The timing and significance of gully incision on the eastern flank of the Faroe–Shetland Channel and its impact on seafloor infrastructure.

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Abstract

The Faroe–Shetland Channel is an area of active offshore development and the safety of the sea-floor infrastructure is paramount. This study has concentrated on a system of down-slope linear gullies and associated debris fans located to the west of Shetland in water depths of between 465m and 995m. Three-dimensional seismic, two-dimensional seismic and multibeam echosounder data have been combined to map the sea-bed morphology and shallow sub-surface geology associated with these features. The localised debris fans and gullies are interpreted as the products of high energy mass-flow fed by an ancient ice-stream constrained to this part of the West Shetland Shelf. During decay of this ice-stream, melt-water plumes of sediment released from the retreating ice front have formed a thin (<5m) laminated sediment drape overlying the debris fans observed from seismic data. At present locally strong oceanic currents rework and redistribute sea-bed sediments into sediment drifts called contourites that cover much of the sea bed of the Faroe–Shetland Channel. These along-slope deposits have been shown to infill erosional features located further northeast along the continental slope, however, these deposits thin to the southwest reflecting the increasing strength of present day oceanic currents impeding deposition. This study shows that slope angles within the down-slope gullies exceed 20° and cut down into earlier contouritic

sediments. The high slope angles recorded on the multibeam echosounder data combined with video data confirm the presence of near-vertical sediment cliffs within the gullies. This is of significance to industry as there are currently producing hydrocarbon fields and continued exploration in and around these sea-bed features.

Introduction

The Faroe–Shetland Channel is located to the north and west of the Shetland Islands and separates the Faroe and West Shetland shelves (Fig. 1). The channel is around 400km in length from the Norwegian Basin to the Wyville–Thomson Ridge, is around 250km at its widest (shelf break to shelf break), and 1600m deep, narrowing to around 120km in width at the southwestern end where the sea floor is around 1000m in depth. The bathymetry of the region strongly influences the hydrodynamic regime. Oceanic currents are the predominant influence on the continental slope and channel floor (Stoker *et al.* 1993) with Turrell *et al.* (1999) describing five major water masses within the Faroe–Shetland Channel, some of which are known to create persistent, strong bottom currents capable of eroding and re-distributing sediments with grain sizes up to and including gravel (Masson *et al.* 2004). It has been suggested that the present day hydrodynamic regime of contrasting directions for the upper and lower water masses has been in place for around the last 14,000 years although the strengths may have changed (Miller and Tucholke 1983; Rasmussen *et al.* 1996; 2002). The channel's role in providing a conduit for exchanging Atlantic Ocean and Norwegian Sea waters may have influenced sediment accumulation on the shelf margins since Late Eocene and Oligocene times (Miller and Tucholke 1983; Rasmussen *et al.* 1996; 2002).

The British Geological Survey began regional geological mapping of the area over 30 years ago with Stoker *et al.* (1993) presenting a summary of the regional geological setting. More recently the British Geological Survey and Jarðfeingi (the Faroese Earth and Energy Directorate) have published a summary of the regional geology which includes the Faroese sector of the Faroe–Shetland Channel (Ritchie *et al.* 2011a) which was not included in the previous Stoker *et al.* (1993) publication.

In this paper, we present a new interpretation of the sea-bed sediments and sea floor geomorphology of a system of down-slope linear gullies and their associated debris fans located in the Faroe–Shetland Channel (Fig. 1). By combining these new interpretations with legacy data and previous studies of the shallow sedimentary structure the questions of the formation and timing of these linear gullies, which are only found on this part of the continental slope on both the Faroese and UK sides of the Faroe–Shetland Channel, can be addressed.

Geological and Oceanographic Setting

The Faroe–Shetland Channel is a Cretaceous to Cenozoic age basin trending northeast-southwest along the northern European margin (Ritchie *et al.* 2011b). Extension, that started during the Early Cretaceous (Valanginian) and was associated with the Atlantic rift system, had largely ceased by the end of the Early Cretaceous (Albian) when thermal subsidence became prevalent (Ritchie *et al.* 2011b). That does not imply that the region became tectonically inactive, as several subsequent periods of extension occurred throughout the Cretaceous during which thick sequences of deep marine clastic sediments were deposited (Ritchie *et al.* 2011b). During the Cenozoic, post-rift subsidence dominated although intermittent episodes of extension, accelerated subsidence, compression and inversion punctuated this period (Ritchie *et al.* 2011b and references therein). The Wyville–Thomson Ridge, which divides the Faroe–Shetland Channel from the Rockall Trough to the south, is interpreted to be a mid-Cenozoic inversion structure (Ritchie *et al.* 2008). Emplacement of igneous rocks associated with the North Atlantic Igneous Province (Early to Mid Cenozoic) has essentially controlled the present bathymetric form of the Faroe–Shetland Channel (Ritchie *et al*. 2011b) with growth of the Wyville–Thomson Ridge anticline and the complementary Faroe Bank Channel syncline during Late Cenozoic (Mid Miocene) times re-establishing a deep-oceanic link between the Rockall Trough and the Faroe–Shetland Channel (Stoker *et al.* 2005; Stoker and Varming 2011). Of great significance is Late Neogene uplift and tilting of the West Shetland continental margin which was accompanied by offshore subsidence and development of prograding sedimentary wedges (Stoker 2002) that have built out the shelf edge by up to 40km (Stoker and Varming 2011). These events had a major effect on the present day oceanographic regime of the Faroe–Shetland Channel.

The West Shetland region has been subjected to repeated extensive glaciations since about 0.44Ma with the late Devensian (marine oxygen isotope stage 2, 25-18 kyr BP) expansion of the British Ice Sheet the most recent to reach the edge of the West Shetland Shelf (Stoker and Varming 2011). The Foula and Rona wedges were glacially fed depocentres linked to the drainage of the northwest sector of the British Ice Sheet (Stoker and Holmes 1991; Davison 2005), with recent research suggesting that the Rona and Foula wedges represent trough mouth fans deposited at the shelf edge during glacial maximum time from a combined Fennoscandian and British ice sheet (Graham *et al.* 2007; Bradwell *et al.* 2008).

The conical plan shape of the Faroe–Shetland Channel and the position of the Wyville–Thomson Ridge at its southwestern end (Fig. 1) have a profound effect on the oceanic currents. In summary, the upper warm North Atlantic Water flows northeast from the Rockall Trough into the Faroe–Shetland Channel over the Wyville–Thomson Ridge and on into the Norwegian Sea where it cools and sinks. This layer of colder water then flows southwest back into the Faroe–Shetland Channel (Masson *et al.* 2010). This layer of colder water comprises the Arctic Intermediate Water, Norwegian Sea Arctic Intermediate Water and the Faroe–Shetland Channel Bottom Water. This cold deep water layer is funnelled southwest through the Faroe–Shetland Channel where it is then deflected north westwards through the Faroe Bank Channel by the Wyville–Thomson Ridge. The Faroe Bank Channel is a narrow conduit around 40km in width between the Wyville–Thomson Ridge and the Munkagrunnur Ridge (Fig. 1) narrowing to around 20km in width between the Faroe Bank and the Faroe Shelf (at the 500m bathymetric contour). There, the flow of the oceanic currents are constricted at the south-western end of the Faroe–Shetland Channel where flow velocities have been recorded to exceed 1.0 $m \cdot s^{-1}$ (Hansen and Østerhus 2000) however, typical flow velocities within the channel are around 0.1 to 0.2 $m \cdot s^{-1}$ with maximum velocities of around 0.6 $m \cdot s^{-1}$ (Saunders 1990; Masson 2001).

The sea-bed sediments of the Faroe–Shetland Channel largely comprise a thin veneer of sand- or gravel-rich sediments on the shelves becoming finer-grained on the continental slope and channel floor. During the Holocene, much of the area has been starved of terrestrial sediment input with material being locally derived by reworking of the underlying Pleistocene and older deposits (Stevenson *et al.* 2011). Post-glacial sedimentation is suggested to be largely controlled by oceanic currents (Masson *et al.* 2004) with sedimentation rates typically <1cm per thousand years (Masson 2001).

On the current swept outer shelf, sand-rich sediments commonly form mobile patches and streaks of negligible thickness overlying, or partially covering, coarser-grained lag and Plio-Pleistocene deposits (Stevenson *et al*. 2011). On the West Shetland Slope, the sea-bed sediments commonly comprise a loose veneer of sand-rich sediments up to 0.1m in thickness within the study area although Masson *et al*. (2004) describe a surficial sand and gravel layer of Holocene age 0.05 to 0.2m in thickness from the mid-slope area near to the Wyville–Thomson Ridge. Those sediments are considered to be the result of reworking and winnowing of underlying Pleistocene deposits by Holocene bottom-currents (Stevenson *et al*. 2011). In water depths >500m, the sea-bed sediments are commonly indistinguishable from the underlying older sediments (Stevenson *et al*. 2011) although loose sediments of between 0.04 and 0.1m in thickness have been recovered from the top of British Geological Survey short sediment cores.

The outer West Shetland Shelf is characterised by iceberg ploughmarks which form through the bulldozing of the sea bed by the keels of icebergs and the base of grounded ice sheets. The ploughmarks are typically modified by current winnowing to have gravel-rich ridges (berms) and finer, sand-rich sediments infilling the hollows. The ploughmarks average 1-3m in depth and 20-80m in width although they can be up to 10m in depth, and up to 300m in some cases (Long *et al.* 2011). The cross-cutting network of furrows, which are up to 5.5km in length, include pits where icebergs may have grounded and rested. Although the iceberg ploughmarks may not significantly modify the shear strength of the underlying glacial sediments, it may instead affect their permeability (Long *et al.* 2011). Iceberg ploughmarks typically have boulders and cobbles exposed on their berms with a fine-grained sediment infill of their troughs derived from winnowing of the berms. Iceberg ploughmarks extend down the continental slope to around 540m water depth. The marks on the slope tend to increase in length and become more parallel to the bathymetric contours with increasing water depth.

On the continental slope contourite deposits are typically found. These fine-grained deposits are thickest to the northeast and thin to the southwest where the increasing strength of oceanic currents limits their deposition. Contouritic sedimentation is strongest during deglacial and interglacial periods and although the speed of sediment movement is not known, there is potential for burial and/or scour of sea-bed installations (Long *et al*. 2011). Contourite deposits within the Faroe–Shetland Channel have been observed to form drifts of up to 200 ms in thickness (A. Leslie (British Geological Survey) pers comm.) but it should be noted that the thickness varies significantly as the drift geometries are complex and the contourite deposits themselves tend to merge with sediments of the slope apron below.

A number of down-slope gullies are incised into sediments of the MacAulay and Morrison sequences on the West Shetland Slope between 60°30′ and 61°N and 3° and 4°W extending down from 465m water depth to the channel floor between 940 and 995m water depth where they connect with a number of debris fans (Fig. 2a and 2b). The Morrison sequence is characterised by prodeltaic and mass-flow deposits. Laminated sediments of the MacAulay sequence can be locally differentiated on the slope and outer shelf. The linear gullies were first observed on a Hydrographic Office survey conducted in the 1960s, using echosounder profiles approximately 400m apart, and subsequently on various sidescan sonar records (Kenyon 1987; Masson 1997; 2001) and sea-bed picks of 3D data volumes (Bulat and Long 2001; Long *et al.* 2004). The various sea-bed images show that the gullies are about 25km in length, a few hundred metres in width, are steep-sided and attain depths varying between 5 and 30m. Some gullies appear to be less pronounced than others, two are tributaries of neighbouring down-slope gullies with short right angle bends into the main gully despite having flowed parallel down slope for more than 10km (Fig. 2c) suggesting partial infilling and implying that these are older and associated with older basin floor fans. These basin floor fans, or debris fans, and associated down-slope gullies are not observed elsewhere in the Faroe–Shetland Channel and are localised to this part of the West Shetland margin. The debris fans are located at the base of slope where there is a reduction in slope angle and form part of the Foula Wedge which represents a depocentre associated with the terminus of an ice stream located between the Scottish mainland and Shetland during the last glacial maximum (marine oxygen isotope stage 2) (Stoker *et al.* 1993; Davison 2005). The debris fans appear to be developed from selected gullies with the formation of levees on the top of the fan although other gullies appear to be deflected by the growing fan (Fig. 2b). The close association of the gullies and debris fans points to a common origin, which has been discussed above. Graham (1990) suggested that the gullies were either the result of an unusual form of slope failure, or erosional features caused by the down-slope movement of semi-liquid sediments.

