Geological evolution and hydrocarbon potential of the Hatton Basin (UK sector), northeast Atlantic Ocean

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ABSTRACT

Introduction

During the Mesozoic and Early Cenozoic, and before sea floor spreading occurred in the North Atlantic Ocean, the North American and Eurasian continents were closely juxtaposed (Fig. 1). In mid-Cretaceous times, the southwestern limit of the Hatton Basin, currently in Irish waters, was close to the rift basins now situated in the Labrador Sea and on Canada's eastern continental margin. Also, the northwestern margin of Hatton Basin was adjacent to southeast Greenland. At present, the Hatton Basin is located on the extreme western margin of the European continent approximately 600 km due west of Scotland (Fig. 2). The extent of the Hatton Basin is defined by the Hatton High (to the west) and the Rockall High (to the east) (Fig. 3). Water depths increase southwards from 1000 m to over 1300 m. The continent/ocean crustal boundary underlies the western flank of Hatton Bank (Kimbell *et al*., 2005).

Commercially, the Hatton Basin is very remote, under-explored and has never been licensed for hydrocarbon exploration. It is currently the subject of ownership negotiations related to the UN Convention on Law of the Sea. It straddles the bilaterally-agreed median line between the UK and Ireland. Owing to data availability, this paper deals only with the northern part of the basin (the UK sector).

Data

This paper is based on 20,000 km of post-1992 mainly high-resolution and conventional industry 2D seismic data, most of which have coincident gravity and magnetic data. The deepest borehole penetration in the basin is currently at Deep Sea Drilling Project (DSDP) Site 116 which terminated at 854 m below sea bed in the uppermost Eocene. Other borehole data include DSDP Site 117 and Ocean Drilling Program (ODP) Site 982 (drilled in the eastern part of the basin) and British Geological Survey (BGS) shallow boreholes 99/1 and 99/2A (maximum penetration 46.5 m) drilled on the top of the Hatton High. The BGS also has a small number of short sea-bed cores taken on the top of Rockall High.

Regional considerations

As might be expected, the gravity map across the Hatton Basin (Fig. 4) shows it to be broadly coincident with a gravity 'low' albeit containing two large near-circular positive anomalies which correspond to the Mammal and Sandastre igneous centres. Several short sea-bed cores comprising gneiss and granulite (including BGS rockdrill cores 56-15/11 and /12 dated at 1900 – 1700 Ma) and mainly basic igneous rocks (dated at 57 – 56 Ma) have been obtained from the Rockall High. Combined with interpretation of the seismic and gravity data, this suggests that Rockall High comprises a massive early Proterozoic metamorphic basement block overlain by Late Paleocene lavas and younger sediments. Consequently the coincident gravity signature is a broad gravity 'high'. In contrast, the gravity signature across the Hatton High (Fig. 4) is much more variable and suggests a more complex structure and geological history. This is corroborated by seismic data which reveal inverted ?Mesozoic basins within the high and a large anticline which constitutes the sinuous high at its northern end. Folds and faults, which are absent on seismic data across the Rockall High, are imaged on the seismic data across the Hatton High.

Hatton Basin Evolution

The crust beneath the basin comprises high-grade early Proterozoic metamorphic basement. This crops out on Rockall High, where it has been sampled, but not on Hatton High where seismic data suggest it does not occur at sea bed. This basement probably constitutes a separate terrane which is younger and significantly different to the Archaean Lewisian Gneiss Complex of the northern Rockall Basin and western Scotland. The boundary between these terranes may coincide with the north-west to south-east oriented feature termed a suture by Dickin and Bowes (2002), the Anton Dohrn transfer (Doré *et al*., 1997) or the Anton Dohrn lineament (Kimbell *et al*., 2005).

Although Atlantic rifting adjacent to the western flank of Hatton High probably started during anomaly 24 time (Early Eocene) (Kimbell *et al*., 2005), the main phase of Hatton Basin rifting (i.e. when the basin 'opened') was probably Early to mid Cretaceous although plate tectonic modelling suggests there may have been an earlier minor precursor phase (Cole and Peachey, 1999). Consequently the fill of the Hatton Basin probably constitutes:

1. pre-opening Palaeozoic and Mesozoic sedimentary rocks,

2. syn-rift Cretaceous sediments,

3. post-rift Late Cretaceous to Paleocene sediments,

4. extensive Late Paleocene flood lavas,

5. post-lava Eocene to Recent sediments**.**

See Figure 5 for a regional cross-section across the basin which illustrates much of the post-rift infill and the nature of the Cenozoic basin margins. From gravity modelling, the combined pre-lava sedimentary thickness of intervals (1), (2) and (3) above has been estimated at up to 4 km thick (Kimbell *et al*., 2007), whereas interpretation of wide-angle seismic data has yielded a figure of up to 5 km for the same interval (Smith, 2006). Pre-lava interval velocities have been estimated in the range 4.5 – 6.1 km/s, although this figure may be somewhat inflated due to igneous intrusions. However, a similar figure of 5.1 – 5.3 km/s has also been suggested by Keser Neish (1993) for pre-Cenozoic sedimentary rocks within the Hatton High. Although not drilled in the centre of the basin, BGS boreholes 99/1 and 99/2A proved Albian (mid-Cretaceous) mudstones and sandstones on the Hatton High (Hitchen, 2004).

Smith (2006) suggested the presence of sub-lava syn-rift tilted fault blocks on the western side of the Hatton Basin based on traveltime inversion of wide-angle data. Wedge-shaped syn-rift seismic packages have also been imaged by new (2007) TGS data from the eastern and western margins of the Hatton Basin (Figs. 6 and 7). Such geometries are probably Cretaceous in age and include potential hydrocarbon traps.

Differential subsidence and uplift has been a feature of the Hatton Basin area through time. During the Albian to Paleocene interval, the ?Mesozoic basin on Hatton High was inverted, folded, faulted and eroded (Fig. 8) whereas the Hatton Basin appears to have escaped similar tectonics. This may in part be due to igneous underplating of the Hatton High associated with the Iceland Plume (White *et al*., 1987).

Several large igneous centres were emplaced during the ?Late Paleocene, and extensive lavas were extruded across most of the area (see Figure 3 for locations, Figure 4 for gravity signatures, and Figure 5 for seismic example across Lyonesse igneous centre). The lavas are estimated to be 1200 m thick in the basin (Smith, 2006) but thinner across the adjacent highs. The lavas degrade the seismic response from deeper levels and hence hinder the identification of Mesozoic hydrocarbon exploration plays in the basin.

Following this volcanic episode, the Hatton and Rockall highs were probably emergent and acted as source areas for shallow-water nearshore sandstones deposited as prograding wedges (McInroy *et al*., 2006). At the end of the Eocene a major compressional event created the North Hatton High anticline (with associated minor thrusts on its southern limb) and 'pop-up' structures in the northern Hatton Basin (Fig. 9) (Johnson, *et al*., 2005). However the Hatton Basin underwent subsidence and, with a new oceanic current regime in place, began to collect a thick sequence of fine-grained mudstones and oozes as proven in DSDP borehole 116.

