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Glacitectonic rafting and associated deformation of mid-Pleistocene glacigenic sediments, near Central Graben, central North Sea; results of a 2D High-Resolution Geophysical Survey

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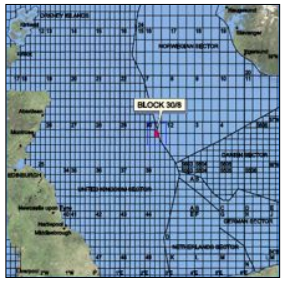
1. WHAT ARE GLACITECTONIC RAFTS?

Glacitectonic rafts are defined as dislocated slabs of bedrock or unconsolidated sediments, transported from their original position by glacial action. These relatively thin, slab-like bodies feature transport distances ranging from tens of meters to hundreds of kilometers. They occur as either single rafts, or multiple stacked bodies associated with a variety of ice-pushed landforms. Internally, rafts frequently appear undeformed although at a larger scale, they may be folded or cut by shear zones and brittle faults.

The processes leading to the detachment, transport and subsequent emplacement of the rafts remain uncertain (Ruszczynska-Szenajch, 1987) despite efforts to characterise them. Furthermore, their regularity and extent across glaciated and formerly glaciated terranes are unknown. This work describes the results of a geophysical 2D seismic survey of thrust-bound glacitectonic rafts and associated deformation structures, occurring within mid-Pleistocene glacigenic sediments of the Central Graben.

2. SITE LOCATION



The surveyed area lies within Block 30/8, located. In the near proximity of the Central Graben, central North Sea, and is located within the coverage of the BGS 56°- 02° 'Fisher' Quaternary geology sheet (Fyfe, J.A, 1986). The mid-Pleistocene at this location is represented by Aberdeen Ground Fm., which provides the earliest evidence for glacial conditions in this region. The Aberdeen Ground Fm. is overlain by the Ling Bank Fm., the base of which is likely to either represent an interglacial of the Elsterian, or be of Cromerian age (Gatliffe *et al.* 1994).

3. 2D SEISMIC DATA COLLECTION

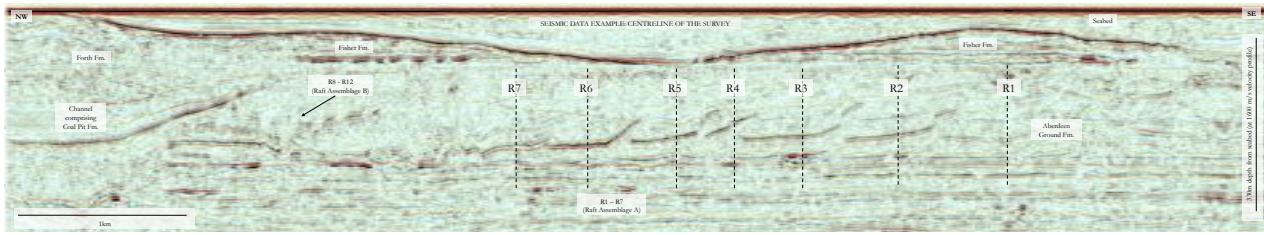
A marine seismic survey was carried out in the region of the Central Graben, central North Sea (Fig. 1). A total of 345 km of data were collected, with 28 primary survey lines oriented at 154.6°/334.6°, and 59 perpendicular cross-lines oriented at 064°/244.6°. A 100m line spacing was used on the main and cross lines, with the survey grid covering a total area of 5.78km x 2.68km. Additionally, three tie lines were run oblique to the primary lines to provide greater coverage over the central area of the survey. 2D High Resolution Seismic (HRS) was acquired using a 4x40 cubic inch sleeve gun array and a 1200m, 96 channel Sercel SEAL 428 streamer. A record length of 2.2s was obtained at a sample rate of 1ms and shot point interval of 6.25m. Positioning was controlled by differential GPS to within an accuracy of ±3 m, with HRS equipment providing a 3m vertical and 15m horizontal resolution. Interpretation was completed in IHS Kingdom. Each high amplitude reflective horizon was digitized across the survey, and gridded to create a depth-converted (1600 m/s) surface of the horizon.