Data and Methods

The Faroe–Shetland Channel has been an area of significant hydrocarbon exploration with the result that much of the channel floor and adjacent slopes have near continuous coverage of 3D seismic data (Fig. 1). The Faroe–Shetland Channel has also been the focus of surveys funded by then Department of Trade and Industry (now the Department of Environment and Climate Change) and the Department of Environment, Food and Rural Affairs as part of their Strategic Environmental Assessment (SEA) (Fig. 1) acquiring data in 2002 and 2006. The aim of the SEA surveys were twofold: 1) to acquire multibeam echosounder data in order to better classify and understand geomorphological features present, and to inform site selection of 2) a comprehensive suite of camera and video 'ground-truthing' sites to characterise the ecology and sea-bed sediments of the study areas. The British Geological Survey has been undertaking systematic survey of much of the UK continental shelf and adjacent deep water areas since 1966 (Fannin 1989). Data were obtained by geophysical surveys calibrated by selective sampling.

The primary use of 3D seismic surveys are for imaging deep sedimentary structures, but they can be used to image the sea-bed reflection (Bulat 2003; Bulat and Long 2001; Bulat and Long 2005; Long *et al*. 2004). This technique is particularly useful in water depths >200m. The 3D seismic generated sea-bed image was first created in 1997 for a joint hydrocarbon industry–British Geological Survey consortium called the Western Frontiers Association (WFA) whose remit is to understand the Health and Safety issues in working offshore north and west of Shetland. A full description of the methodology employed to combine these data and artefacts found is presented in Bulat and Long (2001; 2005) and Long *et al*. (2004). In summary these datasets were combined into a mosaic grid with 100m node spacing and depth converted assuming a water velocity of 1500 $m \cdot s^{-1}$. The resultant mosaic was merged with a regional bathymetric grid generated from the 100m contour dataset of the General Bathymetric Chart of the Oceans (GEBCO www.gebco.net). Much of the grid manipulation and final visualisation was performed using ERMapper, an industry standard tool.

In 2006 the *M/V Franklin* carried out targeted SEA surveys on the eastern flank of the Faroe–Shetland Channel utilising a Kongsberg Simrad EM1002 Multibeam Echosounder system with an operating frequency of 95 kHz capable of operating in water depths down to around 1000m (Stewart and Davies 2007). The surveys were typically carried out at a speed of between 8-12 knots, and sound velocity profiles were collected during data acquisition. The multibeam ecosounder data were processed by onboard hydrographic surveyors and the data presented at the best resolution of 25m cell size. Multibeam echosounder data comprise two types of data. The first are high resolution bathymetric data which, once processed, can be modelled to reveal the topography of the sea bed (Fig. 3). The second are backscatter intensity data that are acquired simultaneously with the bathymetric data and give an indication of the roughness and type of sea-bed sediment (McRea *et al*. 1999). Detailed bathymetric data are required to produce Digital Terrain Models from which derived terrain layers such as slope (Fig. 4), aspect, rugosity and Bathymetric Positioning Index (BPI) can be derived and used to characterise the sea bed (Wilson *et al*. 2007).

A Seatronics drop-frame camera system was used during this survey to 'ground-truth' the multibeam echosounder data (Stewart and Davies 2007). The Seatronics system was fitted with a DTS 6000 digital video telemetry system and a 5 megapixel Kongsberg Simrad digital stills camera mounted opposite each other (with lights fitted either side) at oblique angles to the sea bed for optimal sea-bed coverage. The frame was also fitted with sensors to record depth, altitude and temperature, and an ultra-short baseline beacon to collect accurate positional data for the frame. No compass was fitted to the frame; therefore the orientation of the field of view, e.g. right way up or dip/strike of sedimentary layers, could not be determined from the image data. The field of view was calibrated by attaching a gridded quadrat of known dimensions to the camera frame which could be overlain on the still photographs to allow quantitative analysis of the sea-bed sediments and fauna.

Single channel seismic reflection sparker profiles utilised in this study were collected by the British Geological Survey during its regional mapping programme in the 1970s and the 1980s. The core data included in this paper were collected by the British Geological Survey and include continuously cored shallow borehole information, short (<6m) vibrocore samples and short (<3m) sediment gravity cores. Additionally, reports from the British Geological Survey commercial archive were consulted. Information gleaned from those reports has informed the results and conclusions presented in this study but direct reference and data derived from them have not been presented here.

A regional interpretation of the sea-bed sediments at a scale of 1:250,000 was presented by Graham (1990) based on sieve analysis of samples obtained from Shipek grabs and sub-samples from the tops of sediment gravity cores and vibrocores. Gravel percentage and sand to mud ratio maps were prepared and contoured at intervals corresponding to the divisions indicated on the modified Folk diagram (Graham 1990). This interpretation has been updated for the area surveyed in 2006 (Fig. 5; Stewart 2011). For each digital stills image acquired, a sea-bed sediment classification was assigned based on the modified Folk diagram utilised by Graham (1990). These point classifications were used in conjunction with the existing BGS samples, discussed above, to ground-truth the multibeam echosounder data allowing a complete sea-bed substrate interpretation to be created in an ArcGIS environment (Fig. 5). It should be noted that backscatter data quality was not adequate to allow automated sea-bed sediment, or facies, classification. A geomorphological interpretation of the survey area was also completed using standard geological terms and definitions (Fig. 6; Stewart 2011).

A total of 37 analysed sea-bed samples lie within the 'West Shetland West' survey area, with an additional 10 analysed sea-bed samples within the area covered by the base of slope debris fans (Fig. 5). Nineteen drop frame camera tows were acquired in the 'West Shetland West' survey area totalling 1437 sea-bed photographs which were all analysed using the calibration grid as described above and allocated a sea-bed sediment classification. Of the sea-bed photographs 129 images had to be discarded either due to camera malfunction, blurring which hindered accurate interpretation, or the camera being too high off the sea bed to allow accurate interpretation. A summary of the results from the analysis is presented in Table 1. A greater variety of sea-bed sediment classes were identified within the photographic ground truthing data, for example the presence of clean gravels, than was identified through sea-bed sampling reflecting metre-scale variability in the composition of the sea bed. This could not be reflected in the overall sea-bed sediment interpretation (Fig. 5) as the metre-scale variations could not be mapped onto the coarser-scale multibeam echosounder and 3D seismic sea-bed image where the minimum mapping scale is 1:50,000.

Results

The area of sea bed shallower than 540m water depth is dominated by the presence of iceberg ploughmarks (Fig. 3). Photographic ground-truthing and sea-bed samples confirm that this area hosts gravelly sand and sandy gravel (not found elsewhere in the study area) as well as muddy sandy gravel and gravelly mud. Muddy sandy gravel and gravelly sand is found exclusively within individual iceberg ploughmarks in this zone. The floors of the furrows comprise the mud- and sand-rich sediments which have been winnowed from the upstanding berms and redeposited by Holocene bottom currents within the relatively sheltered furrows. The berms comprised the coarser-grained sediments observed. As discussed above, metre-scale variability in the sediment composition was observed within ground-truthing data as individual iceberg ploughmarks were crossed but could not be fully represented in the overall sea-bed sediment interpretation (Fig. 5).

Muddy sand is only found within the down-slope gullies, down to a maximum water depth of around 740m. Below this water depth, a transition to muddy sandy gravel occurs within the gullies. This boundary is crossed by camera tow WSC 3 (Fig. 5 and 7a) located within one of the down-slope gullies. The majority of the continental slope comprises gravelly muddy sand which grades into muddy sandy gravel between 855m and 925m water depth. This transition from a sand-rich to a gravel-rich sea-bed sediment type is coincident with the zone of thickest contourite deposits and higher bottom-current activity. The increased action of bottom-currents in this area is actively winnowing out and redistributing the finer-grained sediments leaving a coarser-grained lag deposit behind.

A very mixed sediment class is encountered coincident with the base of slope debris fans. A general sediment class of muddy gravel has been assigned to the area coincident with the debris fans, although ground-truthing reveals a mixture of muddy gravel, gravelly muddy sand, slightly gravelly muddy sand, slightly gravelly sandy mud, gravelly mud, mud, sandy mud and muddy sandy gravel reflecting the complex mixture of sediments transported from the upper continental slope by the down-slope gullies (Table 1). Consolidated sediments cropping out at sea bed were only encountered within one camera tow located within one down-slope gully where slope angles exceed 20° (Fig. 7b). The sea-bed photographs show evidence that the consolidated sediments are bedded, with an apparent bed thickness of between 10 and 20cm, with gravel and pebble sized lithic fragments of up to 6cm in diameter sitting on top of the bedded sediments. It should be noted that bed thickness is hard to reconcile as the photographs are taken at an angle oblique to the sea bed which itself is of high slope angle in this instance (in excess of 20°). As this was the only camera tow both to transect completely across a gully and encounter slope angles of this magnitude, it has been interpreted that wherever slope angles exceed 20° within the gully walls, it is likely that consolidated sediments will be exposed. Only 6 of the down-slope gullies within the study area were revealed to have slope angles in excess of 20° and therefore have been interpreted to have consolidated sediments cropping out at sea bed within their walls (Fig. 4 and 5).

Short sediment cores acquired in this area of the West Shetland Slope largely comprised a loose veneer of sediments at sea bed generally <0.1m in thickness overlying clay-rich deposits with common sand or silt laminae and lenses. Pebbles and gravels were common and were observed in a number of cores to form discreet horizons often coincident with sand-rich layers. The maximum length of sediment core acquired from this section of the slope was 2.36m with measured shear strengths recorded to increase down core. Values of up to 15.6 kiloPascals (kPa) were recorded at a depth of 2.36m below sea bed. These sediments are assigned to the Morrison (unit 2) sequence although the late to post-glacial MacAulay sequence is locally differentiated on the slope and outer shelf. Borehole 85/01 proved a 10.5m thick section of debris flow diamictons from the Foula Wedge that can be attributed to the Morrison sequence, overlain by 3.5m of glaciomarine and marine mud attributed to the MacAulay sequence (Stoker and Varming 2011).

Areas of gravel at sea bed were found within 7 of the 19 camera tows. These included a number of boulders and cobbles which appear to stand proud, or sit on top of, the sea floor and may be drop-stones deposited by icebergs calving from the ice front. Two of the camera tows which sampled gravel were located within the down-slope gullies in water depths greater than 790m. In those locations the gravel was covered by a veneer (estimated to be generally <1cm in thickness) of muddy, sandy sediment. The remaining 5 camera tows which sampled gravel are located in water depths shallower than 630m and revealed much cleaner gravels devoid of the fine-grained sediment veneer evident further down-slope. These gravels have formed a lag deposit where the finer-grained sediment fraction have been winnowed by strong bottom-current activity. Further down-slope the gravels have been draped by fine-grained material deposited by along-slope bottom currents.

