Salt tectonics in the Southern North Sea: controls on late Pleistocene-Holocene geomorphology.

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Abstract
This paper discusses how salt tectonics has influenced the late Pleistocene-Holocene geomorphology of the Southern North Sea. It demonstrates that some of the major geomorphic features and some of the fluvial channels courses are intimately related to the inflation of salt cored anticlines and the consequent deflation of the adjacent salt withdrawal synclines.

Key Words
Salt tectonics, Outer Silver Pit, Holocene fluvial channels.

Introduction
During the Upper Permian (*c.* 260 to 251 Ma BP) over 1000 m of marine evaporites (the Zechstein Supergroup) accumulated in the North Sea (Cameron *et al.* 1992). Their subsequent burial promoted mobility on geological timescales resulting in thickness variations from less than 50 m in regions of salt withdrawal to more than 2500 m in some of the major salt diapirs (Cameron *et al.* 1992). Today, the deformed salt deposits encompass a wide range of structural morphologies (Jenyon 1986) and in places, the crests of salt structures are within 100 m of the seabed (Cameron *et al.* 1992). This proximity to the present-day depositional surface suggests that the uplift and penetration of the overburden by Upper Permian evaporites may well have influenced the topography and hence depositional systems in this region in the recent geological past.

Measured uplift rates of emergent and immediately subsurface salt diapirs range from 2 to 7 mm yr^{-1} (Bruthans *et al.* 2006). This invariably leads to the deformation of the overlying rock layers and hence exerts an important control on synkinematic sedimentation patterns, and hence geomorphic processes. Topographic relief produced when salt approaches the land surface in continental settings can vary from 45 m (Al Salif, Yemen; Davison *et al.* 1996) to up to 1500 m (Zagros Mountains, Iran; Talbot & Alavi 1996), whilst in offshore settings e.g. the Mississippi Delta, topographic relief varies between 100 and 240 m (Jackson *et al.* 1994). However, a more appropriate analogy for the influence of salt tectonics on landscape evolution in the Southern North Sea during late Pleistocene-Holocene times is that of the Five Islands, south central Louisiana. Located on a low-relief landscape near the western boundary of the Mississippi River delta plain, the Five Islands comprise five salt domes aligned in an approximately NW-SE trend which have pierced and uplifted overlying late Pleistocene meander belt deposits (Autin 2002). The domes are all nearly circular in plan, surrounded by lowland Pleistocene and/or Holocene delta plain marshes, and attain maximum elevations which range from *c.* 23 m asl on Jefferson Island to *c.* 52 m asl on Weeks Island (Autin 2002). The geomorphic impact of the salt domes is most clearly exemplified by Avery Island, where proximal fluvial channels, although modified by engineering in places, show an overall sub-concentric pattern, encircling the salt dome and following the topography closely.

Relationships between salt structures and late Pleistocene-Holocene fluvial systems.

By comparison with the adjacent onshore landscapes of East Anglia and Continental Europe (Belgium, Denmark) which are characterised by similar subsurface geology, the late Pleistocene-Holocene landscape of the Southern North Sea is likely to have been defined by a low-relief, relatively flat land surface. Once Holocene modifications due to sediment accretion (e.g. sandbanks; Stride *et al.* 1982) or erosion (e.g. by tidal scouring) are factored into consideration, the present-day bathymetry of the Southern North Sea reveals a relatively flat surface with water depths of only 20 to 40 metres in the study area (Cameron *et al.* 1992). It is difficult to reconcile the present-day bathymetry to any distinct structural control by salt tectonics, but it is likely that the subaerial late Pleistocene-early Holocene landscape may well have been influenced by near-surface salt bodies e.g. in the form of relative topographic highs above salt cored anticlines. There is evidence to support this hypothesis from 3D seismic data from the north of this study area. Figure 1 presents a series of timeslices (amplitude, Hilbert transform and phase, 0.1 seconds) from the south of the project area. Near the centre of the timeslice a series of broadly concentric reflectors, diagnostic of a salt diapir (Stewart 1999) are clearly visible (Figure 1*b*). An arbitrary seismic line through the 3D seismic volume (Figure 1e) confirms the structure is a diapir and hence likely to have been expressed by a relative topographic high on the late Pleistocene-Holocene land surface prior to early Holocene marine transgression. There is some faulting associated with the southern flank of the salt diapir (Figure 1*b*). To the southwest of the salt structure an approximately WNW-ESE trending sinuous feature is identified from the seismic time slices (Figure 1*a-d*). This feature is interpreted as a fluvial channel. To the southwest of the presumed fluvial channel there appears to be another, more elongate salt structure. The fluvial channel can therefore be interpreted as occupying a relative topographic low, or even a shallow valley, within the late Pleistocene-Holocene land surface, between two relative topographic highs cored by actively upwelling salt. The topographic low may result from the withdrawal of salt in the subsurface, thereby causing the overburden and land surface to downwarp. Several apparent meander loops can be identified within the fluvial channel, and one meander appears to coincide with one of the radial faults associated with the salt diapir, suggesting a further tectonic control on channel geometry and evolution.