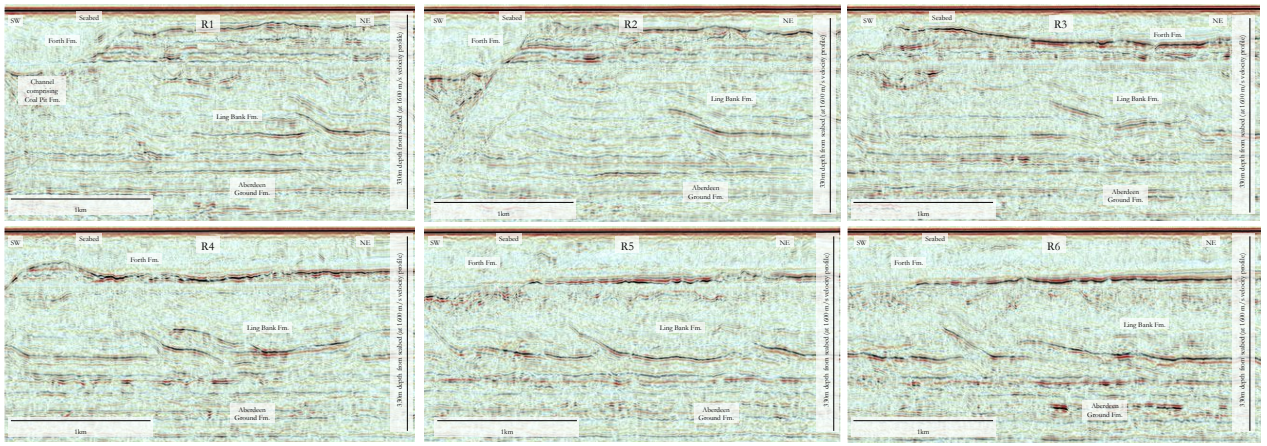
4. GEOLOGICAL SUMMARY

Horizon	Metres below seabed	Metres below MSL	TWT (ms)	Sediment type
Seabed	0	72.8	96	Silty SAND
Forth Fm.	-	-	-	Medium dense to dense silty SAND
Base Forth Fm.	69	142	178	-
Coal Pit Fm.	-	-	-	Medium dense to very dense silty SAND
Base Coal Pit Fm.	105	178	219	-
Ling Bank Fm.	-	-	-	Interbedded SAND and CLAY
Base Ling Bank Fm.	237	310	361	-
Aberdeen Ground Fm.	-	-	-	Hard CLAY with interbedded SAND/SILT
Base Quaternary	667	740	801	-

The Ling Bank Fm. at this location contains a series of discrete, relatively high-angled acoustic reflectors, which are observed in the 2D HRS data (Figs. 2-3), interpreted in this study as glacitectonic rafts. The main acoustic features of rafting include; *i)* a high amplitude reflection from the upper surface indicating contrasting lithologies, and *ii)* internal preservation of bedding planes suggesting deformation partitioned to the basal decollement.

5. 2D HRS DATA EXAMPLES SHOWING GLACITECTONIC DEFORMATION (INLINE AND CROSS-SECTION)





The seven most southerly features (R1-R7) comprise the structurally older series of rafts and are referred to as belonging to raft assemblage A. The 5 rafts comprising raft assemblage B (R8-R12) structurally postdate raft assemblage A, and are observed at a relatively shallow depth throughout the site area. Assemblage A is particularly well-presented in the 2D HRS data, and presented herein within cross-line data examples (see examples immediately above). R2 and R3 each comprise two sections; lower, sub-horizontally oriented sections towards the north adjacent to shallower, more steeply-inclined distal (southern) ends which are described separately as R2a and R3a. Each raft presented is briefly described below:

R1. This structurally oldest raft is 400m long and 32m thick as measured in the centreline. It is emplaced at between 178m - 154m depth, and features a 1.8° dip towards 016° (NW).