The geomorphological interpretation is composed of 5 classes: iceberg ploughmarks, relatively featureless sea bed, contourites, channels/gullies and debris fans (Fig. 6). As discussed above, the area of iceberg ploughmarks are dominated by a complex mix of sand- and gravel-rich sediments. The longest iceberg ploughmark imaged by the multibeam echosounder data is oriented northeast-southwest, is more than 10km in length, up to 450m in width and up to 10m in depth (Fig. 3, black arrow). The majority of iceberg ploughmarks imaged in the study area however are only up to around 4km in length, up to 250m in width and vary between 1m and 4m in depth. Long *et al*. (2011) suggest that iceberg ploughmarks evident at the sea bed were probably formed during the last deglaciation which was underway by about 15 200 ^{14}C years BP (Boulton *et al*. 2002). Analysis of shell fragments recovered from British Geological Survey short sediment cores within the iceberg ploughmark zone suggest that the observed assemblages are post-glacial in composition confirming that the ploughmarks observed at the sea bed post-date the last glacial maximum.

Below the iceberg ploughmark zone, the continental slope forms an area of relatively featureless sea bed (Fig. 6). Slope angles on the continental slope are generally <1° down to around 690m water depth where the seabed becomes hummocky reflecting the presence of sheet-like contourite deposits (Fig. 3 and 4). The along-slope contourite deposits are easily distinguishable in the derived slope map (Fig. 4) where slope angles are locally up to 5° and form low angle, fine grained sediment waves oriented parallel to the continental slope. Sea-bed sediments on the continental slope have been classified as muddy sandy gravel and gravelly muddy sand. The coarser fraction of these sediment classes are derived locally from the underlying Morrison and MacAulay sequences where the coarser-grained fractions have been winnowed out by oceanic currents. The same process has released the finer fraction, the mud and sand, for transport by along-slope currents and subsequent reworking into along-slope contourite deposits.

Twenty individual down-slope gullies and tributaries were imaged by the multibeam echosounder data (Fig. 2a, 2c and 3). The shallowest of these has its head at 465m water depth where it is around 2m in depth and 880m in width. At its termination at 510m water depth it has narrowed to around 670m in width and is around 2.5m in depth. The longest down-slope gully is first discernible at 520m water depth where it is 815m wide and around 4m deep before it merges with another down-slope gully via an abrupt, almost 90° turn at 635m water depth (Fig. 2c). At this depth the combined gully has narrowed to around 560m in width and deepened to around 7.5m. Further down slope the gully continues to narrow and deepen until around 730m water depth where the gully narrows from

310m to 280m in width and deepens considerably from 12m to 30m. This is coincident with an increase in slope angle within the gully walls from 5-10° to >15° reflected in the sea-bed sediments interpretation as the cropping out of consolidated sediments at sea bed and an increase in coarser sea-bed sediments observed on the floor of the gully (Fig. 7b). At the base of this gully, where it meets the base of slope debris fan at around 940m water depth, the gully has widened to around 530m and has shallowed to around 12m in depth (Fig. 8). This gully reaches a maximum depth of 40m between 780 and 820m water depth.

A number of the down-slope gullies do not exceed 5-10m in gully depth below the surrounding sea bed from their start on the upper slope to their termination at the base of slope (Fig. 8). These are characterised by subtle edges on the bathymetric data and the change in backscatter intensity reveals partial infill of these gullies by sandy, muddy sediments probably deposited by along-slope contourite currents during previous deglacial and interglacial periods. These gullies either terminate mid- to lower- slope or are associated with base of slope debris fans which are overlapped by subsequent fans, implying they are older than those gullies that deepen to over 20m below around 700m water depth. Without better chronological control, the order of fan deposition cannot be accurately constrained, however, the sea-bed images allow a relative order of deposition to be determined.

Seven of the gullies have a number of knickpoints identified in their down-slope profiles (Fig. 9). The observed knickpoints are located in water depths of between 730 and 920m and are coincident with a marked increase in gully depth compared to the surrounding sea bed (Fig. 8). It is interpreted here that the knickpoints are not related to a change in base level or sediment supply for example, as observed on other networks of gullies and canyons (Mitchell 2006), but rather with depth varying substrate resistance to erosion. Contourite deposits are thickest between approximately 800 and 1000m water depth (Long *et al*. 2011) and are deemed to be more susceptible to erosion by sediment-laden turbidite flows due to their fine-grained, mobile composition versus the comparatively erosion resistant debris flow diamictons, and glaciomarine and marine muds located elsewhere on the continental slope.

Ten of the down-slope gullies imaged meet with a series of overlapping, base of slope debris fans (Fig. 2 and 6). Of these 10 gullies, 3 feed debris fans which appear to be the most recent and sit on top of the older fans (Fig. 2b). Stoker and Varming (2011) attribute the basin floor fans to the Morrison (unit 2) sequence which was deposited after the onset of extensive shelf-wide glaciation at around 0.44 Ma. The debris fans are up to 10km across and have a chaotic surface character and composition as demonstrated by the variety of sea-bed sediment classes sampled (Table 1). The westernmost debris fan appears to be partially infilling an erosional hollow on the channel floor (Fig. 2a). In several cases the crest of the debris fan is cut by a channel as a continuation of the down-slope gully (Fig. 2b arrowed) giving the appearance of a levée-style construction of the fan. Shallow-seismic data show that the debris fans are covered by a thin layer of laminated sediment (Fig. 10) which is thin enough to reflect the topography of the underlying debris fan deposits characterised by acoustically structureless sediments in the seismic section. Stoker and Varming (2011) report that the laminated sediments can be attributed to the post-glacial MacAulay sequence though it is unclear whether these represent a subsequent drape or contemporary overbank deposits. The MacAulay sequence is reported to be generally less than 5m in thickness and pinches out on the upper slope at about 300m water depth (Stoker *et al*. 1993).

Shallow seismic data from the upper slope supports the interpretation that there is an order of down-slope gully activity (Fig. 11) and a stratigraphy to the development of the base of slope debris fans. From left (SW) to right (NE) on the seismic section, the first and fourth gullies crossed are more pronounced and are associated with two of the most recently deposited base of slope debris fans. The second gully crossed on the seismic section is not as pronounced and is associated with a debris fan which has been overlapped by an adjacent fan. The fifth gully crossed is again less pronounced in the seismic section and is also associated with a debris fan that has been overlapped. The third gully terminates mid-slope and attains a maximum depth below sea bed of <3m. The infilled gully (Fig. 11) also terminates mid-slope and only attains a maximum depth of 1.2m therefore has no visible expression on the seismic section. This may suggest that the shallower gullies are older and their shallowness implies sediment infill. There is also evidence from the seismic section to suggest the presence of buried gullies around 100 ms sub-sea bed that may represent gully incision related to a glaciation pre-dating the late Devensian.

Discussion

Down-slope gullies have been noted on other glaciated margins such as the Scotian slope offshore Canada (Piper *et al*. 1985), the Ross Sea in Antarctica (O'Cofaigh *et al*. 2003) and the north-western Barents Sea continental margin (Pedrosa *et al*. 2011). These gullies are inferred as being eroded by turbidity currents comprising cold, dense, sediment-rich meltwater released from an ice front located at or near the shelf break.

The generally steep Antarctic margin comprises an upper slope that is frequently incised by gullies and channels caused by erosion by turbidity currents generated by sediment-laden meltwater (Noormets *et al.* 2009; O'Cofaigh *et al*. 2003). These gullies differ from those observed on the margin of the Faroe–Shetland Channel in that the gullies of the Antarctic margin often commence at the shelf break, commonly incised shelf wards, indicating rapid initiation of turbidity currents rather than progressive down slope evolution from debris flows (O'Cofaigh *et al*. 2003). The gullies observed in the Faroe–Shetland Channel are likely to be the product of sediment remobilisation of the debris flows which form the Foula Wedge as the gullies are not observed to be incised back into the shelf break but are instead initiated down slope of the Foula Wedge.

In the Faroe–Shetland Channel study area, the upper-most reaches of the down-slope gullies extend into the area of the Foula Wedge and appear to cut into mid-slope debris-flow deposits of the Foula Wedge. Upper slope gullies documented as cutting through debris flow deposits from the Belgica trough mouth fan have been suggested by Noormets *et al.* (2009) as being incised after full-glacial deposition on the continental slope.

The continental margins of the polar North Atlantic are commonly characterised by lower continental slope angles, commonly <1° (O'Cofaigh *et al*. 2003; Pedrosa *et al*. 2011) although values of 2.5° are reported from the Scotian Slope (Piper *et al.* 1985), compared with the comparatively steep Antarctic margin where slope angles of 10-12° are reported from offshore Marguerite Bay (O'Cofaigh *et al*. 2003; Pedrosa *et al*. 2011). The general slope angle of the continental margin covered by the study area is <2°. O'Cofaigh *et al.* (2003) reports that lower slope angles facilitate down-slope sediment mobilisation dominated by debris flow deposition and suspension settling from meltwater plumes and not rapid reworking of material into turbidity currents. In areas of steeper slope angles the turbidity currents cause erosion of channels and/or gullies on the upper slope and sediment transport into the deep ocean effectively bypassing sedimentation on the upper slope resulting in a relatively sediment starved margin resulting in smaller trough mouth fan development (O'Cofaigh *et al*. 2003). Larger trough mouth fans are developed in areas of low continental margin slope angles where incremental accumulation via debris flows, settling of sediment from meltwater plumes and contourite deposition can occur as reported from the North Sea and Bear Island trough mouth fans in the North Atlantic (O'Cofaigh *et al*. 2003) and the north-western Barents Sea continental margin (Pedrosa *et al*. 2011).

Documented gullies are observed to be relatively short in length in the Ross Sea (6-7km); <10km in length offshore the Belgica Trough, the Pine Island Trough and Marguerite Bay (Noormets *et al.* 2009; O'Cofaigh *et al*. 2003; Pedrosa *et al*. 2011); and about 5km in length on the Scotian Slope (Piper *et al.* 1985) compared with lengths of up to 24km observed in the Faroe–Shetland Channel. These upper slope gullies of the Antarctic margin frequently coalesce into larger channels further down slope (Noormets *et al.* 2009; O'Cofaigh *et al*. 2003). Piper *et al.* (1985) report that gullies identified on the Scotian Slope in the vicinity of Verrill Canyon occur only between 400m and 800m water depth and terminate in an area of rotational slumping associated with the head of a canyon system.

Upper slope gullies of comparable length to those described from the Faroe–Shetland Channel have been reported from the north-western Barents Sea (Pedrosa *et al*. 2011) although the gullies identified in the north-western Barents Sea tend to branch more than those observed as part of this study. Pedrosa *et al.* (2011) report that upper slope gullies identified down slope of the Kveithola and Storfjorden trough-mouth fans are formed by density flows generated at the continental shelf edge. The flow energy decreases down slope, generally within 20km from source, after which the flows lose the ability to erode the diamict aprons of the continental slope (Pedrosa *et al.* 2011).

Pedrosa *et al.* (2011) reports that the upper slope gullies merge with the continental slope morphology and disappear by 1000-1200m water depth.

This study has shown that although a lack of chronological data from the base of slope debris fans means that the exact timing of incision of the linear gullies and deposition of the debris fans cannot be accurately constrained, the relative order of incision inferred from the comparison of the amount of sediment infill, depth of incision and the slope angle of the internal gully walls can be determined. The exact process of gully switching is unknown at this time due to the lack of chronological data which could be used to correlate debris fans to known fluctuations in the ice sheet. Borehole data from the Rona Wedge reveal mass flow deposits up to 17m in thickness separated by thinner (<10m), layered packages separating the mass-flow packages which contain a mix of cold and temperate, shelf and deep-water microfossils that implies periods of interstadial, or interglacial when sediment supply to the slope is reduced (Stoker and Varming 2011). This is evidence that once shelf wide glaciation was established at 0.44 Ma, the ice margin itself was not static and fluctuations occurred which may account for different gullies being active at any given time. The fluctuations would also account for the evidence of incision by the gullies into earlier contourite deposits reworked during these short interglacials.