Hydrocarbon Prospectivity

The presence of a source rock is the biggest single risk for a working petroleum system in the Hatton Basin. However, on a regional pre-Atlantic opening scale, the southern end of the Hatton Basin may have been adjacent to the Labrador margin, which includes the Hopedale Basin which has proven gas fields (DeSilva, 1999) with possible source intervals in the Cretaceous through to the Eocene. Numerous examples of Lower, Middle and Upper Jurassic and Lower Cretaceous potential source rocks have been proved by drilling along the Atlantic seaboard of the British Isles (Hitchen and Stoker, 1993; Butterworth *et al*., 1999) and in the Rockall Basin gas and condensate have been recovered from UK and Irish wells 154/1-1 and 12/2-1 respectively. Based on an assumed present depth of burial of 5.5 km below sea bed, Jurassic source rocks (if present) in the Hatton Basin would have been mature for oil throughout the Cenozoic. Several natural oil slicks have been documented in the area (Hitchen, 2004) including one in the northern Hatton Basin (Fig. 4).

Potential reservoir intervals in the Hatton Basin include Cretaceous syn-rift packages, Paleocene sandstones related to thermal uplift and Eocene fans and prograding wedges.

There are numerous potential trap styles in and around the Hatton Basin. These include Cretaceous syn-rift tilted fault blocks, truncation of dipping ?Mesozoic sediments beneath the base Cenozoic unconformity, Eocene prograding wedges, updip Eocene pinchouts at the basin margin (Fig. 10), fans at the base of lava escarpments (Fig. 11) and compressional and inversion structures created during the Late Eocene.

Acknowledgements

The seismic data shown in Figures 6, 7 and 8 is taken from the TGS HR07 (2007) survey and is shown with the permission of TGS (www.tgsnopec.com). This paper is published with permission of the Executive Director of the British Geological Survey (NERC).

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Figure 1. Reconstruction of the North Atlantic region at approximately 100 Ma (mid-Cretaceous) showing the palaeo-location of the Hatton Basin. Reconstruction based on output from ATLAS plate reconstruction software, Cambridge Paleomap Services Ltd. CG: Central Graben, CSB: Celtic Sea Basin, EB: Erris Basin, EOB: East Orphan Basin, FP: Flemish Pass Basin, FSB: Faroe-Shetland Basin, HB: Hatton Basin, HDB: Hopedale Basin, JB: Jeanne d'Arc Basin, LB: Laurentian Basin, MB: Møre Basin, PB: Porcupine Basin, RB: Rockall Basin, SB: Scotian Basin, SH: Sea of Hebrides Basin, SLB: Saglek Basin, SPB: Southern Permian Basin, ST: Slyne Trough, VB: Vøring basin, VG: Viking Graben, WAB: Western Approaches Basin, WB: Whale Basin, WOB: West Orphan Basin.

Figure 2. Present day location of the Hatton Basin in the North Atlantic Ocean.

Figure 3. Principal features of the Hatton Basin and adjacent structural highs. *Denotes geological feature name (bathymetric feature names are, from west to east, Hatton Bank, Hatton Basin, Rockall Bank and Rockall Trough). Precise locations of the TGS profiles illustrated in this abstract (Figs. 6, 7 & 8) have been omitted for commercial reasons.

Figure 4. Bouguer gravity anomaly map of the Hatton Basin and adjacent structural highs. Most central igneous complexes (see also Fig. 3) correspond with near-circular positive anomalies. See text for comment about natural oil slicks. Confidence ratings of individual oil slicks taken from Hitchen (2004).

Figure 5. BGS high-resolution seismic profile (00/01-19, 18 & 45) across the Hatton Basin (located in Fig. 3) illustrating the simple post-rift Cenozoic geometry of the basin.

Figure 6. Seismic profile from the northern Hatton Basin illustrating possible syn-rift tilted fault blocks in the pre-Cenozoic succession and a small inversion structure possibly related to Early Cenozoic sill intrusion. Data shown courtesy of TGS (UK).

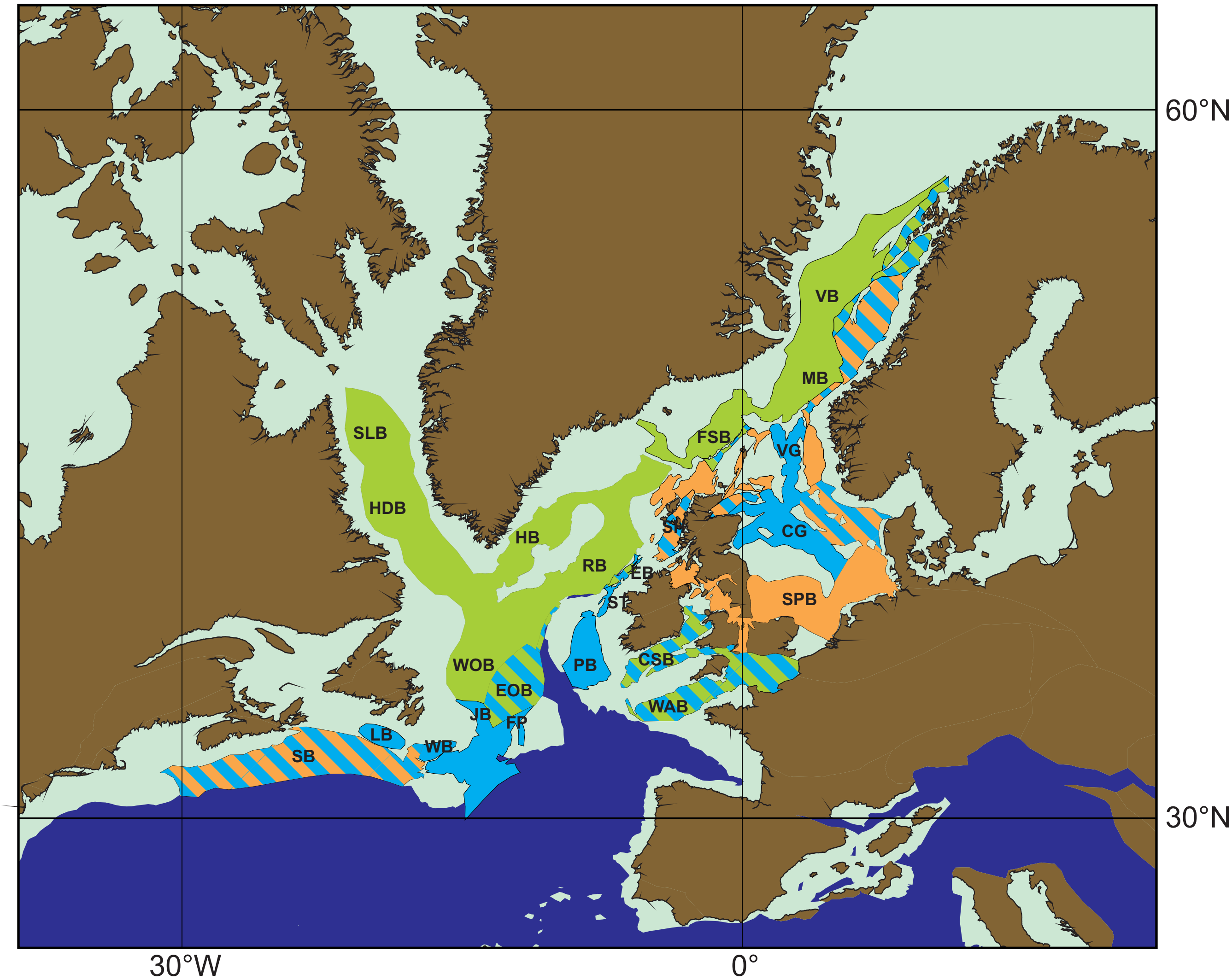
Figure 7. Seismic profile from the eastern flank of the Hatton Basin illustrating pre-Cenozoic sub-basalt syn-rift wedge-shaped seismic packages. Data shown courtesy of TGS (UK).