R2. R2 occurs in two discrete sections; the main body of the raft (R2) and a small segment adjacent to the north (R2a). R2 emplaced at 178m depth below seabed, is 137m in length and oriented at a 4.1° dip towards the north. R2a 130m in length, is emplaced at a slightly shallower depth than R2 (at 146m), and is oriented at a relatively steep 10.4°. Raft thickness for R2 is approximately 28m.

R3. Similarly to R2, comprises a main sub-horizontally oriented raft and an adjacent, steeply dipping section towards the north (R3a). R3 is 512m in length, and dips at 4.2° towards the north. It reaches a maximum 178m depth, and shallows to 154m depth towards the south. Raft R3a is slightly shallower, at a minimum depth of 126m towards the north. R3a inclined at 14.4°.

R4. This raft is 28m thick, 260m in length, and oriented at 11.2° dip towards the north. At its northernmost extent, the lowest part of the raft is 178m below seabed, and towards the south, the highest section reaches 138m depth. The overall inferred tectonic direction of R4 is found to be 165°.

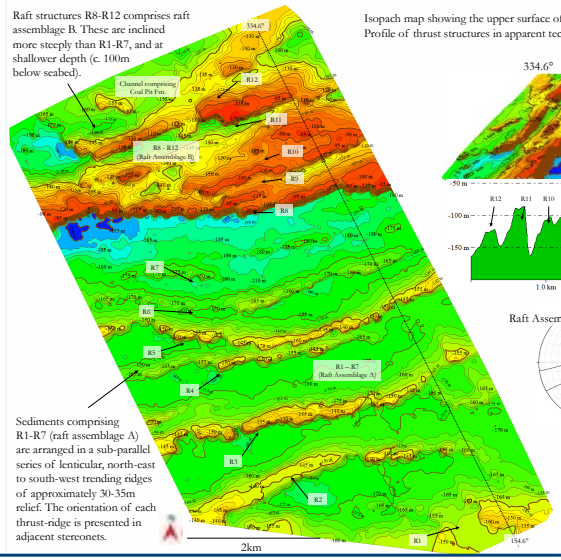
R5. R5 is 475m in total length, and is divided into a deeper northern end (178m depth), which dips shallowly towards the north, and a higher, steeply-dipping (21° towards the north) southern end which reaches 138m depth at the southernmost margin of the raft. The overall inferred tectonic direction of structures associated with R5 is 163°.

R6. R6 is 525m in length, 24m thick, and occurs at a depth of 185m (22m above the base of LBK). It is inclined at an angle of approximately 13°.

R7. R7 (not imaged in cross-section) represents the northernmost extent of raft assemblage A, the northern end of which is situated 1430m south of the perpendicular channel. The raft is 575m in length and dips towards the north, where the majority of the feature occurs at a similar depth to that of R6. The southern end of R7 is slightly elevated, oriented at <2° dip towards the north, and lies 48 m above the base of LBK.

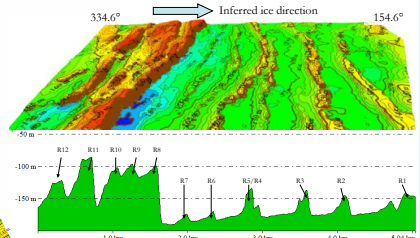
7. INTERPRETATION

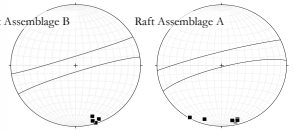
Raft structures R8-R12 comprises raft assemblage B. These are inclined more steeply than R1-R7, and at shallower depth (c. 100m below seabed).