It is interpreted that the oldest gullies relate to the earliest development of the Foula Wedge during the initial onset of the late Devensian shelf-wide glaciation. As described above, minor fluctuations in the ice front during this overall period of glacial maxima could account for the change in incision between gullies. The most recent phase of gully incision resulted in a number of gullies that can be traced back into deposits of the Foula Wedge and took place soon after deposition on the Foula Wedge ceased. Stoker and Varming (2011) suggest that ice recession, on this part of the continental margin, began in the area of the Foula Bight located on the outer shelf immediately upslope from the linear gullies and base of slope debris fans with Boulton *et al.* (2002) reporting that the late Devensian ice sheet was in significant retreat by about 15 200 ^{14}C years BP. Therefore, significant sediment contribution to the Foula Wedge in terms of accumulated debris flows would have ceased by this time.

The late to post-glacial (late Devensian (25 ka) to Holocene) MacAulay sequence is proven to drape the Foula Wedge, continental slope and base of slope debris fans. Stoker and Varming (2011) report that seismic data from the Foula Wedge indicate that the MacAulay sequence comprises both onlapping and draped reflection patterns indicative of bottom-current activity combined with hemipelagic rainout of sediment during deposition. The MacAulay sequence is also documented to form a <5m in thickness, laminated drape on top of the base of slope debris flows. It is unclear however, whether these deposits form a subsequent drape or contemporary overbank deposits (Stoker and Varming 2011). With post-glacial sedimentation rates suggested by Masson (2001) to be typically <1cm per thousand years, it could be concluded that a deposit up to 5m in thickness must be the main product of deposition of sub-glacial meltwater sediment suspension (also known as plumites) as well as post-glacial (Holocene to present day) hemipelagic rainout. Release of sediment-laden meltwater would have ceased by about 12 090 ±900 ^{14}C years BP, the minimum age by which the late Devensian ice sheet had terminated on Shetland (Hoppe 1974).

There is little evidence for deposition of contourites in this area of the continental slope during the Holocene, contrary to evidence further east, along slope, where up to 80cm of Holocene sediments have been deposited in the headwall of the Afen Slide (Long *et al*. 2011). This is due to the conical shape of the Faroe–Shetland Channel, funnelling and accelerating oceanic currents which results in no net deposition in the vicinity of the study area but rather is reported to be an area of active reworking of sediment (Masson *et* al. 2004). It is suggested here that the remobilised, fine-grained sediments (contourites) partially infill the down-slope gullies in water depths >840m as gully depth has been recorded as decreasing significantly below this water depth. This is coincident with the area of thickest contourite deposits and most bottom-current activity between 800m and 1000m water depth (Long *et al.* 2011). Sea-bed photographs within the down-slope gullies indicate a veneer of fine-grained sediment (estimated to be generally <1cm in thickness) draping gravel- and sand-rich sediments but there is little evidence of significant sediment accumulation within the gullies associated with the final retreat of the ice margin. This, combined with the high slope angles and bedded sediments cropping out within the gully walls implies that significant reworking of these incised features has not occurred. This suggests along-slope current flow on the upper-slope may sporadically be caught by the largest down-slope gullies, becoming channellised down-slope flow, flushing any accumulated fine-grained sediments out.

Although the move from sea-bed installations being placed on the continental shelf to the deeper water of continental slope may be characterised as placing structures on sloping ground, the general slope angle of the continental slope west of Shetland is only one or two degrees and therefore has minimal effect on sea-bed foundations. However, this study has described deep geomorphological structures with slopes in excess of 20°. Such slopes should be avoided for the positioning of sea-bed templates which might need repositioning, albeit by only a short distance, of proposed wells. The sudden changes in slope angles either between the sides and floor of the gullies or between the sides of the gully and the surrounding seabed would impose difficulties should any pipeline need to be installed. Trenching or rock dumping could locally reduce higher slope angles encountered within the gullies but could be expensive options. The presence of these linear, down-slope gullies extending from the basin floor to the upper-slope will put constraints on longitudinal development such as pipelines or cables to be orientated up slope rather than oblique to slope. Although not observed, it is possible that these down-slope gullies deflect bottom currents. Therefore, if a sea-bed installation is placed within one of these gullies, it will be necessary to conduct multiple, long term current monitoring to develop a hydrodynamic model for the site.

The development of a hydrodynamic model for the West Shetland Slope would also help clarify what the potential effect of contouritic sedimentation and along-slope bottom currents are on proposed sea-bed installations. As present, the speed of sediment movement is not known and therefore there is the potential for burial and/or scour of sea-bed installations.

Conclusions

Sea-bed imagery based upon commercial 3D seismic surveys has been combined with multibeam echosounder data to provide a better understanding of the origin and geometry of linear down-slope gullies and base of slope debris fans. Combining this bathymetric information with sea-bed photographs, acquired primarily for the characterisation of biological fauna, has revealed a much more complex sea-bed sediment regime than that previously interpreted. The generalised prediction that the outer continental shelf comprises predominantly sand- and gravel-rich sediments which become progressively muddier down the continental slope is not supported by the addition of 1308 analysed sea-bed photographs. It has instead been revealed that the complex interplay of sea-bed sediments reflect the different processes acting upon this part of the Faroe–Shetland Channel and a significant update to the sea-bed sediment interpretation to be made. All too often sea-bed video and photographic data collected for environmental surveys is overlooked in considering ground conditions. This study has shown that critical information on the composition and geomorphology of the sea-bed can be gathered from this dataset. Traditional sampling techniques such as the Shipek Grab would have been unable to recover cobble and boulder sized clasts proving the benefit of using photographic data in sea-bed sediment interpretation due to the information on variability in sediment size it brings.

This study has confirmed, using multibeam echosounder data, that slope angles can locally exceed 20° within the down-slope gullies which is of importance to offshore operators looking to install sea-bed infrastructure. This is further enforced by visual observations of bedded consolidated sediments cropping out at sea-bed on examined sea-bed photographs. Anecdotal evidence from these sea-bed photographs suggests that slope angles probably greatly exceed 30° locally and may indeed reach the vertical in some areas but this could not be resolved via ship-borne data acquisition techniques. Autonomous Underwater Vehicle (AUV) or Remotely Operated Vehicle (ROV) site survey, capable of acquiring sub-metre scale resolution data in deep water would aid in realising fully the variation on slope angles encountered within the down-slope gullies.

The authors propose that the down-slope gullies of the West Shetland Slope are incised by turbidite currents emerging down-slope from accumulated debris flow deposits of the Foula Wedge. The Foula Wedge is itself associated with the terminus of an ice stream that has repeatedly reached the shelf edge since 0.44 Ma. This main process of gully incision was replaced by incision by turbidity currents generated by sediment-laden sub-glacial meltwater emanating from the front of the ice stream as it began to retreat from the shelf edge which continued until substantial decay of the ice margin was well underway (about 15 200 ^{14}C years BP). These sediment-laden plumes were also depositing laminated, plumite sediments on top of the base of slope debris fans, continental slope and the Foula Wedge. The release of sediment-laden meltwater would have ceased by about 12 090 ±900 ^{14}C years BP, the minimum age that the ice margin withdrew to the coast of the Shetland Isles during the course of deglaciation. Post-glacial to present day sedimentation rates are limited to hemipelagic rainout and sediment remobilisation by bottom-currents which amounts to a sedimentation rate of <1cm per thousand years.

Acknowledgements

This work has been supported by the British Geological Survey ongoing regional mapping program (MAREMAP; www.maremap.ac.uk). Compilation of the 3D seismic sea-bed image was undertaken by J. Bulat (British Geological Survey) as part of research carried out on behalf of the Western Frontiers Association (membership: Agip, Amerada Hess, BP, Conoco, Enterprise, ExxonMobil, Norsk Hydro, Shell, Statoil, Texaco, TotalFinaElf). All of the hydrocarbon companies, geophysical contractors and the former Faroese GEM Network (membership: Agip, Amerada Hess, Anadarko, BPAmoco, Conoco, DONG, Elf, Enterprise, ExxonMobil, Marathon, Murphy, Phillips, Saga Petroleum Føroyar, Shell, Statoil, Texaco, TotalFina and Veba Oil & Gas) are gratefully acknowledged in providing funding and data for that significant body of work. The authors would like to thank the captain, crew and survey staff of the *M/V Franklin* for multibeam echosounder and photographic ground-truthing data acquisition and processing in 2006. Kerry Howell, Colin Jacobs and Jaime Davies participated onboard the *M/V Franklin* along with the author HAS. The manuscript was improved following the constructive comments of the reviewers. The authors publish with the permission of the Executive Director of the British Geological Survey (NERC).

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Figure Captions

Fig. 1. Sketch map showing the location of the Faroe–Shetland Channel with generalised bathymetric contours (derived from Gebco (www.gebco.net), value in metres) and areal coverage of the 3D seismic sea-bed image and multibeam echosounder data. The dotted line represents the Faroes–UK median line. Hydrocarbon fields are sourced from the Department of Environment and Climate Change. Abbreviations: FBC=Faroe Bank Channel; FW=Foula Wedge; MR=Munkagrunnur Ridge; RW=Rona Wedge; WTR=Wyville–Thomson Ridge.

Fig. 2. a. Part of the sea-bed image (illuminated from the northeast) derived from first returns of 3D seismic surveys covering the zone of linear gullies and debris fans (modified from Bulat and Long 2005). For location see Fig. 1. b. Detail at the base of slope showing the interconnection of the gullies with the base of slope debris fans. Arrows show where the crest of the fan is cut by a channel. c. Detail showing tributaries merging with the primary gully mid-continental slope.

Fig. 3. Multibeam bathymetry data acquired over the 'West Shetland West' area showing down-slope gullies, base of slope debris fans and iceberg ploughmarks. Black arrow indicates a very large iceberg ploughmark, >10km in length, up to 450m wide and up to 10m deep. For survey outline see Fig. 1.

Fig. 4. Slope angles derived from the multibeam bathymetry data showing the continental slope with angles of <2° and up to 30° slope within the walls of the down-slope gullies. Note that values >30°

are spurious values generated by data spikes located at the edge of the multibeam bathymetry dataset. For survey outline see Fig. 1.

Fig. 5. Updated sea-bed sediment interpretation using existing sea-bed samples, video ground-truthing and multibeam echosounder data (including derived layers). Sea-bed sediment sample stations and their associated Folk classification (Folk 1954) are included. Photographic ground-truthing tows WSC 2 and 3 are labelled. For survey outline see Fig. 1.

Fig.6. Geomorphological interpretation based on the extent of the multibeam echosounder dataset and the extent of base of slope debris fans as mapped from the 3D seismic sea-bed image. For survey outline see Fig. 1.

Fig. 7. a. Perspective view (vertical exaggeration x4) of camera tow WSC 3 looking south west with selected sea-bed photographs and edges of the down-slope gully delineated by the white lines. From left to right the photographs show: muddy sand; slightly gravelly muddy sand; muddy sandy gravel; muddy sandy gravel. b. Perspective view (vertical exaggeration x4) of camera tow WSC 2 looking north east with selected sea-bed photographs. From left to right the photographs show: gravelly muddy sand; bedded, consolidated sediments; muddy sandy gravel; gravelly muddy sand. For location of camera tows see Fig. 5.

Fig. 8. Graph showing the change in the relative depth of individual gullies with increasing water depth.

