Giant submarine landslide triggered by Paleocene mantle plume activity in the North Atlantic

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ABSTRACT

The 290-km-long ‘Halibut Slide’ is the world’s largest epicontinental submarine landslide. Between 64 and 62 Ma, plume-related uplift in the North Atlantic and far-field stresses caused reactivation of major intra-plate faults. This reactivation caused instability of Cretaceous chalk slopes across the North Sea Basin, triggering the Halibut Slide. Megascours, up to 1 km wide, 150 m deep, and 70 km long, indicate slope failure from an intra-shelf high east of mainland Scotland, and subsequent flow down an ~1.1° slope. Megascours were gouged by cuboid chalk blocks, up to 1 km wide and 170 m high, some of which out-ran the main slide body by up to 10 km. The Halibut Slide has a decompressed volume of 1450 km³ and a basal slide surface extending over ~7000 km². Subsequent elastic sediment input points and dispersal pathways were controlled by the underlying Slide topography for ~10 m.y. The discovery of this major submarine landslide provides new insights into the response of sedimentary systems to regional and deeply rooted tectonic events, and the initiation of long-term sediment routing patterns.

INTRODUCTION

Submarine landslides are the largest mass movements known on Earth and are important seascape modifiers, creating some of the largest single-event deposits known (e.g., Calvès et al., 2015). Submarine landslides can generate tsunamis (e.g., Dawson et al., 1988), damage submarine infrastructure (Mulder et al., 1994), and modify post-failure sediment distribution (Ortiz-Karpf et al., 2015). Understanding the formation and behavior of large submarine landslides is therefore important for both geohazard assessment and hydrocarbon reservoir prediction.

Using an extensive basin-scale three-dimensional (3-D) seismic reflection data set, integrated with core and wireline log data, this study aimed to (1) document and characterize the submarine landslide ‘Halibut Slide’ (North Sea Basin, 56°N, 3°E), and (2) interpret slide genesis with reference to major basinal processes, principally mantle upwelling and associated tectonic adjustments.

GEOLOGICAL SETTING

The central North Sea Basin comprises a Cenozoic sag basin overlying a failed Mesozoic rift. Paleocene sedimentation was initiated due to uplift and subsequent southeast tilting of the northern United Kingdom (UK) landmass (Den Hartog Jager et al., 1993) associated with rifting and magmatic underplating in the North Atlantic at ca. 62 Ma (White and Lovell, 1997). The Moray Firth paleo-shelf is estimated to have undergone up to 390 m of uplift during the Paleocene (Nadin and Kusznir, 1996). Early Cenozoic fault reactivation within the Moray Firth has also been linked to North Atlantic tectonism (e.g., Underhill, 1991). Aeromagnetic data showing offset dike swarms across the WSW-ENE-trending fault zones that cross-cut Northern Ireland and Scotland, combined with dating of igneous centers and dike swarms in Northern Ireland, showed that these crystal-scale strike-slip faults were active in the early Paleocene between 64 and 62 Ma (Cooper et al., 2012). Paleocene sand-rich intervals within the Maureen, Lista, and Sel Formation of the central North Sea Basin have been related to episodic hinterland uplift caused by plume activity in the North Atlantic (White and Lovell, 1997; Mudge and Jones, 2004). The oldest of these intervals, the ‘Maureen Reworked Unit’ (MRU), overlies the Intra-Danian unconformity at 62.7 Ma (Mudge, 2015). The MRU is contemporaneous with some of the earliest volcanism in the North Atlantic, such as the British-Irish Paleogene Igneous Province at 63.2 ± 0.6 Ma (Wilkinson et al., 2016).

DATA AND METHODOLOGY

This study utilizes the full-offset pre-stack Kirchoff time-migrated central North Sea PGS (Oslo, Norway) MegaSurvey Plus (https://www.pgs.com/data-library/europe/nw-europe/northsea/cns/) 3-D seismic data set complemented by the post-stack time-migrated merged PGS MegaSurvey covering the Moray Firth (Fig. 1). Vertical seismic resolution within the Paleocene interval is 25–33 m (given an interval velocity of ~3–4 km s⁻¹ and a dominant frequency of ~30 Hz) with a bin spacing of 12.5 × 12.5 m in the MegaSurvey Plus. A sub-sampled 50 × 50 m line spacing was used for analyzing the MegaSurvey. Both surveys have a 4 ms sample rate and are processed to zero phase, with a downward increase in acoustic impedance represented by a trough (blue reflection). Conversions between thickness in two-way traveltime (TWT) and depth were performed using a sonic-log–derived average interval velocity of 4.3 km s⁻¹ (range between 3.1 and 5 km s⁻¹) for the Halibut Slide.

