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Relating Cenozoic North Sea sediments to topography in southern Norway: The interplay between tectonics and climate

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ABSTRACT

About 482 000 km^3 of sediment (ca 24 m/Ma) accumulated in the North Sea during the Cenozoic. Early Cenozoic sedimentation was likely due to uplift of the circum North Atlantic landmasses related to continental break-up. Kilometre-scale transient uplift, and in some areas permanent uplift, generated sources for progradational influx of clastic sediments from Scotland, the Shetland platform and, to a lesser degree, southwestern Norway. The Eocene sedimentation pattern was similar to the Palaeocene, with lower rates of accumulation associated with flooding and tectonic quiescence. Sediment influx from the Shetland platform continued throughout the Cenozoic while supply from southern Norway increased markedly around the Eocene–Oligocene, coeval with the greenhouse–icehouse transition. Mass balance calculations of sediment and eroded rock volumes suggest that while some topography along the western margin of Norway may be pre-Cenozoic, significant uplift of the main Paleic surface in southern Norway occurred around the early Oligocene. Sedimentation rates were almost ten-fold higher than the Cenozoic average in the Plio-Pleistocene, slightly higher than the global average. Mass balance calculations indicate that Plio-Pleistocene erosion over-deepened a pre-existing topography.

1. Introduction

Tectonic and climatic driven erosion work in complex feedback loops (Hay et al., 2002; Molnar, 2004). These two processes control rate of erosion, chemical and mechanical weathering, sediment provenance, sediment composition, and direction and form of sediment influx (Milliman and Syvitski, 1992; Petit et al., 2007; Ruddiman, 1997; Von Blackenburg, 2005; West et al., 2005). Interplay between the processes makes it difficult to quantify their relative influence on sediment production, which has led to contrasting interpretations of the geological evolution of many areas, including the North Atlantic region (Anell et al., 2009).

Differences in geological models of uplift of the North Atlantic region are due to conflicting interpretation of evidence for vertical movement in Svalbard, Norway, Scotland, East and West Greenland and Eastern Canada (Anell et al., 2009; Doré et al., 2002). Much of the evidence can indicate either substantial tectonic uplift or significant changes in climate and eustatic sea-level (Molnar and England, 1990) (Table 1). For the mountains of southern Norway, arguments for predominant climate control on changes in sedimentation patterns require long-lived isostatic balancing of the mountain chain from its formation during the Caledonian orogeny (440 Ma) (Nielsen, 2002), while other studies support recent (late Cenozoic) kilometre-scale tectonic uplift (Gabrielsen et al., 2010a; Japsen et al., 2007, and references therein).

In this study we analyse rate and source of Cenozoic sedimentation in the North Sea (Fig. 1) based on interpretation of marine 2D reflection seismic data. We relate the interpretations to the tectonic, eustatic and climatic history of the area. We compare the offshore sediment volumes in the North Sea to estimates of the volume of rock eroded from onshore southern Norway. In particular, volumes of sediment removed below the main Paleic surface of Norway are estimated in an attempt to better constrain the timing of peneplanation, uplift and subsequent incision.

2. Geological background

Extensional tectonics in the North Atlantic region, including the North Sea, may have begun as early as the late Carboniferous (Haszeldine and Russell, 1987; Lyngsie and Thybo, 2007), although continental separation between Greenland and Norway was not initiated until the late Palaeocene (Doré et al., 1999). The onset of early Permian–Triassic rifting in the North Sea (Fig. 1) is poorly constrained but mid-Permian extension is inferred in Greenland and may have propagated as far south as the Viking and Central Graben (Glennie, 1995). Significant rifting in the North Sea is thought to have occurred in the late Jurassic–early Cretaceous. This rifting ended in the

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Table 1
The great debate—observations, implications and limitations. (Compilation based on Anell et al. (2009), Doré et al. (2002), Gabrielsen et al. (2010a, 2010b), Hay et al. (1988), Miall (1996), Overeem et al. (2001)).