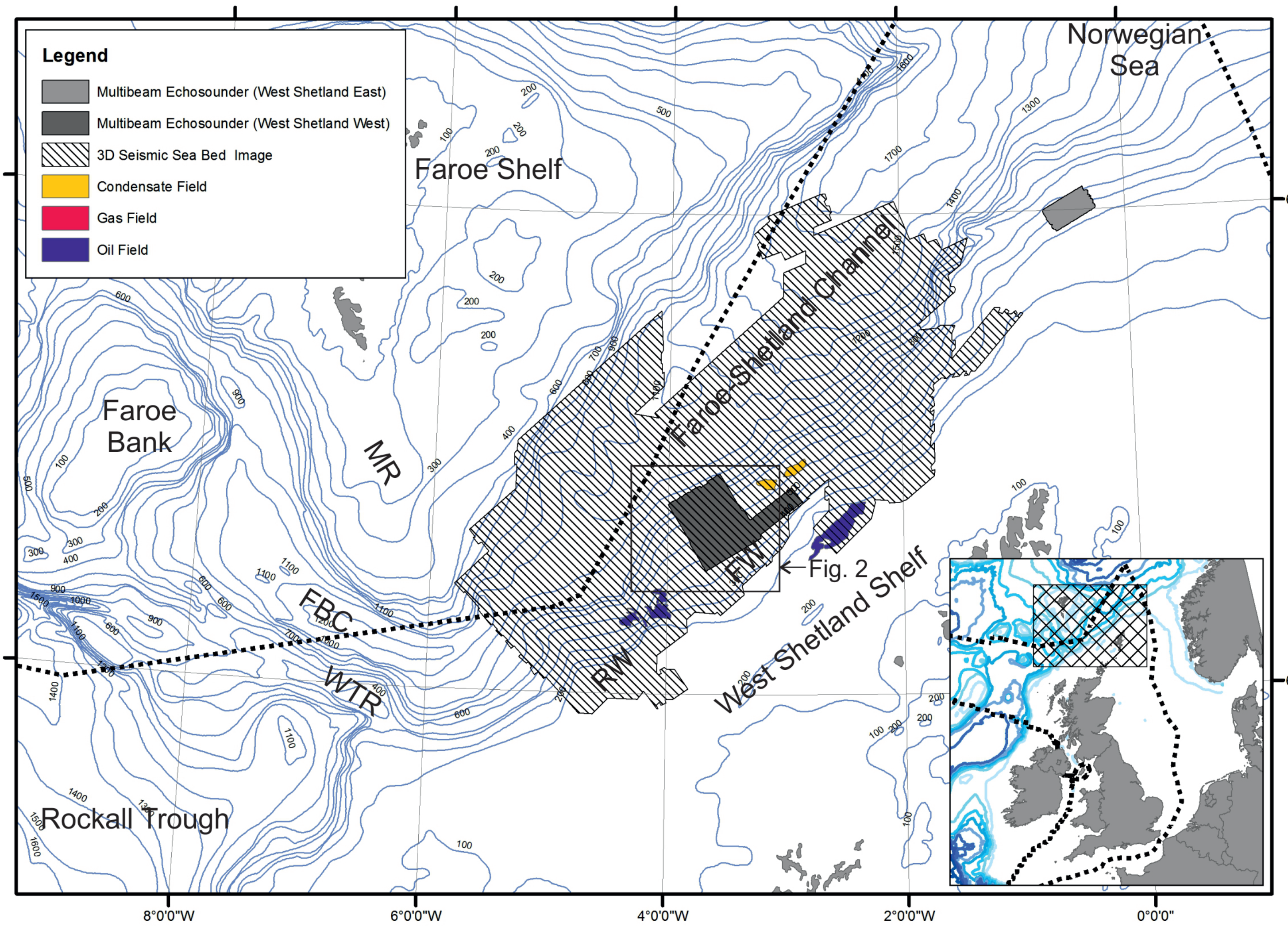
Fig. 9. Down-slope profiles from 7 individual gullies with possible knickpoints (arrows) highlighted. See the inset map for the location of each gully.

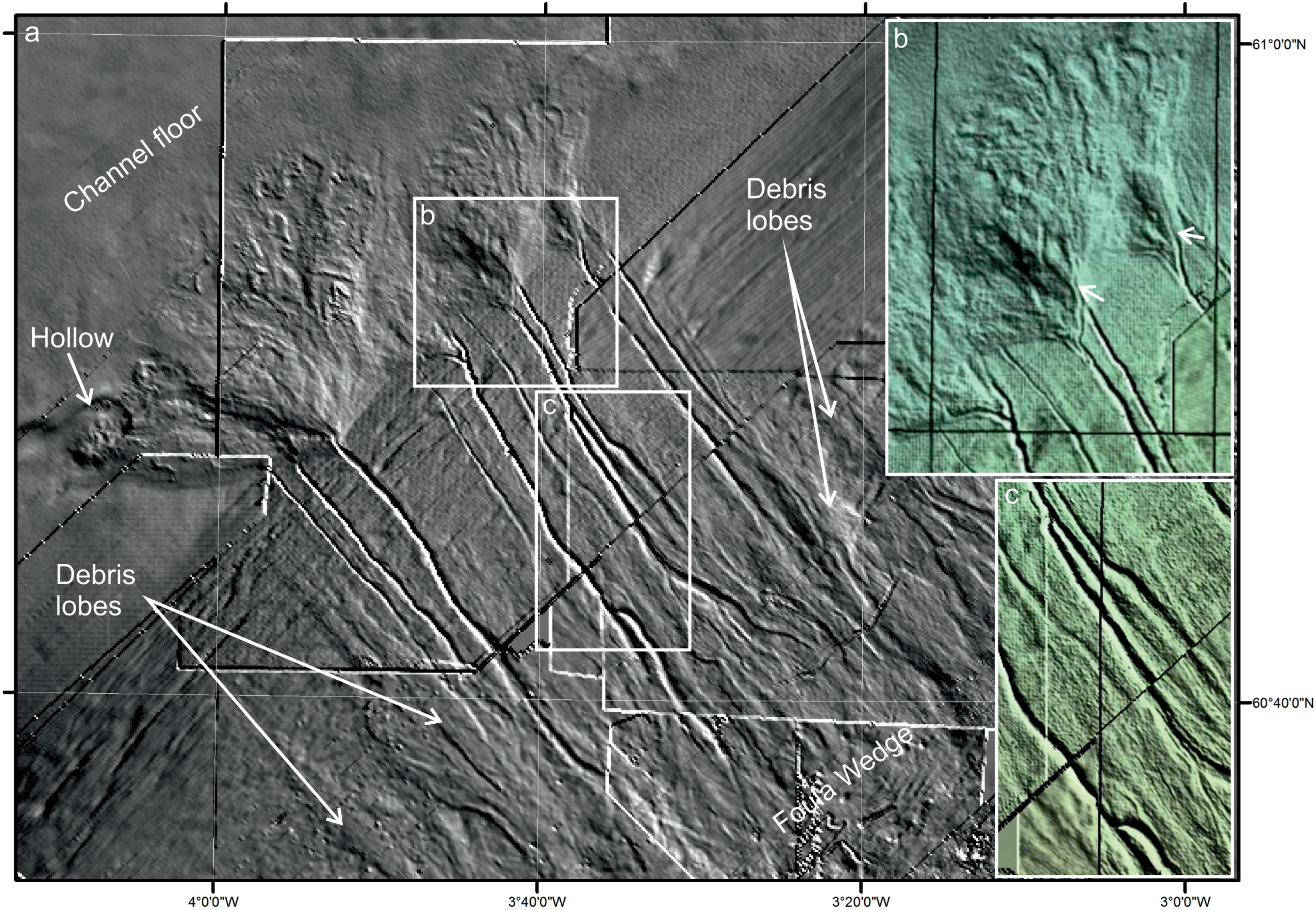
Fig. 10. British Geological Survey sparker profile 79/14/29 fixes 8-16 crossing two of the linear gullies (the upslope gully is 500m in width and 13m in depth with a maximum slope angle within the gully of 5°; the down slope gully is 270m in width and 21m in depth with a maximum slope angle within the gully of 19°) and part of the debris fan at the base of the continental slope. The buried debris flow unit lies within sediments of the Morrison and MacAulay sequences. Sediment cores (sampling <2m below sea bed) coincident with this seismic line indicate sediments on this section of the continental slope comprise very soft clays (shear strength <20 kPa) with occasional clasts covered by a veneer of loose sediments. Note that the oblique angle of acquisition to the continental slope gives a false impression of gully incision into any post-glacial sedimentary drape. For location see Fig. 6.

Fig. 11. British Geological Survey sparker profile 84/05/28 fixes 150-164 show gullies at the sea floor. Notches within the sedimentary (contouritic) sequence may indicate the presence of buried gullies. For location see Fig. 6.

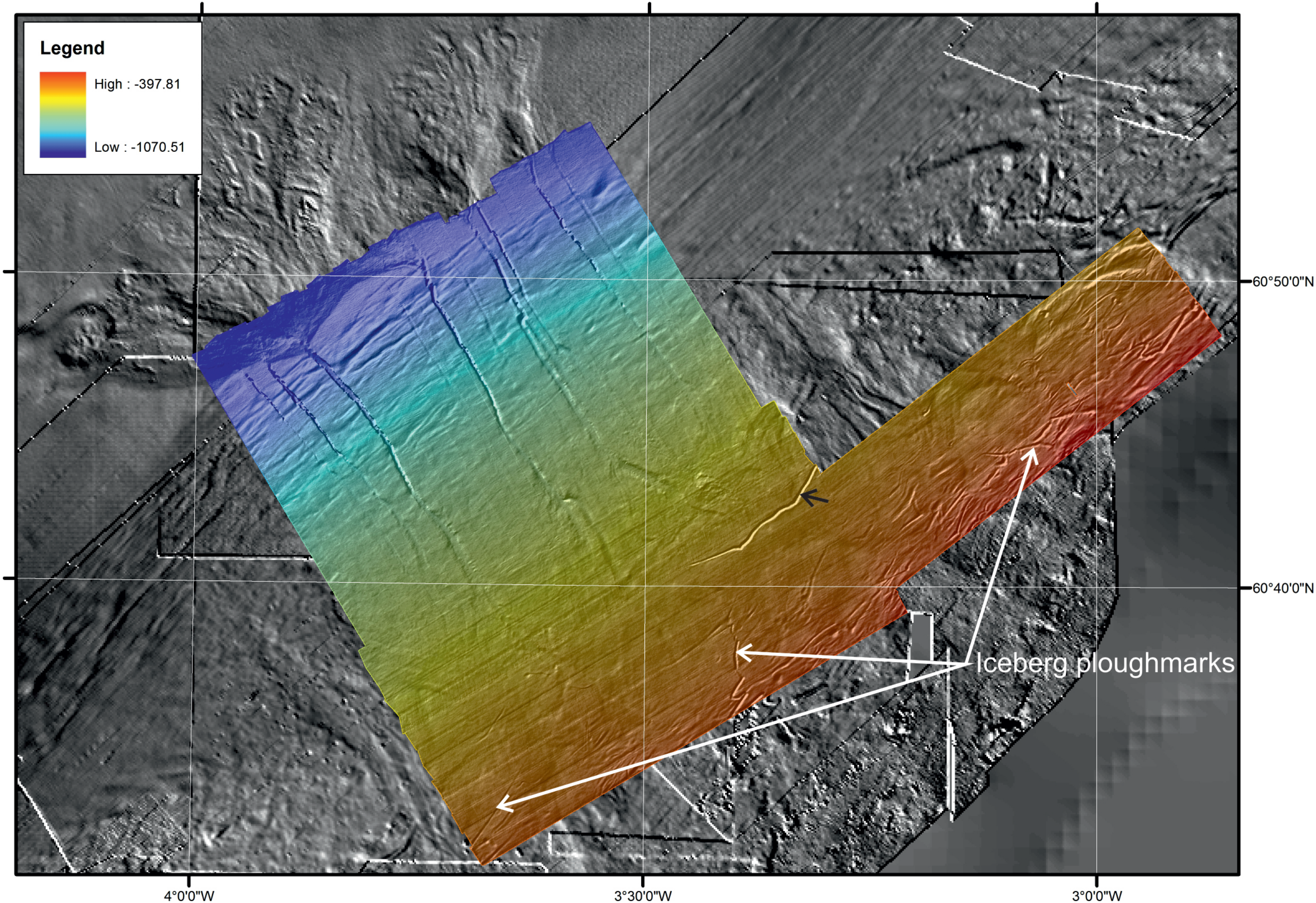
Table 1. Summary of all ground truthing within the 'West Shetland West' multibeam echosounder survey area and area of base of slope debris fans.