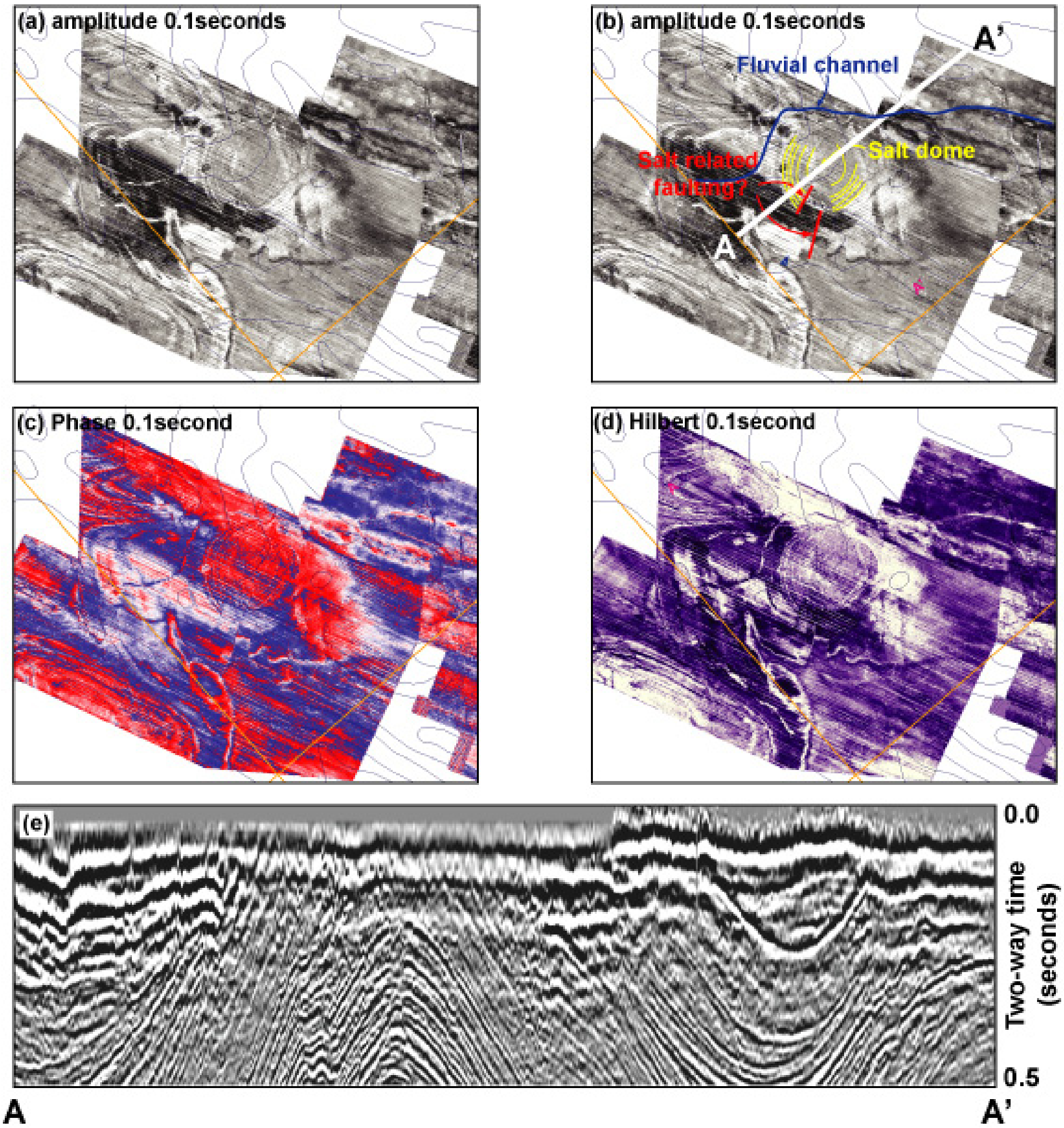

Figure 1 (a) Amplitude time slice (0.1 seconds) centred on prominent salt dome with a characteristic concentric reflector pattern. (b) Amplitude time slice (0.1 seconds) with interpretation. A fluvial channel which flows sub-parallel to the salt dome is identified, and it is suggested that salt-related faults have also influenced the direction and geometry of the fluvial channel. (c) Phase (seismic attribute) time slice (0.1 seconds). (d) Hilbert (seismic attribute) time slice (0.1 seconds). (e) Uninterpreted arbitrary seismic line A-A', confirming that the concentric feature identified in (a-d) is a salt dome.

Figure 2 contains an amplitude timeslice (0.076 seconds) and seismic section. These show an apparently north-westerly draining network of channels, which flow towards the eastern end of the Outer Silver Pit. The first-order tributary to this drainage network overlies the axis of a salt-cored anticline (Figure 2b). A seismic profile through the channel shows that the channel body directly overlies a possible collapse graben above the salt swell (Figure 2c&d). This observation suggests that the formation of the collapse graben led to the development of a topographic depression in the land surface which was exploited by the fluvial channel.

