Jæren area that were sourced from the Oslofjord region (Fig. 1). He claimed that these clasts were incorporated in a till deposited by a 'Skagerrak-glacier' which moved westwards from the Oslofjord area and south-central Sweden along the axis of the Skagerrak Trough parallel to the Norwegian coast around southern Norway and into the Jæren area (Fig. 1). However, Andersen (1964) later questioned this interpretation, instead arguing that the clay-rich 'Skagerrak till' was a glaciomarine deposit with dropstones. The notion of a NCIS was later reinvigorated when Rokoengen and Rønningsland (1983) documented north-flowing ice in the northern part of the NC based on seismic data.

Around 1980, the British Geological Survey (BGS) and the Norwegian Continental Shelf Institute (IKU, now Sintef Petroleum Research) initiated a mapping program of shelf areas in the North Sea. A series of seabed and Quaternary geology maps (scale 1:250,000) covering the whole UK part of the North Sea were produced, and a regional Plio/Pleistocene stratigraphical framework was developed with a series of lithostratigraphic units of regional extent (Stoker et al., 2011). IKU covered the northern North Sea with high-resolution single-channel shallow seismic data and

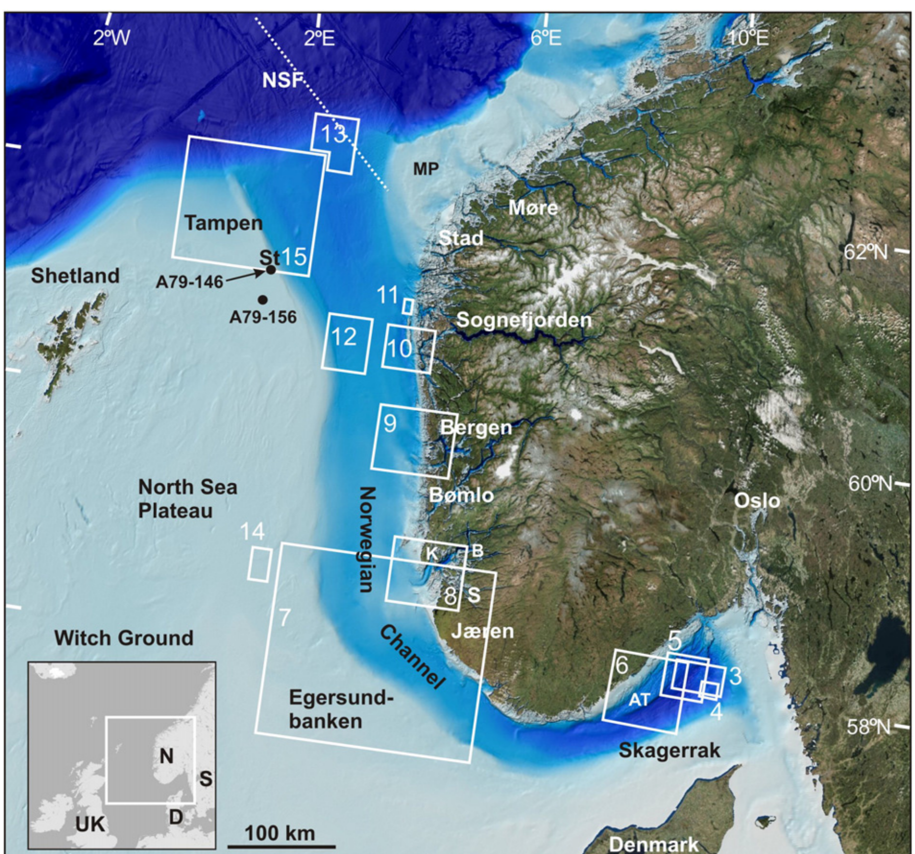

Fig. 1. Overview map with location of other figures. Bathymetry from the Norwegian Hydrographic Service and Olex AS. AT — Arendal Terrace, B — Boknafjorden, K — Karmsundet, MP — Måløy Plateau, NSF — North Sea Fan, S — Stavanger, St — Statfjord. Stippled line locates seismic line in Fig. 13A.

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