Figure 8. Seismic profile across part of Hatton High illustrating an inverted basin containing a faulted, folded and eroded ?Mesozoic succession. BGS boreholes 99/1 and 99/2A, projected onto this profile, proved Albian rocks just below sea bed. Data shown courtesy of TGS (UK).

Figure 9. BGS high-resolution seismic profile (02/02-15) across the northern part of Hatton Bank (located in Fig. 3) illustrating ?Late Eocene compressional features which both affect the sea bed (the North Hatton Bank anticline) or are completely buried by thick younger Cenozoic sediments.

Figure 10. BGS high-resolution seismic profile (00/01-56) from the north-east Hatton Basin (located in Fig. 3) illustrating the updip pinch-out of the sand-prone Eocene interval beneath younger mud-prone sediments.

Figure 11. BGS seismic profile (93/02-C) from the central Hatton Basin (located in Fig. 3) illustrating the presence of a clastic fan at the base of a large basalt scarp.



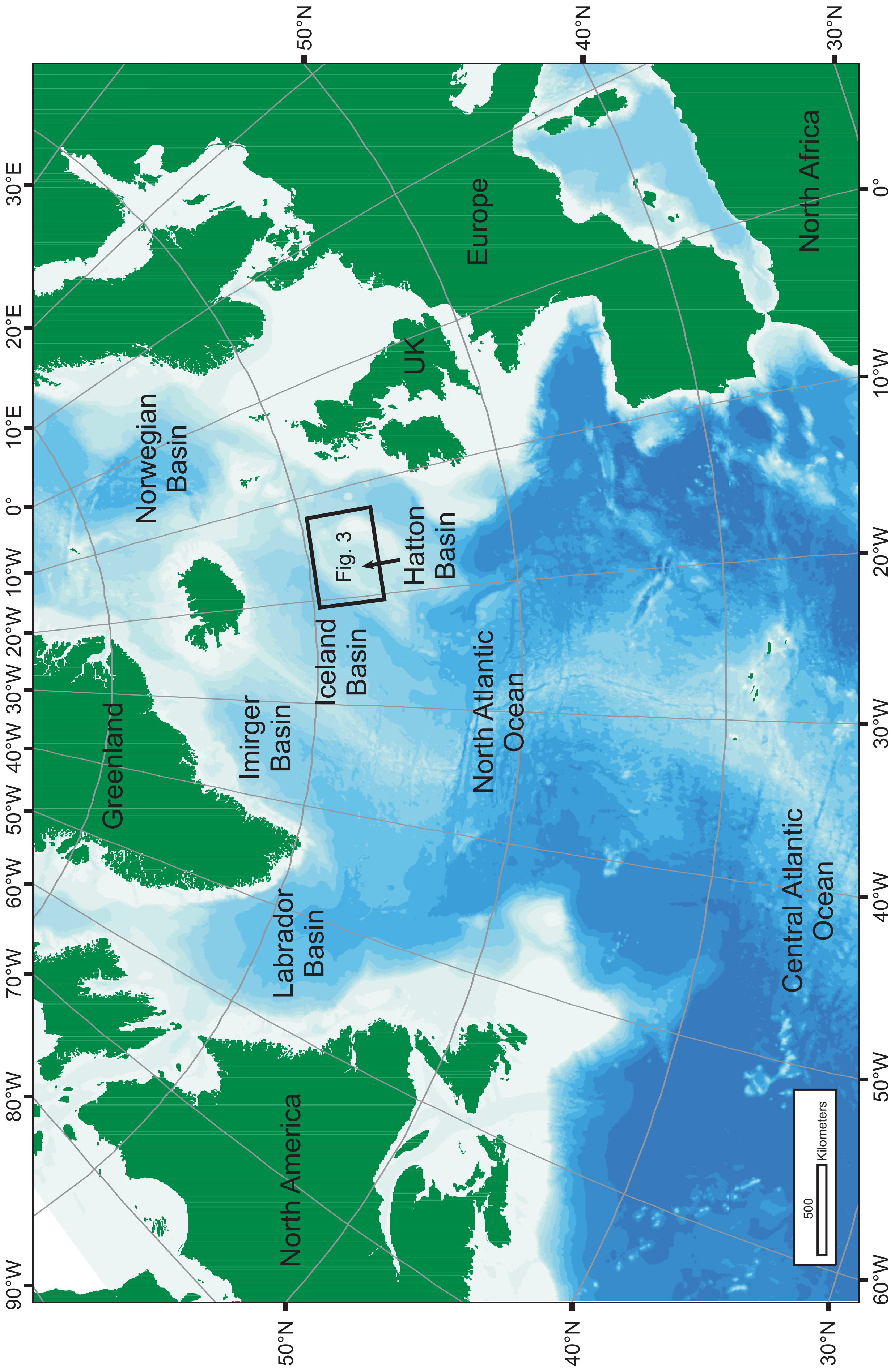
Present day land areas
Present day water depths < 2 km
Present day water depths > 2 km

Rotated to position at 100 Ma only. These do not represent paleo-land mass or paleo-water depth.

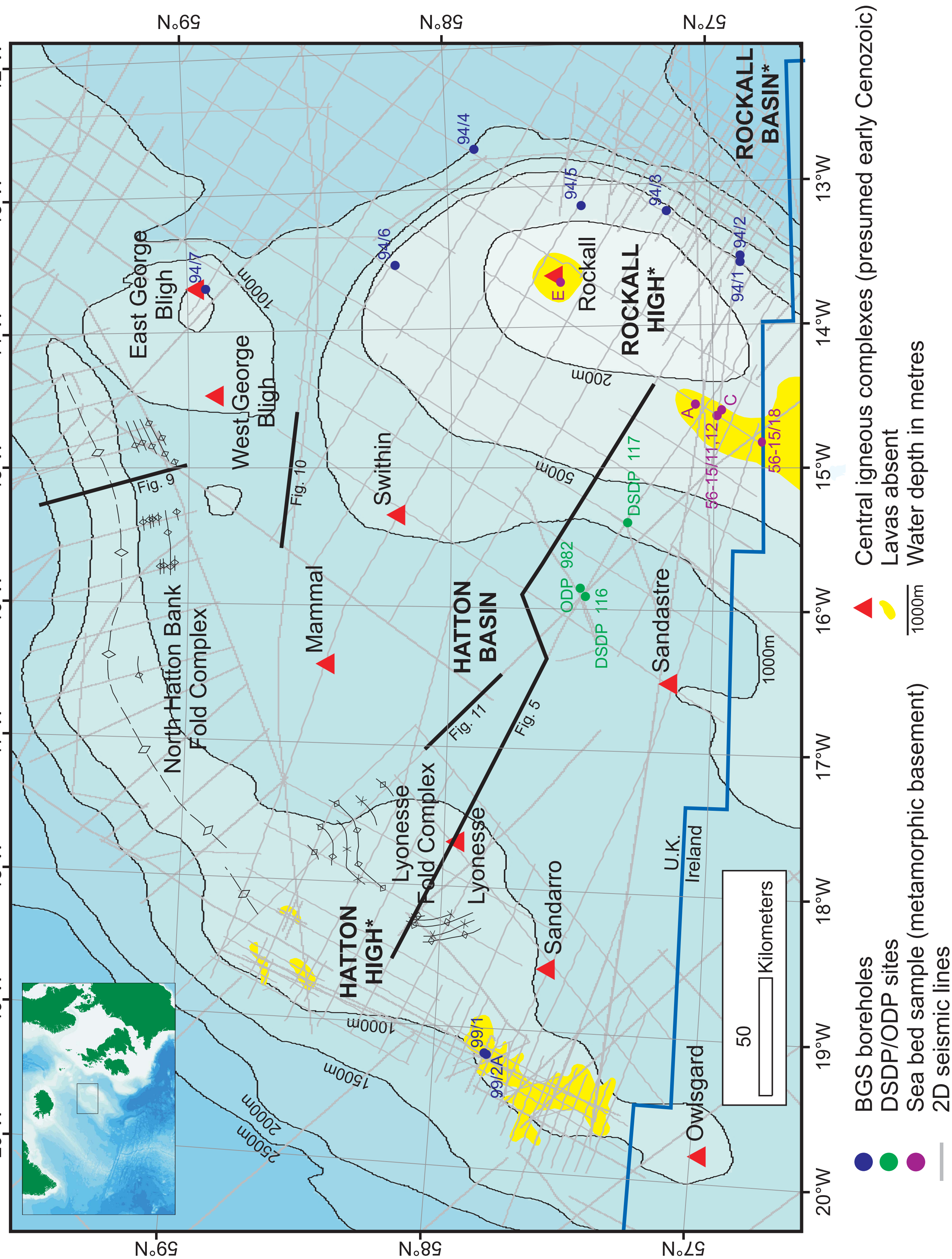
Mesozoic rift basins (main age of formation)