Sediments comprising R1-R7 (raft assemblage A) are arranged in a sub-parallel series of lenticular, north-east to south-west trending ridges of approximately 30-35m relief. The orientation of each thrust-ridge is presented in adjacent stereonets.

Isopach map showing the upper surface of rafting approximately 185-100m below sea level (left). Profile of thrust structures in apparent tectonic direction, and 3D view in NW–SE direction (right).



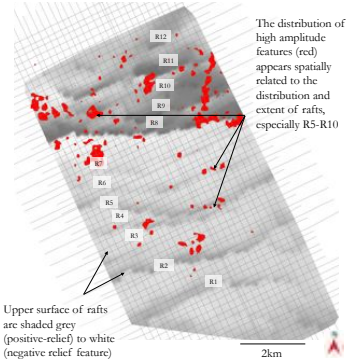


The mean direction of reverse-thrusts (see stereonets above) comprising Raft Assemblage A is 165°, and for those comprising Raft Assemblage B is 170°. Assemblage A features a wider range of raft orientations, partially caused by the undulating profile of Raft 5. These undulations are interpreted to be related to raft stacking over earlier generations of raft, creating an 'imbricate-stack' structure as described elsewhere by Burke *et* al. (2009).

6. ASSOCIATED GEOHAZARDS

Several incidents of shallow gas are present throughout the survey region, as demonstrated by an amplitude extraction from 0.34 - 0.38s TWT (195m – 225m below seabed) shown below.

The high amplitude events (red) are concentrated in the uppermost 20-30m of Aberdeen Ground Fm., lowermost Ling Bank Fm., and the boundary between the two. They occur in close vicinity to the basal thrusts of rafts R4-R11. They are interpreted as pockets of migrated gas, which have accumulated in zones of pressure-shadow caused by the removal and re-orientation of sediments associated with raft elevation.



The distribution of high amplitude features (red) appears spatially related to the distribution and extent of rafts, especially R5-R10

Upper surface of rafts are shaded grey (positive-relief) to white (negative relief feature)

7. SUMMARY

- Using 2D HRS data, this research identifies a series of glacitectonic rafts comprising glacigenic sediments of the Ling Bank Fm., situated within the central Graben region of the central North Sea. Individual rafts are >35m thick and between 800m (R1) to 400m (R4) in length.
- The surveyed section features shortening of approximately 28% within the cross-lines, and 12% throughout main-lines. These relatively high values are principally caused by stacking of rafts into imbricate thrust-sheets (proposed as an emplacement structure for rafts by Burke *et al.*, 2009), with a typical overlap of rafts in the range of 20-100m.
- Detailed analysis of raft characteristics (size, angle of maximum dip, tectonic orientation) and cross-cutting relationships indicate a progression through several discrete phases of structural development within the imbricate thrust stack:

  i) Initial stages of rafting (R1-R2) are transported towards the southwest (200°), and are emplaced at a low angle of inclination (<4°)
  ii) A second stage of rafting (R3–R4) is emplaced towards the south (170°), but is more steeply inclined
  iii) The final stage of rafting within assemblage A (R5-R7) truncates earlier features (R4) and is emplaced towards a bearing of approximately 170° at a low angle of inclination
  iv) A second tectonic event is associated with the emplacement of R8-R12 (Raft Assemblage B)

- At this site, the major controls on raft detachment are interpreted to be i) the glacially-related development of permafrost to an estimated depth of ~100m, alongside ii) the development of saturated subglacial sediments. These sediments developed within the channel oriented perpendicular to raft direction at the northernmost extent of the survey area, creating a zone of reduced effective pressure. This detachment control for rafting is favoured by Bluemle and Clayton (1984).
- Finally, detailed mapping of high amplitude seismic reflections throughout the survey area indicates the presence of several extents of shallow gas (located between 195 to 225m depth) located in close proximity to the deformed and inclined rafted sections. These localised concentrations represent a possible risk to exploration and drilling activities across other areas of previously glaciated terraine.

ACKNOWLEDGEMENTS

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