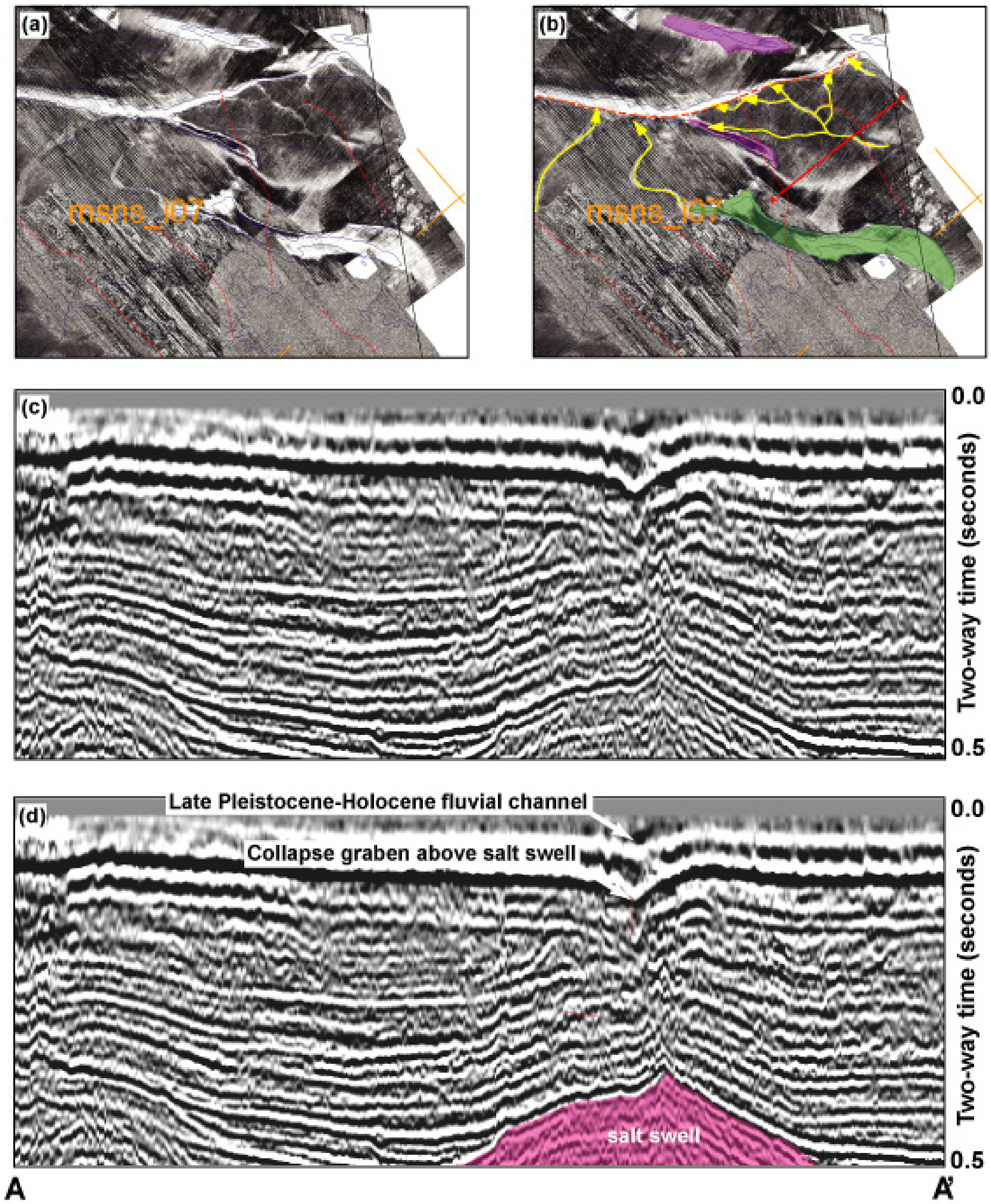

Figure 2 (a) Amplitude time slice (0.076 seconds). (b) As (a) but with interpretation; late Pleistocene-Holocene fluvial channels signified by yellow arrows, Holocene sand waves shown in purple, with the green annotation signifying a Pleistocene tunnel valley. (c) Seismic section. (d) Part of seismic section (c) with interpretation.

More conclusive evidence for the direct control of collapse graben on late Pleistocene-Holocene fluvial systems is presented in Figure 3. This figure contains part of an E-W trending shallow seismic (sparker) profile, 81/03/53, located in the western part of the Outer Silver Pit. Sparker profiles provide higher resolution compared to offshore 2D and 3D seismic reflection surveys. Immediately below the seafloor reflector is a thin package of Holocene reflections. These are draped over a thicker package of mostly sub parallel Pleistocene reflections, the thickness of which varies laterally. In several places along the line the reflections within the Pleistocene succession terminate against packages of chaotic and complex reflections, which most likely represent infilled tunnel valleys. The base of the Pleistocene succession is marked by an approximately horizontal unconformable surface, beneath which are the steeply dipping, truncated, pre-Pleistocene succession. Here, the pre-Pleistocene succession has been folded above an upwelling body of salt into an asymmetric anticline, the hinge of which has been truncated. Near the truncated hinge of the fold the Pleistocene succession shows a marked thinning. This is indicative of growth of the fold during Pleistocene times (Figure 3b). At the hinge itself, the seafloor has a striking horst-graben-horst type morphology (Figure 3c&d). This suggests that the overburden above the salt-cored fold has begun to collapse. The fact that the seafloor itself shows such a spectacular collapse graben-style suggests that this overburden deformation has occurred within the very recent past, and may indeed be continuing through to the present day. These observations provide convincing evidence for neotectonic activity driven by salt diapirism. Examination of the Pleistocene succession within the collapse graben reveals a series of characteristic seismic facies units, with sequences of sub-horizontal reflectors downlapping onto inclined reflections; these are interpreted as channel fill deposits. It seems apparent therefore that the collapse graben identified here was active during late Pleistocene times, and moreover, that several fluvial channels were flowing along the axis of the graben.