Mainly Permo-Triassic
Permo-Triassic and Jurassic
Mainly Jurassic
Jurassic and Cretaceous
Mainly Cretaceous

Figure 1

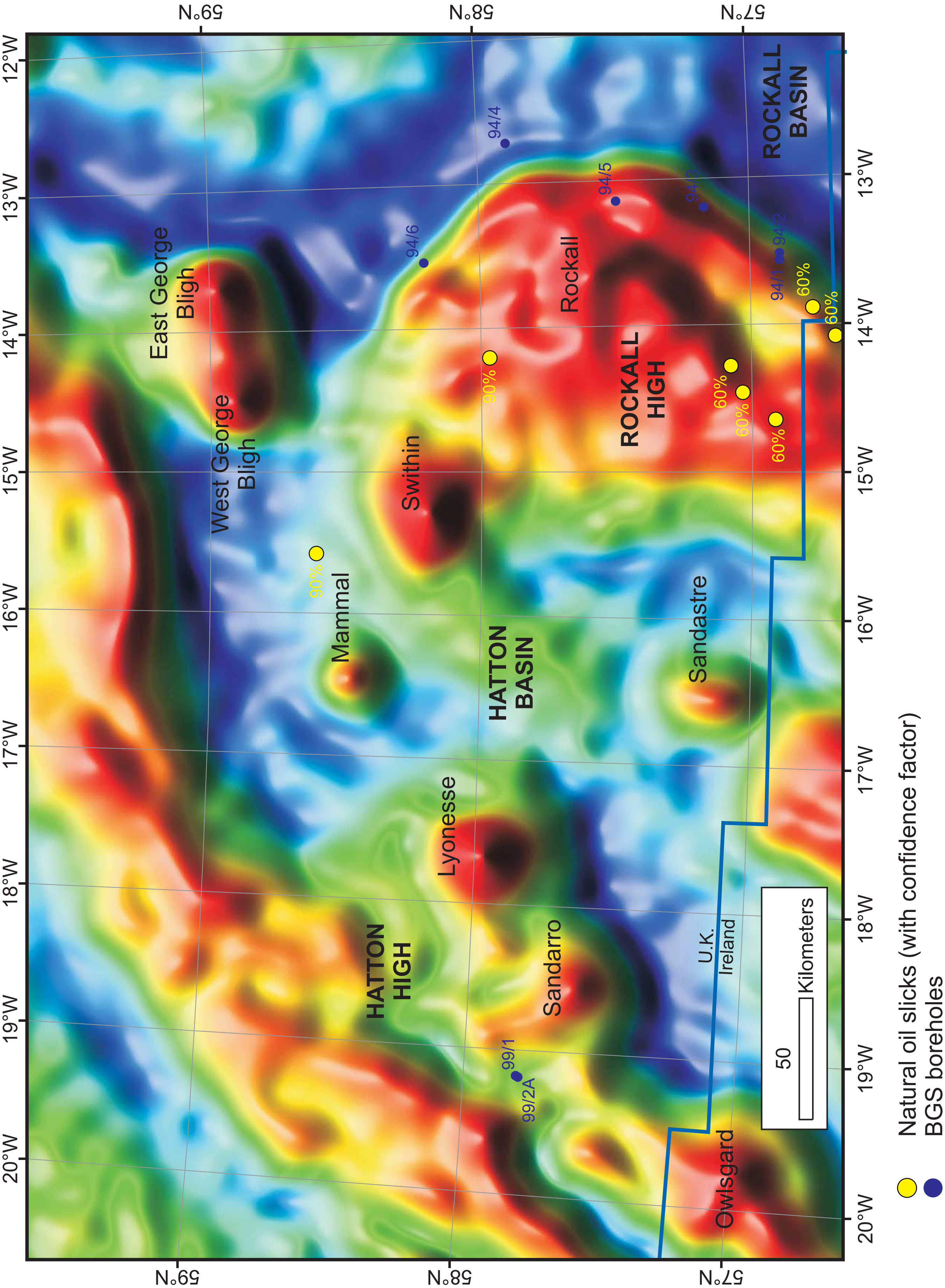


Greenland
Norwegian Basin
Imirger Basin
Iceland Basin
Fig. 3
Hatton Basin
UK
Europe
North Africa
North Atlantic Ocean
Labrador Basin
North America
Central Atlantic Ocean
500
Kilometers
50°N
40°N
30°N
90°W
80°W
70°W
60°W
50°W
40°W
30°W
20°W
10°W
0°
10°E
20°E
30°E



12°W
13°W
14°W
15°W
16°W
17°W
18°W
19°W
20°W
59°N
58°N
57°N
East George Bligh
West George Bligh
North Hatton Bank Fold Complex
Lyonesse Fold Complex
Lyonesse
Mammal
Swithin
HATTON BASIN
HATTON HIGH*
ROCKALL HIGH*
ROCKALL BASIN*
Rockall
Sandastre
Sandarro
Owlsgard
U.K.
Ireland
Fig. 5
Fig. 9
Fig. 10
Fig. 11
94/1
94/2
94/3
94/4
94/5
94/6
94/7
99/1
99/2A
ODP 982
DSDP 116
DSDP 117
56-15/11,12
56-15/18
A
C
E
200m
500m
1000m
1500m
2000m
2500m
50
Kilometers
BGS boreholes
DSDP/ODP sites
Sea bed sample (metamorphic basement)
2D seismic lines
Central igneous complexes (presumed early Cenozoic)
Lavas absent
Water depth in metres

Figure 3



12°W
13°W
14°W
15°W
16°W
17°W
18°W
19°W
20°W
59°N
58°N
57°N
East George Bligh
West George Bligh
Swithin
Mammal
HATTON BASIN
Lyonesse
HATTON HIGH
Sandarro
Owlsgard
Sandastre
U.K.
Ireland
Rockall
ROCKALL HIGH
ROCKALL BASIN
94/1
94/2
94/3
94/4
94/5
94/6
99/1
99/2A
90%
60%
50
Kilometers
Natural oil slicks (with confidence factor)
BGS boreholes