Folk classification	**Number of sea-bed samples**		**Number of sea-bed photographs**	
	Survey area	Debris fans	Survey area	Debris fans
Slightly gravelly muddy sand: (g)mS	2	2	9	
Slightly gravelly sandy mud: (g)sM	3	3		
Gravel: G			379	
Gravelly mud: gM	3	1		
Gravelly muddy sand: gmS	8	1	211	19
Gravelly sand: gS	10			
Mud: M	2	1		
Muddy gravel: mG	2	1		
Muddy sand: mS			84	
Muddy sandy gravel: msG	5		473	121
Sandy gravel: sG	2		9	
Sandy mud: sM		1		
Consolidated sediments: R/Rv			3	
TOTAL	**37**	**10**	**1168**	**140**

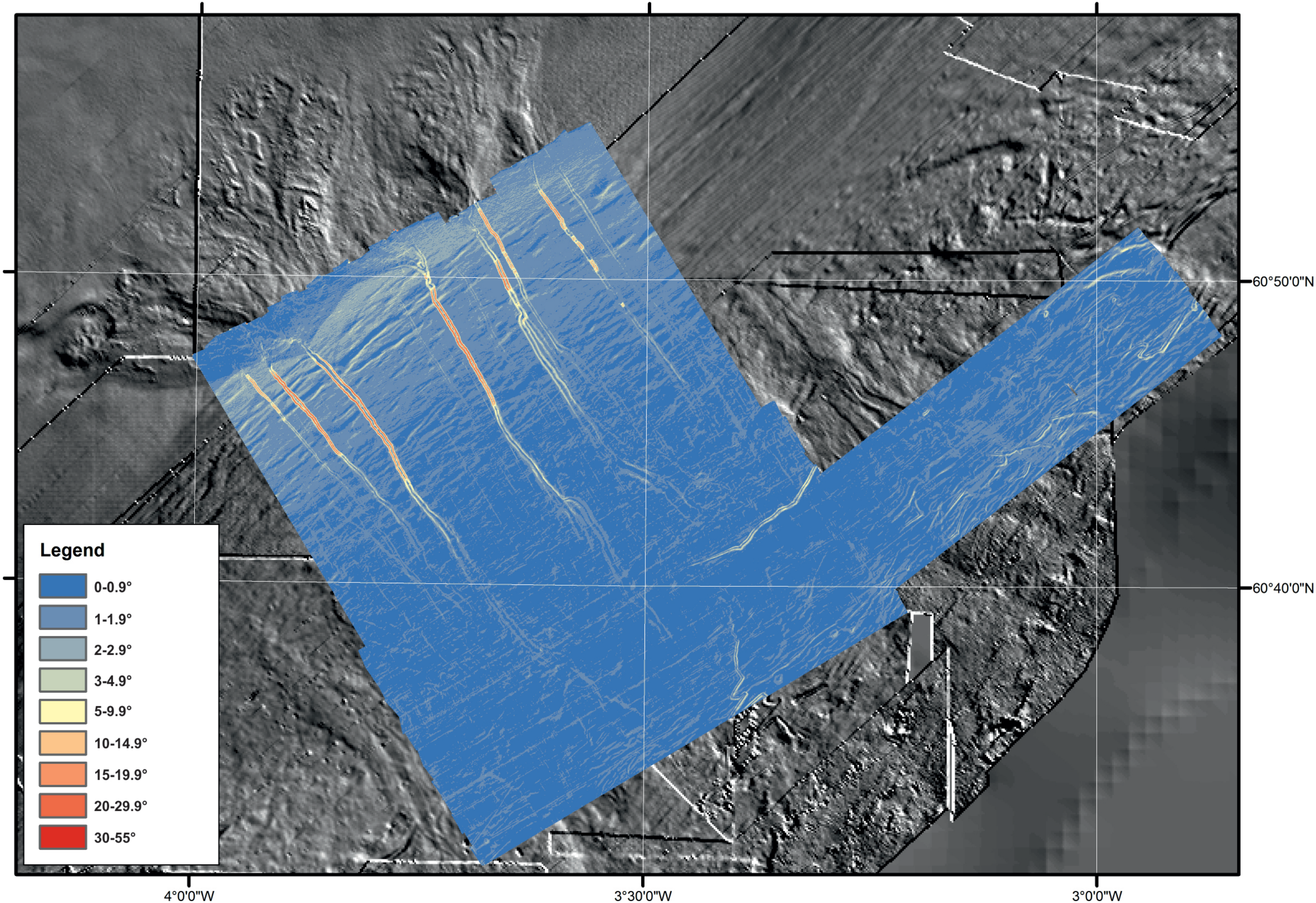

Legend
Multibeam Echosounder (West Shetland East)
Multibeam Echosounder (West Shetland West)
3D Seismic Sea Bed Image
Condensate Field
Gas Field
Oil Field
Norwegian Sea
Faroe Shelf
Faroe-Shetland Channel
Faroe Bank
MR
FBC
WTR
RW
FW
Fig. 2
West Shetland Shelf
Rockall Trough
62°0'0"N
60°0'0"N
8°0'0"W
6°0'0"W
4°0'0"W
2°0'0"W
0°0'0"



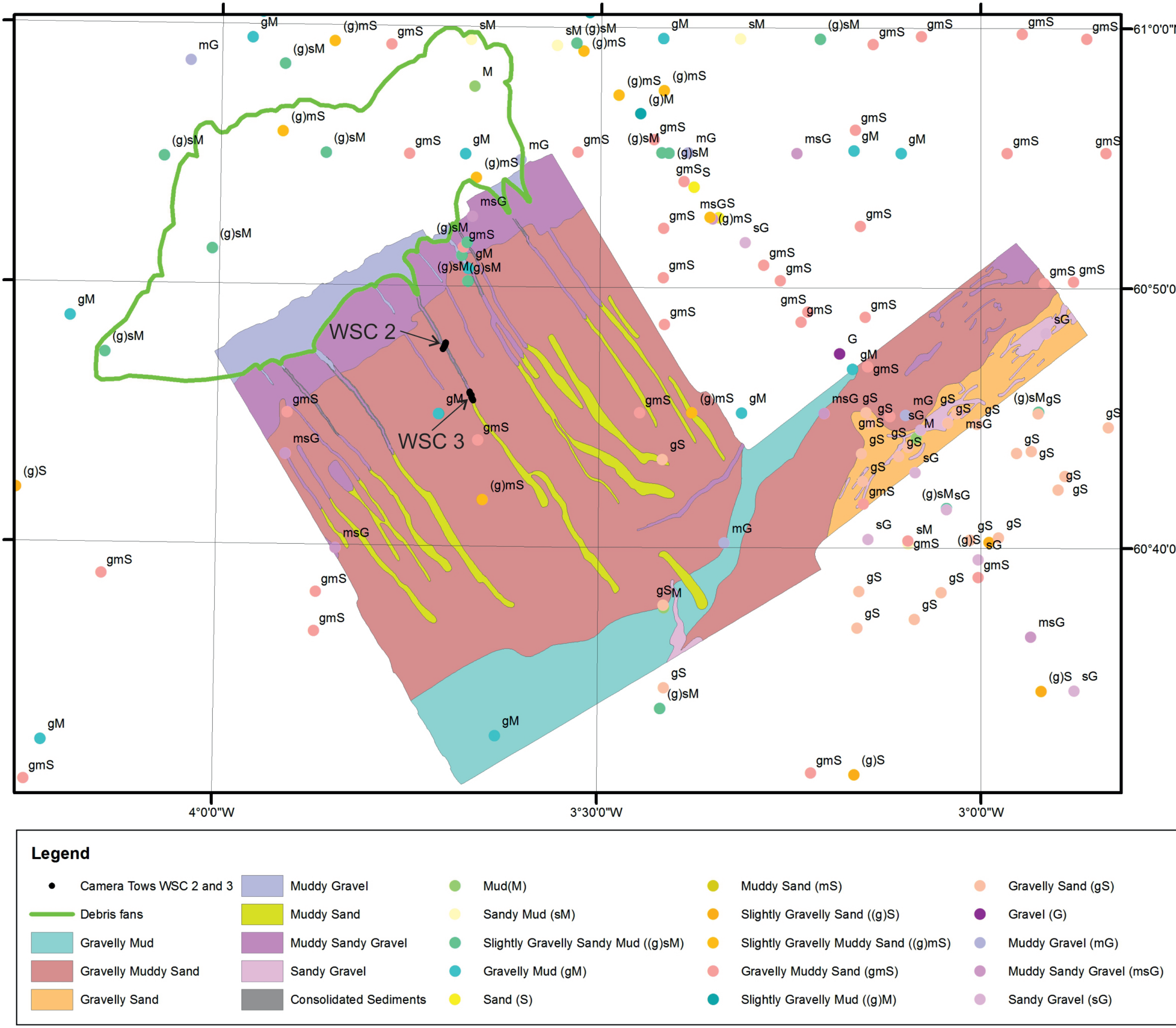
a
b
c
Channel floor
Hollow
Debris lobes
Debris lobes
Foula Wedge
61°0'0"N
60°40'0"N
4°0'0"W
3°40'0"W
3°20'0"W
3°0'0"W



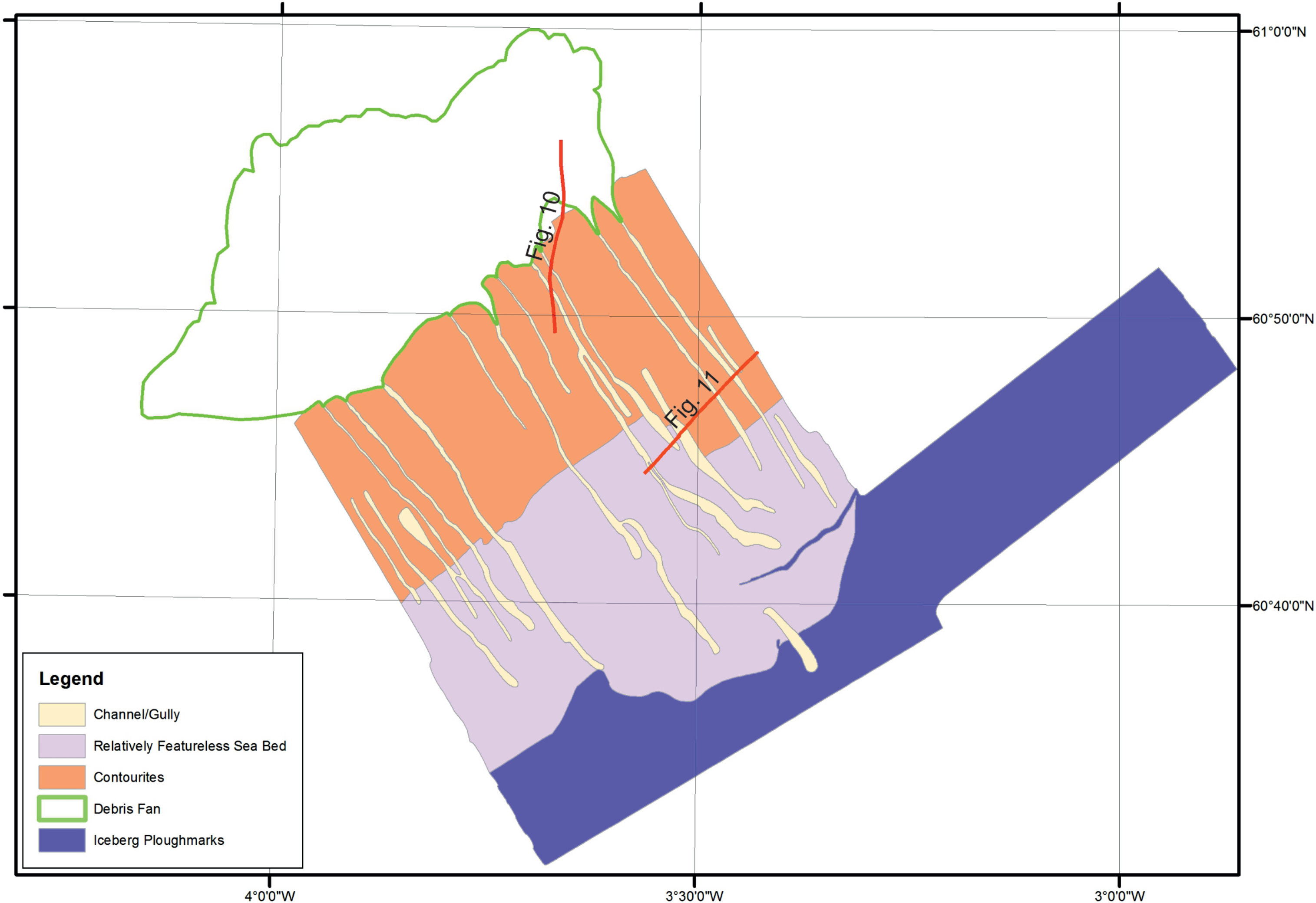
Legend
High : -397.81
Low : -1070.51
Iceberg ploughmarks
60°50'0"N
60°40'0"N
4°0'0"W
3°30'0"W
3°0'0"W