Observation	Implications	Limitation
Peneplains	Uplift of base-level, i.e. area must have been base-levelled following Caledonian orogeny and then uplifted. Several levels = several uplifts.	Age hard to define—aside from being post-Caledonian (420 Ma). Several levels hard to distinguish may be single surface with varying elevation due to differential uplift, faulting etc. High elevation peneplain formation possible? Formation and preservation not well understood.
Prograding sediment wedges	Uplift has generated an increase in erosion and hence sedimentation.	Climate and sea-level fall often coincide with progradation suggesting causal relationship.
Tilt of Tertiary sediments	Late Neogene uplift caused tilt and erosion.	Ice streams and sea-level fall caused deep marginal erosion—extrapolation may explain apparent tilt. Sediments tilt naturally during subsidence.
Change in direction of sediment influx	New sources became available due to uplift, a climatic control would imply increase from all sources, so tectonic control must apply.	Localised inversion can change drainage patterns, transition to icehouse may have altered effect of erosion on different areas.
Missing overburden	Uplift has caused erosion of nearshore sediments causing missing overburden, dated to Neogene.	Ice streams and sea-level fall caused deep marginal erosion—extrapolation may explain missing overburden. Tilt was generated in response to isostatic uplift.
Passive mechanisms	Flexural rebound and isostatic adjustment probably created significant elevation. If there was sufficient rift-related elevation of Norway there is no need for tectonic uplift in the Cenozoic.	Episodic sediment input from various sources suggests tectonic origin. If there was already significant elevation, one would observe continuous sedimentation.
Basin inversion and alpine compression	Localised increase in sedimentation may reflect localised inversion generating clastic input into basins, timing of sedimentation often coincides with Alpine phases.	Difficult to ascertain impact of compression, far-field stresses may not propagate far into Alpine foreland, magnitude varies depending on modelling parameters.
Input from Norway in Oligocene	Suggests tectonic uplift of southern Norway because shift is distinct and relatively sudden. Tilted deltaic complexes offshore southwestern Norway indicate tilt.	Many studies suggest that clastic input is caused by climate change. Why did sedimentation offshore western Norway diminish so radically if there was uplift?
Braided river systems in Denmark in Miocene	Braided river systems tend to be associated with tectonism.	Other studies suggest bifurcation increases as temperature decreases.
Similarities to other passive rift margins	Strandflat (scarp retreat?) and asymmetry (steep westward, gentle eastward) and similarity to other passive margins suggests that Norway was uplifted as a rift flank in post-Jurassic time	Norway's rifting history is longer and break-up was further from margin where uplift occurred. One should expect a similar uplift of Great Britain.
Chalk in North Sea in Cretaceous	Low terrigenous input = No elevation of Norway in Cretaceous, thus uplift must be post-Cretaceous.	7–12 km of sediment offshore mid-Norway accumulated in the Cretaceous, suggesting elevation. Maybe drainage was in another direction and not into the North Sea. The Cretaceous was associated with major transgression, which probably affected sedimentation. Localised clastic input along the margins does occur.
2.5 Ma sharp increase in sedimentation	Uplift of margins generated great increase in sedimentation.	Timing coincides with glaciation in Norway. Glacial is more powerful than fluvial erosion processes which may explain increase in sedimentation. In the last 4 Ma sediment accumulation has increased globally, suggesting climatic origin.

earliest Cretaceous with a rift-jump to the Møre, Vøring and Faroe–Shetland Basins (Roberts et al., 1999), after which the North Sea thermally subsided and filled with sediment sourced from the surrounding landmasses, interrupted periodically by basin inversion (Ziegler, 1990).

During the Cenozoic more than 3 km of sediment accumulated in the North Sea with the main depocentre above the Central Graben (Michelsen et al., 1998; Sørensen et al., 1997). Early Cenozoic sedimentation was dominated by sandy, east and southeast prograding sediment sourced from Scotland and the Shetland Platform (Jordt et al., 1995; Mudge and Bujak, 1994). Since the Oligocene sediment has been increasingly sourced from Fennoscandia and also, in the Miocene, from the great river systems of northwest Europe that drained from the south (Hall and Bishop, 2002; Overeem et al., 2001).

During the early Cenozoic the climate in the North Sea area was dominantly tropical to sub-tropical, but significant climatic cooling occurred at the end of the Eocene, around the Palaeogene–Neogene transition, and during the Pliocene (Buchardt, 1978; Rasmussen et al., 2008; Zachos et al., 2001). The greenhouse–icehouse transition at the Eocene–Oligocene transition correlates with the occurrence of large ice-sheet in Antarctica (Zachos et al., 2001). Eustatic sea-level fluctuated during the Cenozoic, with substantial shoaling associated with climatic cooling. Overall sea-level is thought to have fallen ca 100–200 m since the Eocene (Haq et al., 1987; Miller et al., 1998; Vail and Hardenbol, 1979).

3. Data and methods

3.1. Sediment accumulation rates

We map seven regional Cenozoic stratigraphic units (PAL 1–3, NEO 1–4) (Fig. 2), separated by regional unconformities/sequence boundaries (Anell et al., 2010, submitted). The seven units represent distinct time-periods and are mapped across the North Sea using 36 000 km of vertical incidence 2D seismic lines (Fig. 1). Sediment accumulation rates are estimated by assuming constant deposition during each period and no post-depositional erosion. We apply ages from previous interpretations of the stratigraphic record (Köthe, 2007; Michelsen, 1995; Rasmussen et al., 2008; Stoker et al., 2005). The maps are made in Z-Map Plus (©Landmark graphics) and show two-way-time travel. We use available velocity–depth profiles for the North Sea (Storvoll et al., 2005) for calculations of volume and average accumulation rates. For each unit we calculate the rate of accumulation within the 500 m isopach/s and at the point of maximum thickness (i.e. within the thickest isopach) (Table 2). We also calculate and compare the rate of accumulation and the total accumulation of sediment in the Moray Firth and Viking Graben to that of the Central Graben.

Mass estimates are based on bulk density values estimated by averaging 35 density logs in 500 m depth intervals from the Norwegian Petroleum Directorate wells. The data is from the Norwegian sector, and we assumed that it approximates density/depth trends for the whole North Sea.