Figure 4

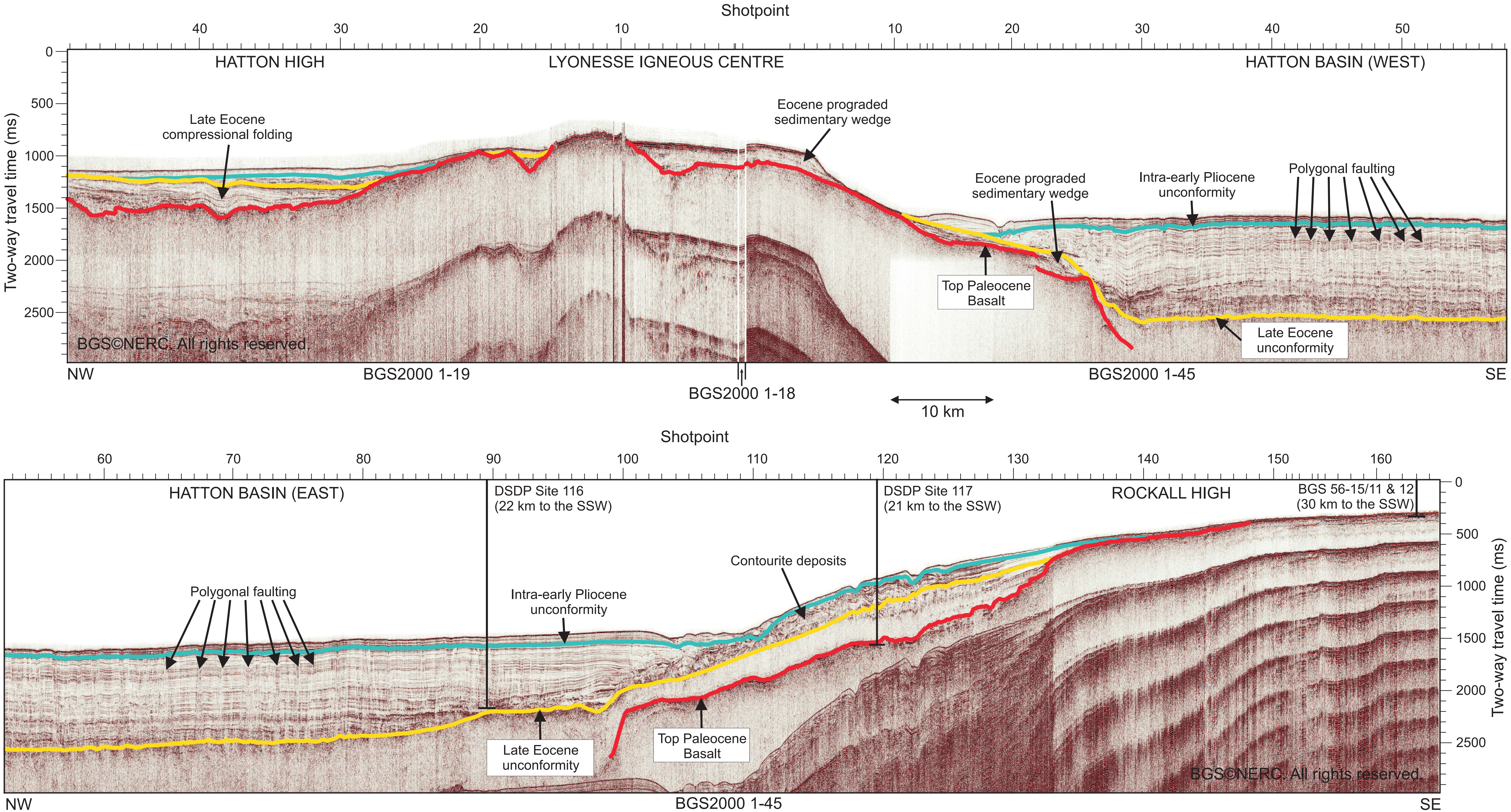
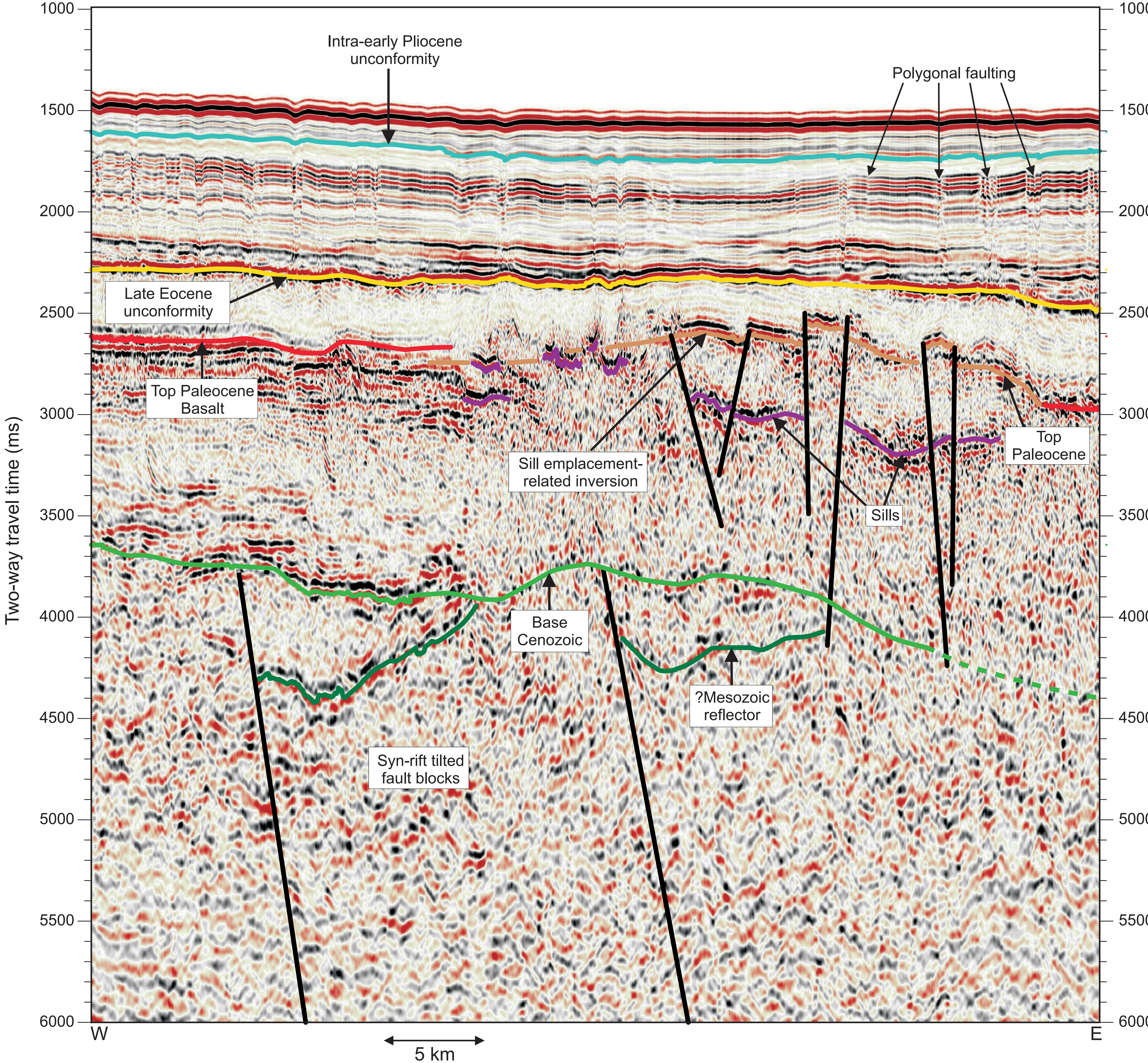