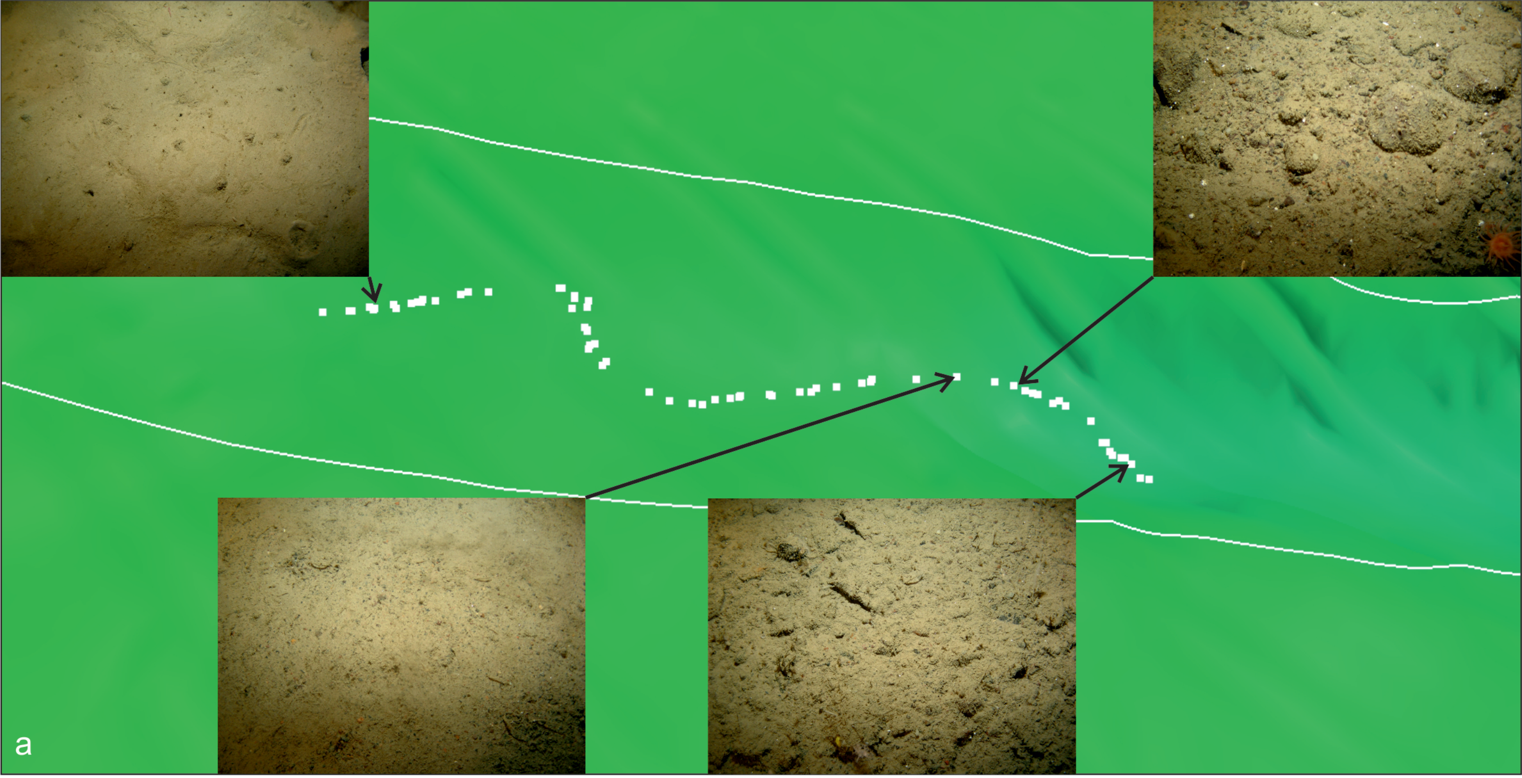
60°50'0"N
60°40'0"N
4°0'0"W
3°30'0"W
3°0'0"W
Legend
0-0.9°
1-1.9°
2-2.9°
3-4.9°
5-9.9°
10-14.9°
15-19.9°
20-29.9°
30-55°

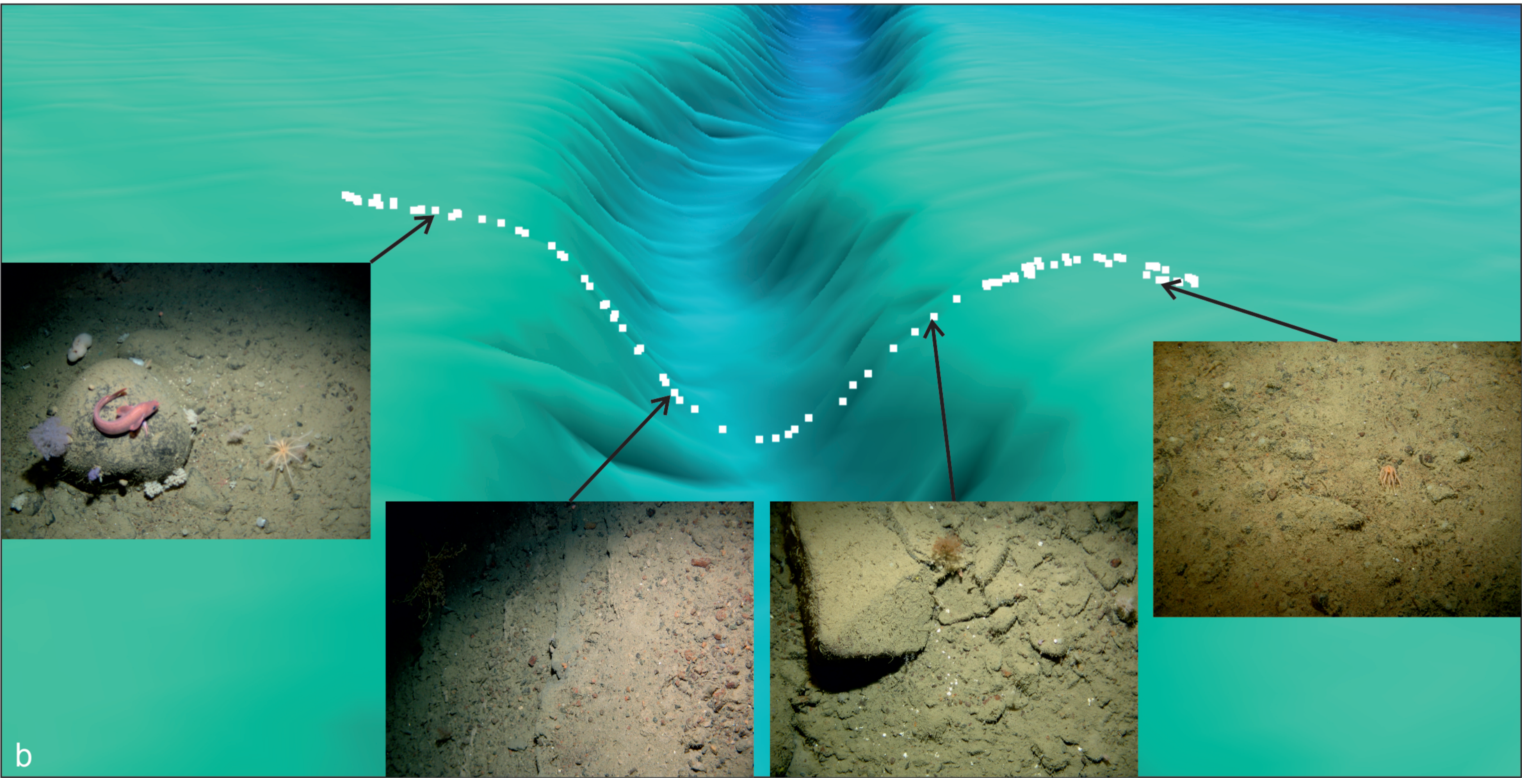


61°0'0"N
60°50'0"N
60°40'0"N
4°0'0"W
3°30'0"W
3°0'0"W
WSC 2
WSC 3
Legend
Camera Tows WSC 2 and 3
Debris fans
Gravelly Mud
Gravelly Muddy Sand
Gravelly Sand
Muddy Gravel
Muddy Sand
Muddy Sandy Gravel
Sandy Gravel
Consolidated Sediments
Mud(M)
Sandy Mud (sM)
Slightly Gravelly Sandy Mud ((g)sM)
Gravelly Mud (gM)
Sand (S)
Muddy Sand (mS)
Slightly Gravelly Sand ((g)S)
Slightly Gravelly Muddy Sand ((g)mS)
Gravelly Muddy Sand (gmS)
Slightly Gravelly Mud ((g)M)
Gravelly Sand (gS)
Gravel (G)
Muddy Gravel (mG)
Muddy Sandy Gravel (msG)
Sandy Gravel (sG)



61°0'0"N
60°50'0"N
60°40'0"N
4°0'0"W
3°30'0"W
3°0'0"W
Fig. 10
Fig. 11
Legend
Channel/Gully
Relatively Featureless Sea Bed
Contourites
Debris Fan
Iceberg Ploughmarks