Seismic picks were tied stratigraphically to wells (Fig. 1B). Synthetic seismograms were extracted from a database of 975 wells (TGS Facies Map Browser, http://www.tgs.com/products-and-services/geological/interpretation-products-and-services/facies-map-browser/) available within the study area to give further confidence in the picks, and were combined with wireline log (primarily gamma-ray and sonic) and core data for interpretation of lithology (Fig. 1; Figs. DR1 and DR7 in the GSA Data Repository⁴). A 12 m cored section was logged from the Halibut Slide within well 22/30a-1 (Figs.DR1 and DR2).

RESULTS

Halibut Slide Observations

The Halibut Slide (HS) exhibits a maximum of ~170 m of mound relief above the Top Chalk surface (Figs. 1 and 2) and forms a continuous hard reflection, with overlying reflections onlapping the mound (Fig. 3A). Within the HS, reflections are discontinuous and dim, with some isolated bright reflections (Fig. 2). Below the HS, the Top Chalk reflection is also discontinuous and frequently shows truncation and dimmed amplitudes. The mapped slide deposit maintains a relatively consistent thickness, thinning from ~170 m to 100 m over 170 km, before abruptly pinch-out over a distance of 10 km down-dip at the intra-basinal Erskine Ridge (Figs. 1, 3A, and 3B). Megascours cut into the Top Chalk surface are up to 1 km wide, up to 150 m deep, and extend for ~80 km down-dip within a 20-km-wide scour ‘belt’ that defines the inferred lateral limits of the basal slide surface. The orientations of the most prominent

⁴GSA Data Repository item 2018169, supplemental Figures DR1–DR7, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.
megascour (Fig. 3C) indicate that the main failure event may have been sourced from the Grampian High, offshore northeastern Scotland (Fig. 1). Unfortunately, the headwall cannot be observed due to post-failure erosion of the Top Chalk surface (Fig. 3C). The HS was heavily influenced down-dip by existing seafloor topography, such as the northerly confining Halibut Horizon, which the HS has been named after. The measured length of the basal slide surface (290 km) is thus the minimum length of the slide. The majority of the slide volume extends from 90 km to 290 km down-dip on the basal slide surface, although uncertainty exists due to poorer seismic resolution within the up-dip survey.

Spectral decomposition and color blending of 10 Hz, 30 Hz, and 50 Hz seismic frequencies (Fig. 3A) show a clear bright body trending from the shelf toward the deep basin along a narrow corridor (~30 km wide). End-Danian paleobathymetric reconstructions indicate the slope of this corridor was inclined at ~1.1° (Joy, 1992). This bright corridor is terminated by a 30 × 30 km lobate body in the deep basin (Figs. 3A and 3E). Bright specks within the HS range in width and length from ~50 m to over 1 km (average of ~500 m) and are up to 170 m thick. Along the length of the HS, the spectral decomposition signature partitions a relatively continuous response from the southern part of the body to a speckled response in the north (Fig. 3A).

A similar speckled and lobate feature is evident more proximally, trending east-west (Fig. 3A), at a saddle-shaped low within the center of the Mesozoic Forties-Montrose High (FMH) (Figs. 1, 3A, and 3D). The specks have the same dimensions as those described within the main Halibut Slide body, suggesting a common origin. Lineations radiating from the FMH ‘low’ extend beyond the FMH speckled body and differentiate it from the distal HS, which is characterized by a laterally continuous terminal boundary (Figs. 3D and 3F).

The Halibut Slide is composed of chalk megascours within a mud- rich matrix, as indicated by logged core data (Fig. 1; Fig. DR1), wireline logs (Fig. 2; Figs. DR2 and DR3) and petrophysically derived carbonate and porosity distributions (Kilhams et al., 2015).

In total, the Halibut Slide has a length of at least 290 km and a minimum depositional extent of 200 km. The main slide body has an average width of ~30 km and average thickness of ~97 m, with the ~35-km-long splayed slide having an average width of ~20 km and average thickness of ~80 m. In total, this equates to a compacted volume of ~640 km³. If we assume the chalk was compacted to ~150 m (maximum scour depth) and that the majority of the slide volume is dominated by chalk (megascours), then the decompacted volume is estimated at 1450 km³, based on a chalk porosity drop from 0.6 at 150 m to 0.1 at 3000 m (Mallon and Swarbrick, 2002).

Halibut Slide Interpretation

Based on its geometry, internal seismic character, and the megascours, we interpret this feature as a large submarine landslide (herein termed a ‘slide’) deposited by variable sediment-transport mechanisms, including sliding, debris