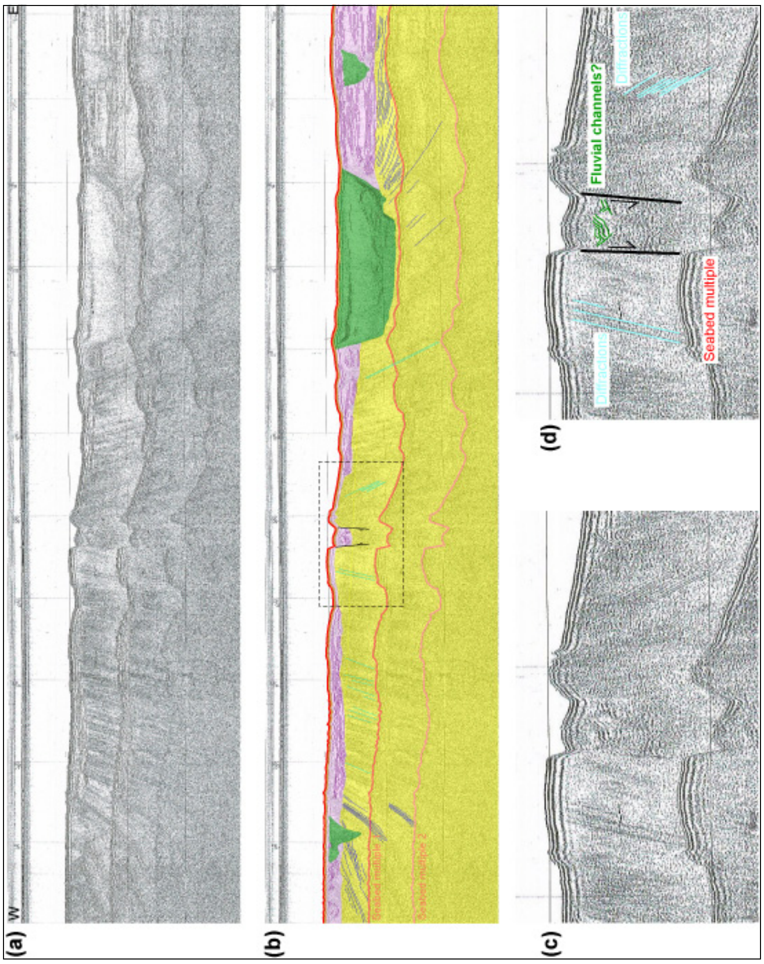

Figure 3 (a) Part of BGS sparker profile 81/03/53 which trends east-west through the Outer Silver Pit. (b) Sparker profile 81/03/53 with interpretation. Seafloor reflector and seafloor multiples shown in red. Tunnel valleys shaded in green, Pleistocene sediments in purple and pre-Pleistocene sediments in yellow. Reflections within the Pleistocene succession are picked in dark purple. Within the pre-Pleistocene succession discernable reflections are marked by dark blue picks, whilst diffractions *(which mark the radial scattering of incident seismic energy) are shown in light blue. (c) Close up of boxed region indicated in (b). (d) Close up of collapse graben with interpretation, showing channel development within collapse graben.*

Conclusions.

Salt tectonics is responsible for some of the late Pleistocene-Holocene geomorphology of the Southern North Sea. 2D and 3D seismic reflection datasets provide evidence that salt structure locally influenced late Pleistocene-Holocene drainage patterns, with rivers either flowing around the relative topographic highs above near surface salt domes, or flowing along the topographic depressions created by collapse structures in the immediate overburden above actively upwelling salt structures. A shallow seismic profile from the Outer Silver Pit (81/03/53) provides spectacular evidence that recent salt movement leading to collapse graben formation has not only controlled the location of late Pleistocene-Holocene fluvial systems, but also directly controls the morphology of the seafloor. It is clear therefore that halokinetic activity, which dominates the structural fabric of the Southern North Sea basin, has also played a critical role in the late Pleistocene-Holocene geomorphic evolution of this region.

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