Shotpoint
40
30
20
10
10
20
30
40
50
Two-way travel time (ms)
0
500
1000
1500
2000
2500
HATTON HIGH
LYONESSE IGNEOUS CENTRE
HATTON BASIN (WEST)
Late Eocene compressional folding
Eocene prograded sedimentary wedge
Eocene prograded sedimentary wedge
Intra-early Pliocene unconformity
Polygonal faulting
Top Paleocene Basalt
Late Eocene unconformity
BGS©NERC. All rights reserved.
NW
BGS2000 1-19
BGS2000 1-18
BGS2000 1-45
SE
10 km
Shotpoint
60
70
80
90
100
110
120
130
140
150
160
HATTON BASIN (EAST)
DSDP Site 116 (22 km to the SSW)
DSDP Site 117 (21 km to the SSW)
ROCKALL HIGH
BGS 56-15/11 & 12 (30 km to the SSW)
Contourite deposits
Polygonal faulting
Intra-early Pliocene unconformity
Late Eocene unconformity
Top Paleocene Basalt
BGS©NERC. All rights reserved.
NW
BGS2000 1-45
SE
Two-way travel time (ms)
0
500
1000
1500
2000
2500

Figure 5



Intra-early Pliocene unconformity
Polygonal faulting
Late Eocene unconformity
Top Paleocene Basalt
Sill emplacement-related inversion
Sills
Top Paleocene
Base Cenozoic
?Mesozoic reflector
Syn-rift tilted fault blocks
Two-way travel time (ms)
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
W
E
5 km

Figure 6

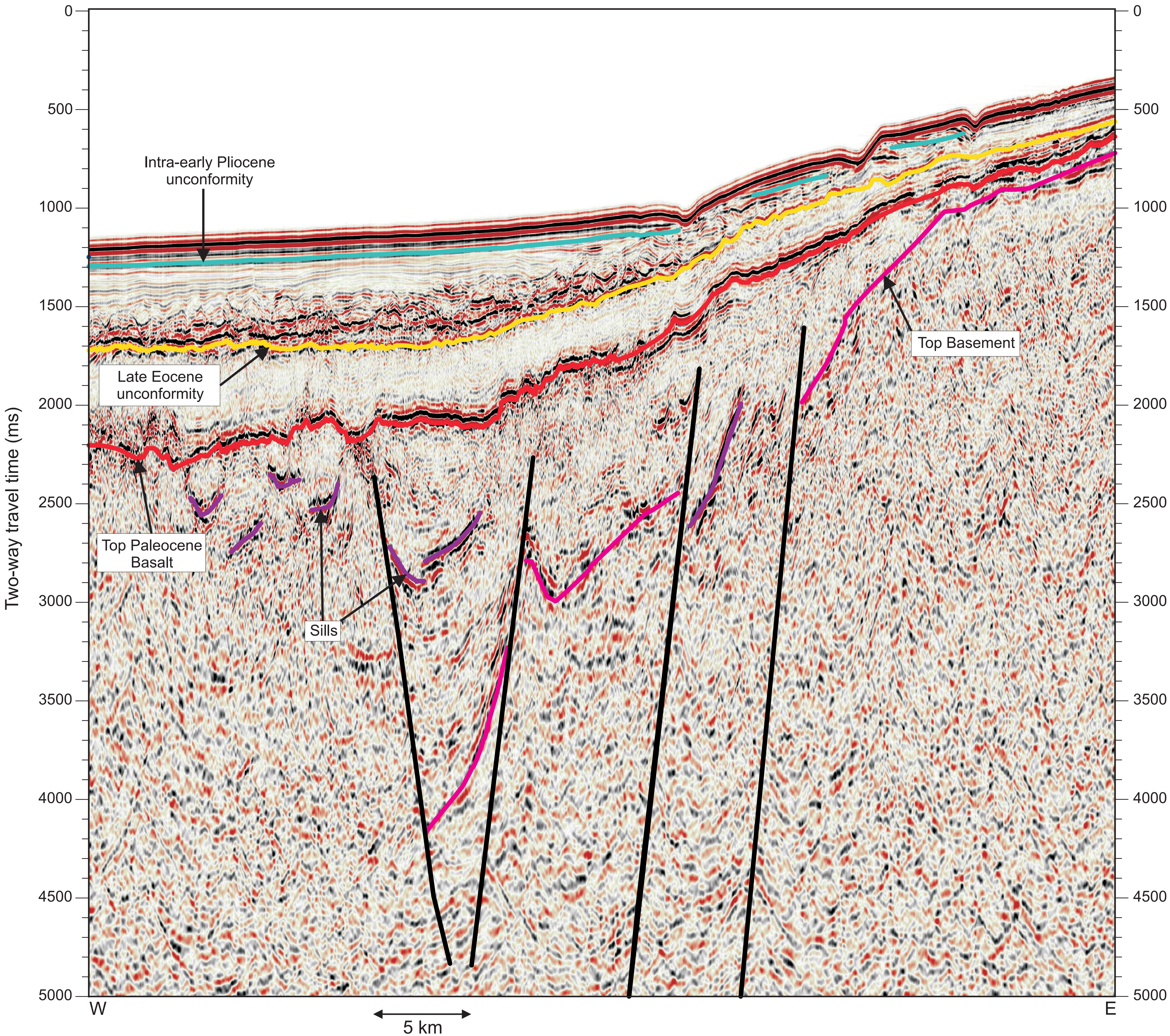

Intra-early Pliocene unconformity
Late Eocene unconformity
Top Paleocene Basalt
Sills
Top Basement
Two-way travel time (ms)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
W
E
5 km