Figure 1. A: Paleocene paleogeography of the North Atlantic and present-day extent of Cenozoic volcanism. The uplift caused by this volcanism caused Paleogene deposition in the North Sea and adjacent basins (modified from Ahmadi et al. [2005] and Mudge [2015]). The trend of the plume during the Late Paleocene is also indicated, showing the North Sea Basin at its southeast margin (modified from Hartley et al., 2011). B,C: Seismic reflections (B) and corresponding stratigraphic interval (C) (absolute ages from Mudge, 2015). D: The relationship between mantle plume activity and clastic (yellow) or remobilized chalk (gray) deposition in the early Paleocene of the North Sea. Absolute ages from Mudge (2015). The Halibut Slide (HS) is represented by Top Maureen within well 22/30a-1; white box indicates logged core position. Solid red line shows North Atlantic volcanic activity from White and Lovell (1997); dashed red line and black solid lines show earliest volcanic activity from Wilkinson et al. (2016) (no relative volcanic activity level is implied by dashed line); fault activity from Cooper et al. (2012). All dates are tied to the magnetic chronology of Gradstein et al. (2012). U/C—unconformity; RWU—reworked unit; Sst—sandstone; M—Maureen stratigraphic cycles (Mudge, 2015); E—Ekofisk stratigraphic cycles (Mudge, 2015); T—stratigraphic cycles (Mudge, 2015); WG—West Greenland; EG—East Greenland; BIPIP—British and Irish Paleogene Igneous Province; NAIP—North Atlantic Igneous Province; BF—Banff fault; CG—Central Grampian High; HBF—Highland Boundary fault; HH—Halibut Horst; JH—Jaeren High; OMF—Outer Moray Firth; SVG—South Viking Graben; UH—Utsira High; WF—Walls fault; WP—Western Platform; WSSF—West Shetland Spine fault.

Figure 2. Flattened and interpreted seismic section through the Halibut Slide (HS, location in Fig. 1A). Well 29(5/5xx) intersections indicate dog legs in seismic line. The section has been flattened to mitigate the effects of post-depositional deformation. Megascours can be identified based on seismic reflection shape and amplitude. Gamma ray signatures are typically discontinuous within the HS because of its poorly sorted composition (Gamma values decrease right-to-left).
flows, and probably associated turbidity currents. The allochthonous chalk within the Halibut Slide is suggested to have been either derived from the shelfal headwall or incorporated as the slide gouged and eroded the sea bed down-dip, as evidenced by the up to 150 m of chalk removal within the megascours (Fig. 3C). It is proposed that the radial sub-body of the Halibut Slide described at the FMH was formed by flow splitting as part of the Halibut Slide escaped the lateral confinement of the FMH through its saddle-like depression (Fig. 3A). The splayed slide experienced acceleration into the depression and confinement at its margins, before flow expansion and deceleration as it moved past the FMH confines and into the low of the eastern depocenter (Figs. 3A and 3D). The radiating lineations that spread laterally from the axis of the splayed slide are interpreted as erosional scours caused by megascours gouging the substrate (Fig. 3D; Fig. DR3). Out-running megascours seen at the ends of megascours support this interpretation (Figs. 3D and 3F). The diverging pattern of the scours reflects flow deceleration as the splayed slide became unconfined and began to disaggregate (Figs. 3A and 3D).

DISCUSSION AND CONCLUSION
The Halibut Slide is the largest epicontinental submarine landslide known on Earth, and its emplacement is one of the most significant stratigraphic events within the geological history of the North Sea Basin. Paleocene plume-related uplift affecting the Scottish mainland and the Moray Firth (Nadin and Kusznir, 1996) caused tectonic rejuvenation and southeastward tilting of the western basin margin at ca. 63 Ma. Between 64 and 62 Ma, far-field stresses due to a combination of plume-related uplift and the Alpine orogeny caused reactivation and accumulation of up to 1 km of slip along major crustal-slope west-northeast–trending strike-slip faults that crosscut Ireland and Scotland and entered the North Sea around the flanks of the Moray Firth (Fig. 1) (cf. Underhill, 1991; Cooper et al. 2012). The Halibut Slide headwall region is located adjacent to these faults, lying ~50 km east of the Great Glen Fault Zone and 100 km north of the Highland Boundary Fault Zone (Figs. 1, 3, and 4). Multiple episodes of fault displacement would be required to accumulate 1 km of slip between 64 Ma to 62 Ma (cf. Wells and Coppersmith 1994; Cooper et al. 2012). It is therefore suggested that the
combination of far-field stresses and local reactivation of major tectonic lineaments preceded the North Sea Basin margin for catastrophic slope failure, resulting in the emplacement of the Halibut Slide. Other potential mechanisms contributing to slump-related slide initiation at this time include increased pore pressures associated with elevated heat flow, the hydrostatic effects of elevating the chalk aquifer above sea level, and loading of the slope by prograding clastic systems (Fig. 4). These mechanisms are believed to be less important due to the distal position of the basin compared with the main thermal anomaly, the relatively minor uplift accumulated during the earliest plume impinement, and the time lag between initial uplift and clastic progradation. The Halibut Slide represents the largest single depositional event within this period of major tectonic upheaval in the North Sea Basin, heralding the onset of subsequent Paleogene siliciclastic sediment supply. Sediment routing and deposition of the Paleogene deep-marine siliciclastic systems was controlled by the underlying Halibut Slide topography for ~10 m.y. (Fig. 4; Fig. DR6). The discovery of the Halibut Slide demonstrates the close relationship between major mantle and lithospheric processes and the sedimentary history of the North Sea Basin.

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