a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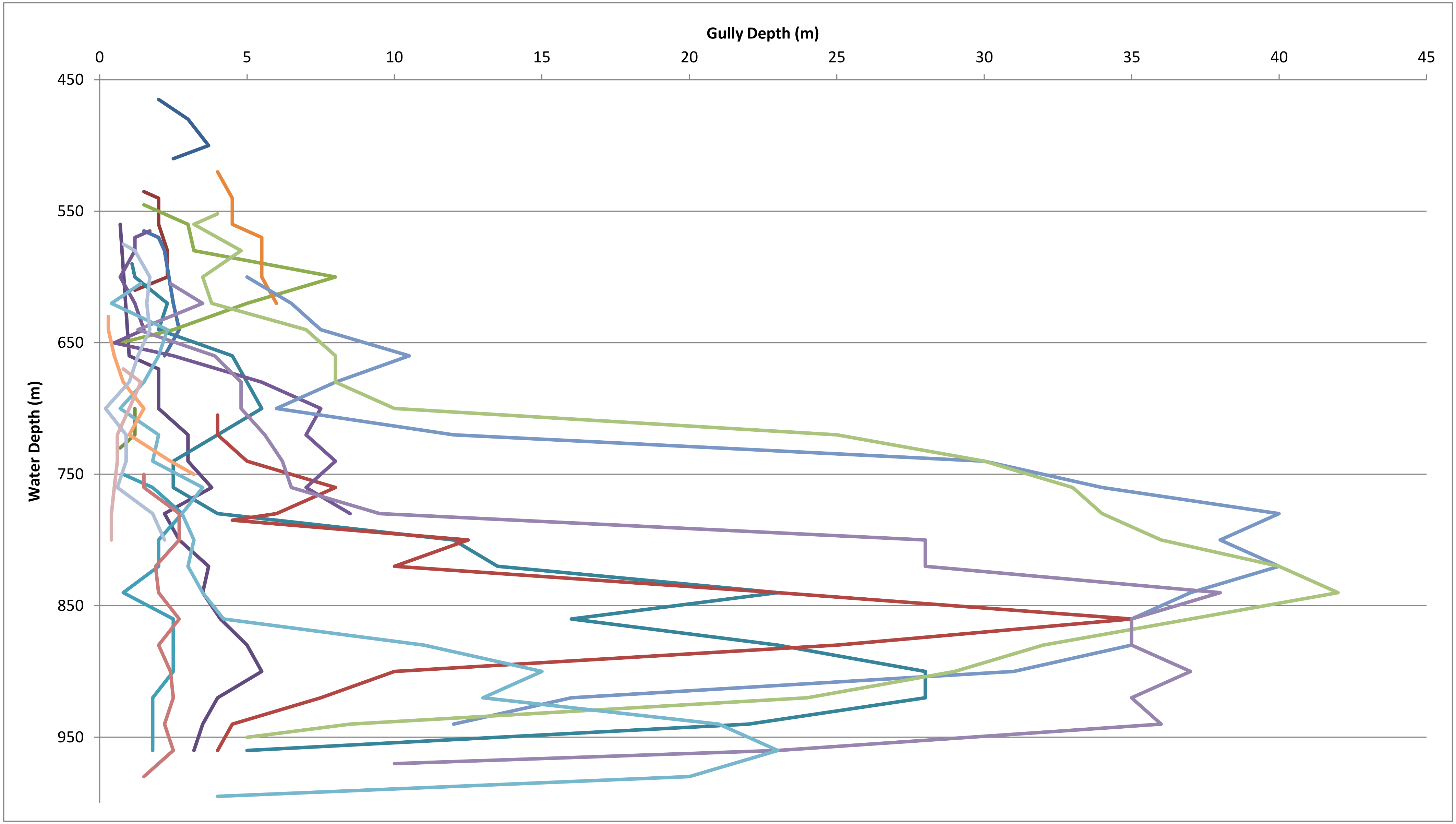
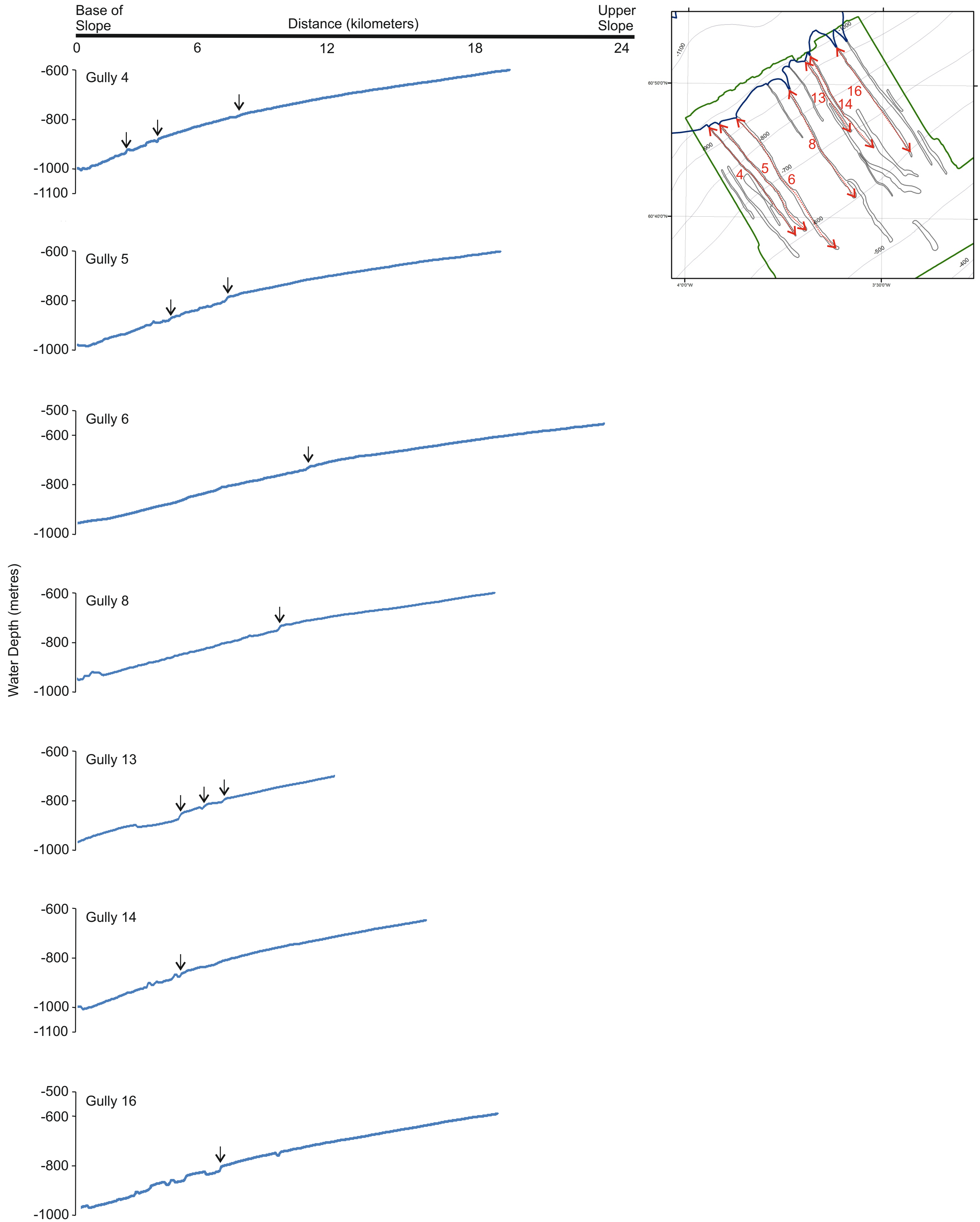
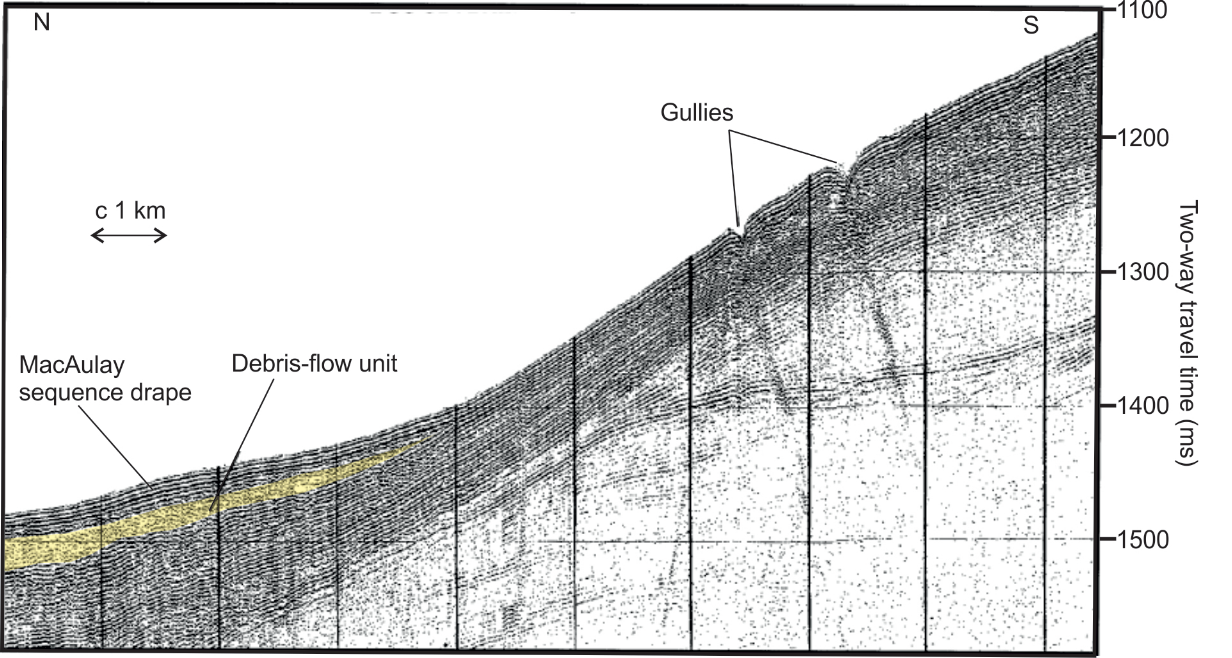
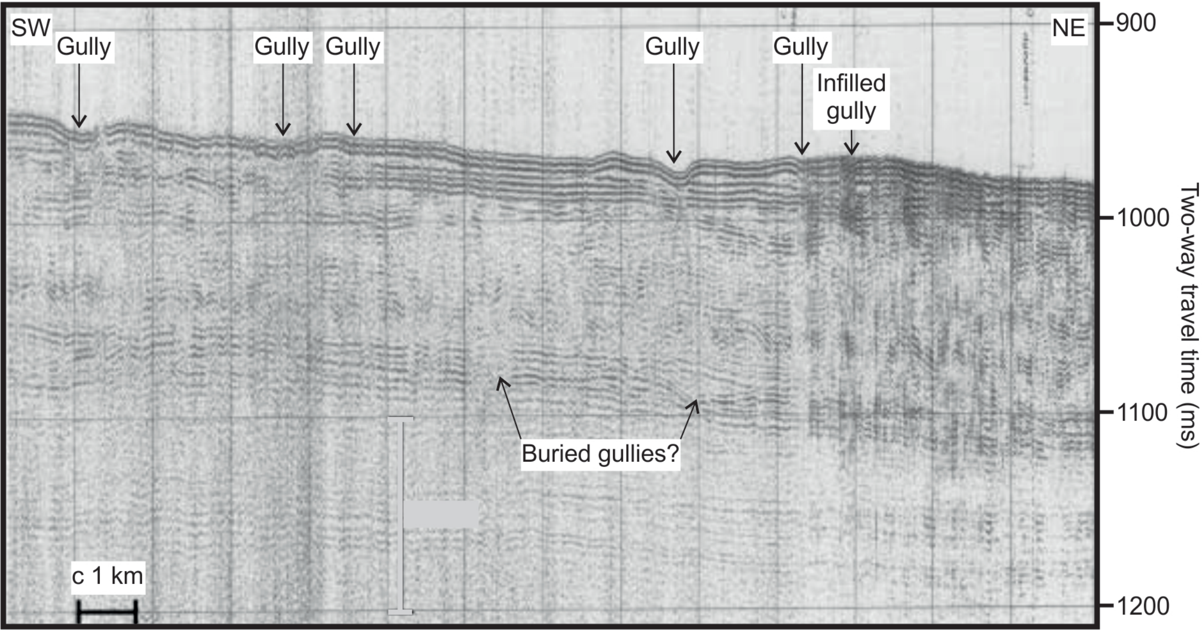


Gully Depth (m)
0
5
10
15
20
25
30
35
40
45
450
550
650
750
850
950
Water Depth (m)



Base of Slope
Distance (kilometers)
Upper Slope
0
6
12
18
24
Water Depth (metres)
Gully 4
-600
-800
-1000
-1100
Gully 5
-600
-800
-1000
Gully 6
-500
-600
-800
-1000
Gully 8
-600
-800
-1000
Gully 13
-600
-800
-1000
Gully 14
-600
-800
-1000
-1100
Gully 16
-500
-600
-800
-1000
4
5
6
8
13
14
16


N
S
Gullies
c 1 km
MacAulay
sequence drape
Debris-flow unit
1100
1200
1300
1400
1500
Two-way travel time (ms)


SW
NE
Gully
Gully
Gully
Gully
Gully
Infilled gully
Buried gullies?
c 1 km
900
1000
1100
1200
Two-way travel time (ms)