Figure 7

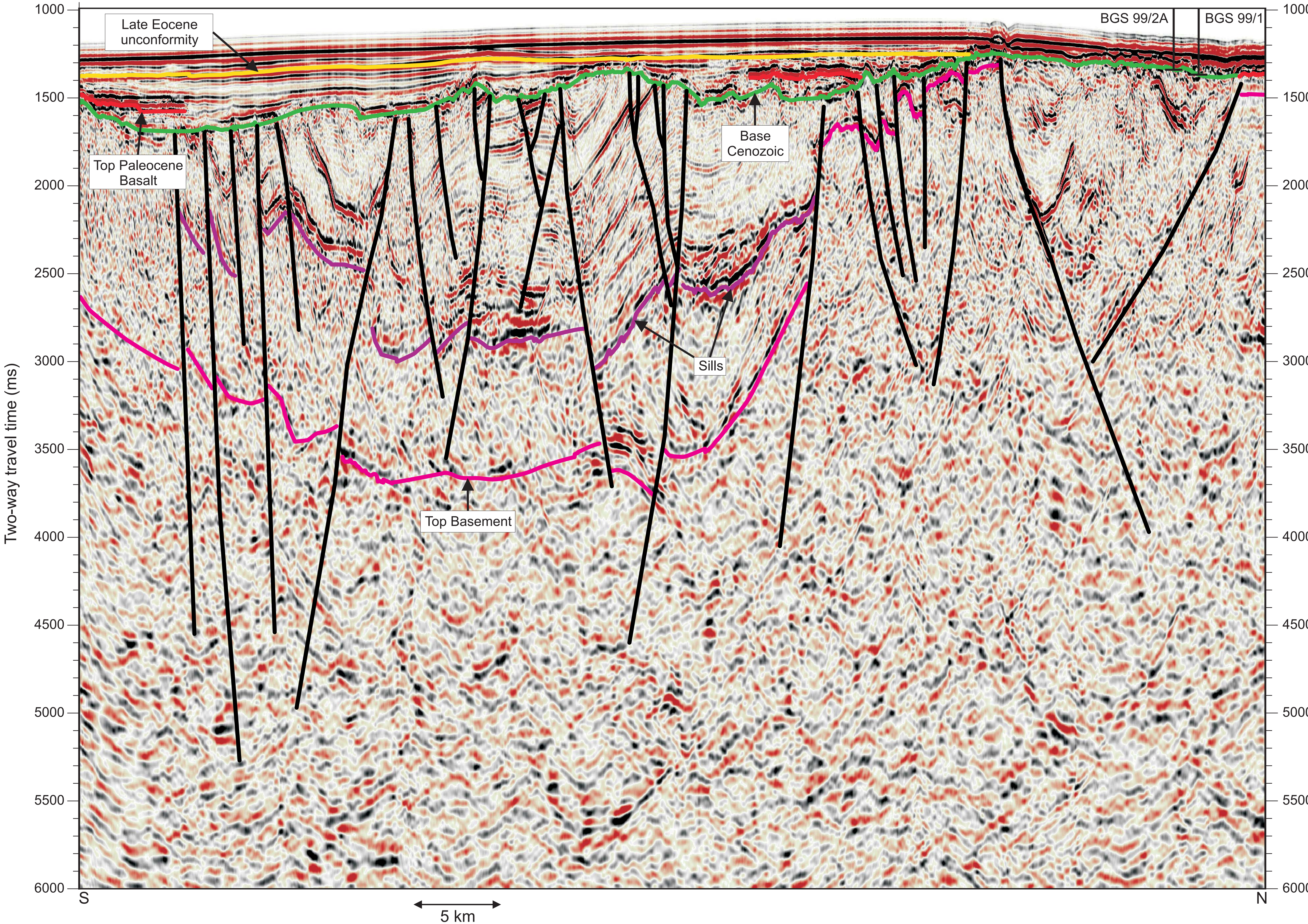
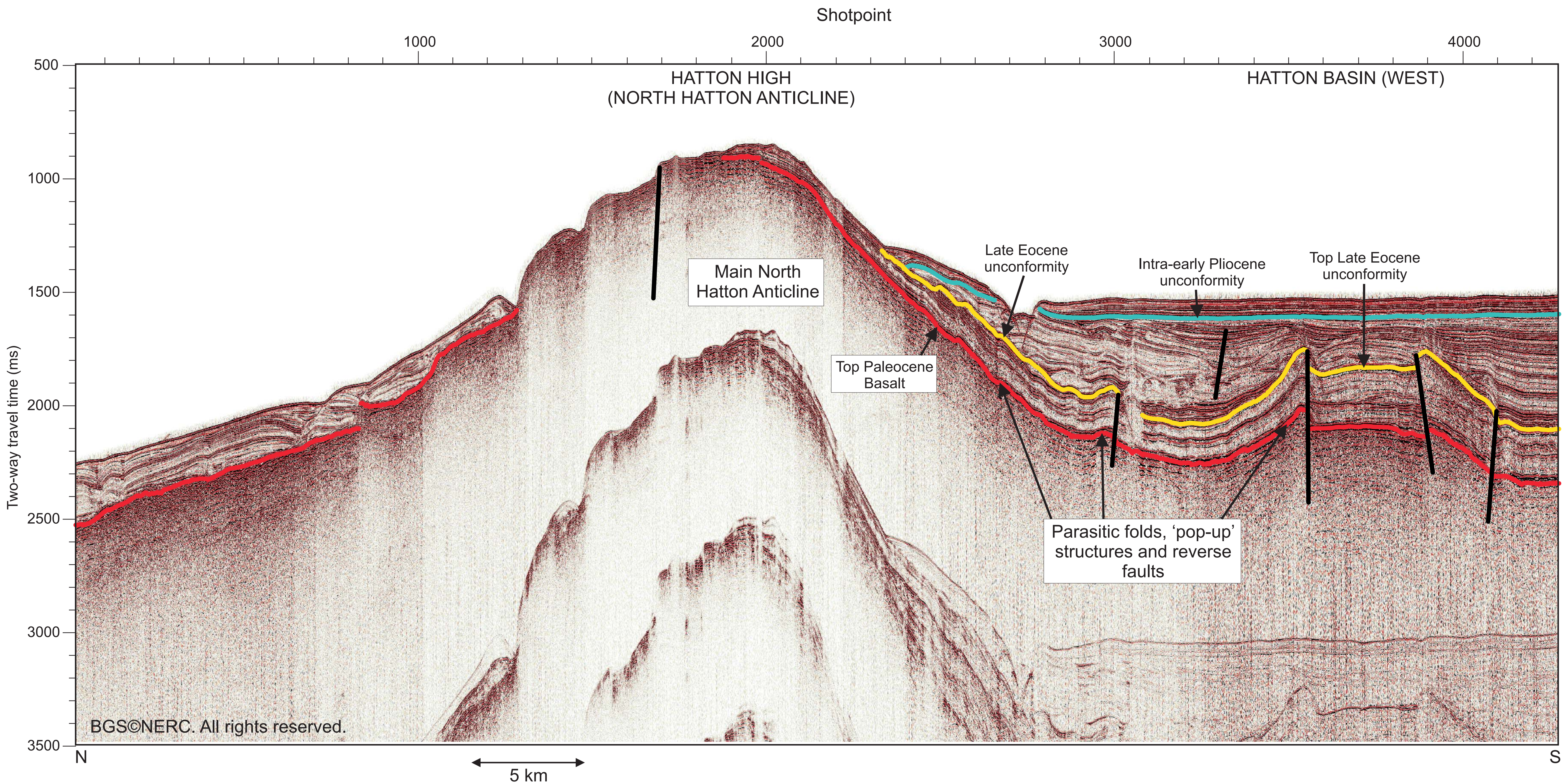
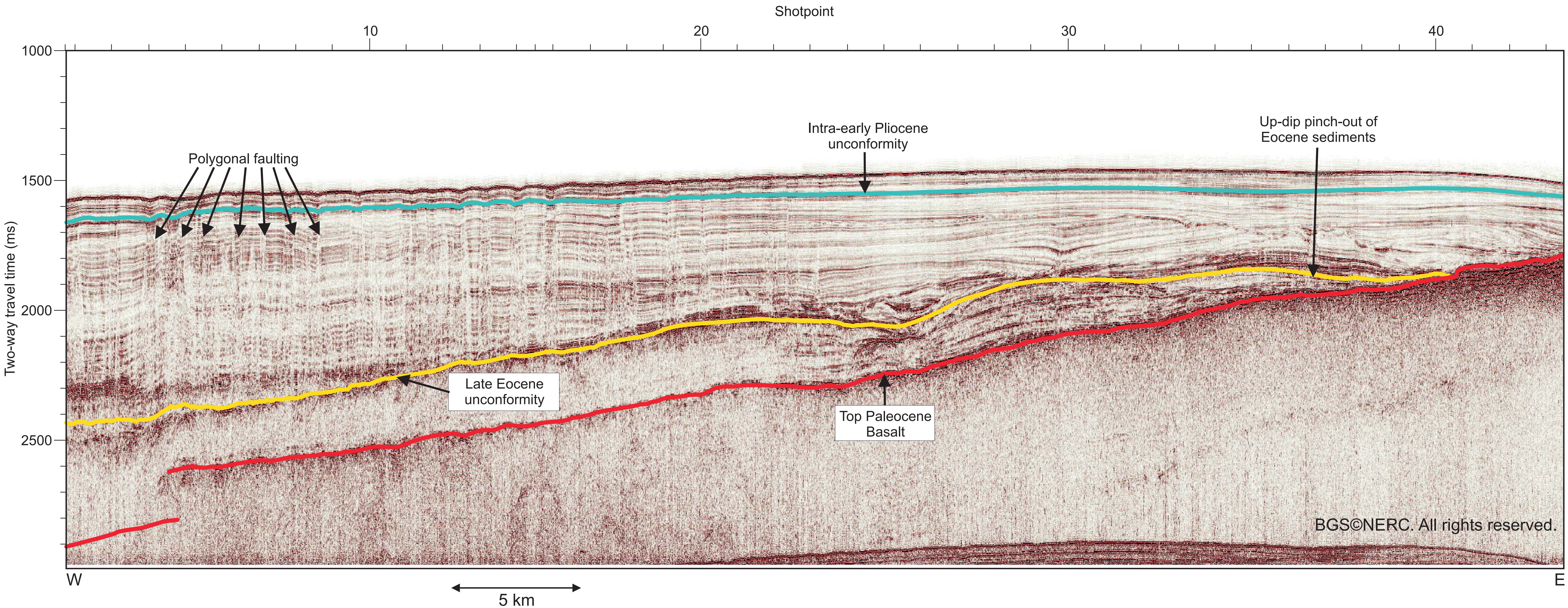

Late Eocene unconformity
Top Paleocene Basalt
Base Cenozoic
Sills
Top Basement
BGS 99/2A
BGS 99/1
Two-way travel time (ms)
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
S
N
5 km

Figure 8



Shotpoint
1000
2000
3000
4000
500
1000
1500
2000
2500
3000
3500
Two-way travel time (ms)
HATTON HIGH
(NORTH HATTON ANTICLINE)
HATTON BASIN (WEST)
Main North
Hatton Anticline
Late Eocene
unconformity
Intra-early Pliocene
unconformity
Top Late Eocene
unconformity
Top Paleocene
Basalt
Parasitic folds, 'pop-up'
structures and reverse
faults
BGS©NERC. All rights reserved.
N
S
5 km

Figure 9



Shotpoint
10
20
30
40
1000
1500
2000
2500
Two-way travel time (ms)
Polygonal faulting
Intra-early Pliocene unconformity
Up-dip pinch-out of Eocene sediments
Late Eocene unconformity
Top Paleocene Basalt
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W
E
5 km

Figure 10

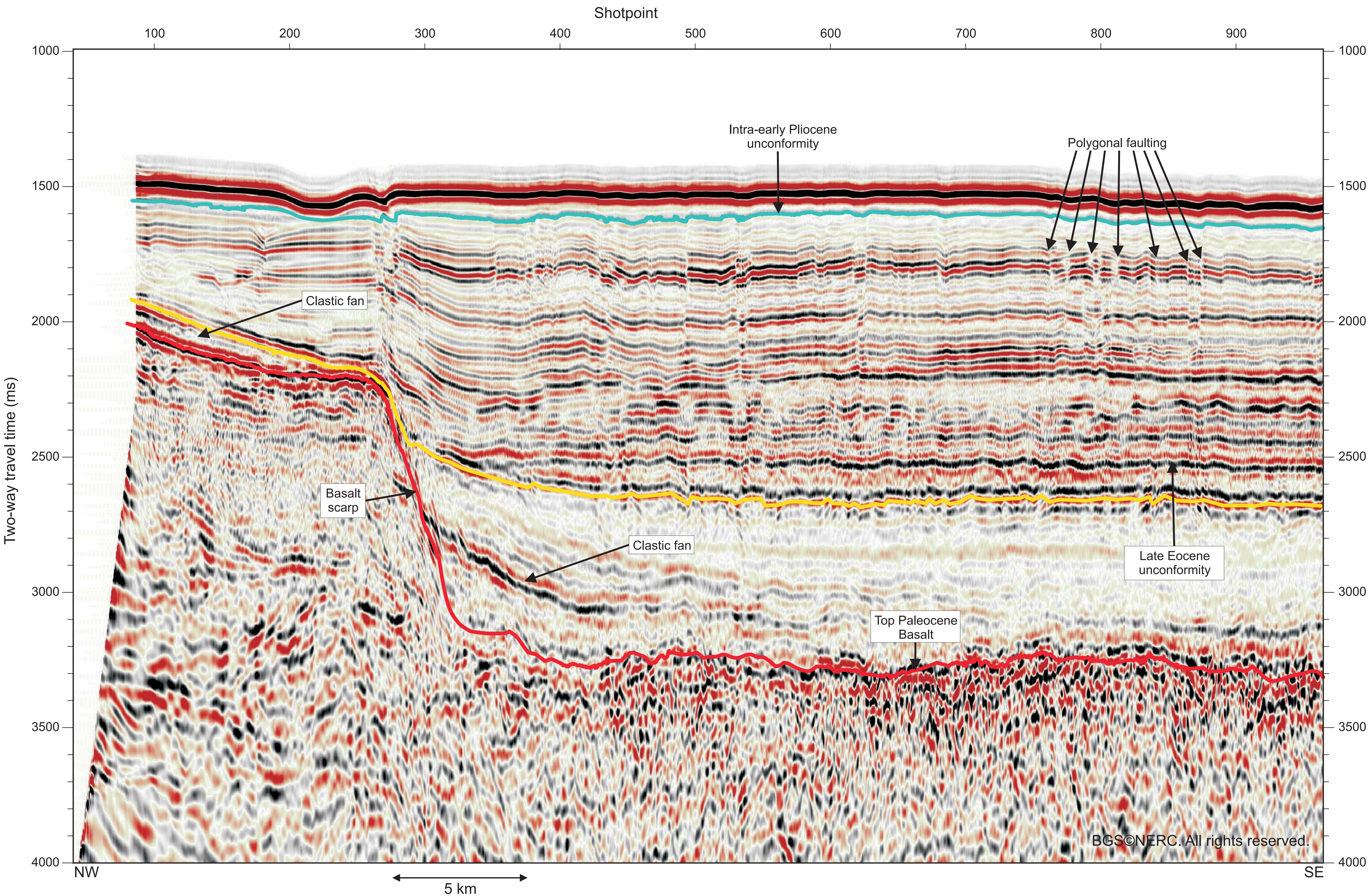
Shotpoint
100
200
300
400
500
600
700
800
900
1000
1500
2000
2500
3000
3500
4000
Two-way travel time (ms)
Intra-early Pliocene unconformity
Polygonal faulting
Clastic fan
Basalt scarp
Clastic fan
Late Eocene unconformity
Top Paleocene Basalt
NW
SE
5 km
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Figure 11