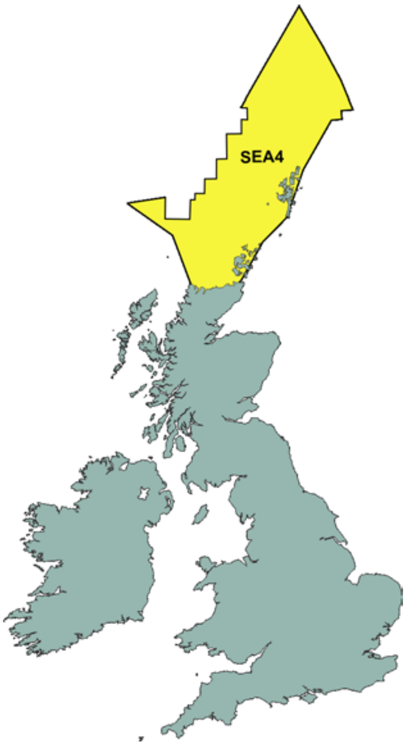
DTI Strategic Environmental Assessment Area 4 (SEA4):

SUB-SEABED GEOLOGY

Continental Shelf & Margins Programme

Commercial Report CR/03/080



BRITISH GEOLOGICAL SURVEY

COMMERCIAL REPORT CR/03/080

DTI Strategic Environmental Assessment Area 4 (SEA4):

SUB-SEABED GEOLOGY

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Key words

Geology, hydrocarbons, seismicity

Front cover

DTI SEA4 area of study

Bibliographical reference

HITCHEN, K., HOLMES, R., MUSSON, R.M.W., COOPER, R. M. and JONES S.M. 2003 . DTI strategic Environmental Assessment Area 4 (SEA4): Subseabed geology . *British Geological Survey Commercial Report* CR/03/080.

Edinburgh, British Geological Survey, 2003

Foreword

This report is the product of a desk study by the British Geological Survey (BGS) in response to a contract from Geotek Ltd to report on the subseabed geology of the Department of Trade and Industry Strategic Environmental Assessment area 4 (SEA4) which includes the UK Continental Shelf and Slope.

This report has been produced separately from two other reports have been produced under the same contract for SEA 4:

1. BGS report CR/03/081 Continental shelf seabed geology and processes
2. BGS report CR/03/081 Geological evolution Pilot Whale Diapirs and synergy with the seabed habitat.

Acknowledgements

Funding for this programme of research was managed by Geotek Ltd and funded by the Department of Trade and Industry.

Contents

Summary

The SEA 4 region is underlain by continental crust situated on the north-western part of the Eurasian tectonic plate. The oldest continental crust >590Ma (Pre-Cambrian) of interest to oil production, it is divided by a major fault, the Moine Thrust, into ages ranging in age from >2500Ma (Archaean) to the west in which potentially commercial hydrocarbons been discovered and 2500 - 590 Ma (Proterozoic) to the east which is not currently prospective for commercially-produced hydrocarbons.

The <590Ma sedimentary basins and intervening highs have evolved from pre-, syn- and post-depositional responses to deformation during crustal compression and extension. Many of the modern regional crustal structures retain a NE-SW trend, inherited from events 440-410Ma year ago (Caledonian Orogeny). The results from <65Ma regional NW-SE trending deformation events are also included within the major basin structural configurations.

During 60-50 Ma (Late Paleocene to Early Eocene) the region was affected by uplift and in the NW by extrusion of thick volcanic lavas and intrusion of igneous sills. Interactions between historically significant shifts of long-term global climate cooling, an increase in the short-term periodicity and intensity of global climate change and changes to the rates and orientation of crust deformation have been particularly important from 25Ma to the present day (Neogene to Quaternary). These interactions have driven global-to-local changes to basin geological structure, marine circulation, sea level and sediment supply and removal rates and have resulted in the evolutionary changes to submarine basin geometries and lithologies. The modern seabed habitat has thus resulted from the remoulding of inherited basin geometries and lithologies by the processes affecting seabed.

The structural history of the region has created a wide variety of potential hydrocarbon trapping mechanisms. The 154-136Ma (Late Jurassic, Kimmeridgian to Ryazanian) Kimmeridge Clay Formation is the principal source rock of the area. The Foinaven and Schiehallion oilfields started production in late 1997 and 1998 respectively both from 60-55Ma (Upper Paleocene) sandstone reservoirs. Geological and technical problems have so far prevented the development of the massive 440-390Ma (Devono-Carboniferous) Clair Field which is the largest undeveloped oilfield on the UK continental shelf. Other hydrocarbon accumulations have been discovered in 245-208Ma (Triassic), 208-146Ma (Jurassic) and 146-65Ma (Cretaceous) intervals in the West Shetland area in the most prospective parts of the SEA 4 region.

1 Regional setting

The SEA 4 region is situated on the north-western part of the Eurasian tectonic plate (which extends out to the Mid Atlantic Ridge) and is underpinned by continental crust. The continent-ocean crustal boundary is aligned NE-SW and is situated to the north-west of the Faroe Islands. This boundary developed at about 55Ma (end Paleocene) as the North American plate separated from the Eurasian plate.

The thickness of the crust varies across the SEA 4 region. Beneath the Orkney-Shetland Platform and the Faroe Islands it is of 'normal' thickness (in the order of 30km). However, midway between these locations the crust is highly extended and thinned with the thickness reduced to between 18 and 22km. This thinner crust is approximately coincident with the NE-SW orientated Faroe-Shetland Basin.

The most important intra-plate rifting (crustal thinning) event occurred during the mid Cretaceous although subsequent, less severe rifting also episodically affected the region through the Late Cretaceous and during the Paleocene (Dean *et al*. 1999). There is also evidence for earlier extensional phases in the Permian and mid Jurassic.

2 Geological history

During the late Silurian Caledonian Orogeny (440-410Ma), mid Proterozoic (approximately 1500-900Ma) Moinian psammites and pelitic schists, which comprised the orthotectonic mobile belt, were thrust north-westwards over the quartzo-feldspathic gneisses, ultrabasic to acid intrusives and metasediments of the Archaean (older than 2500Ma) Lewisian complex which formed the foreland to the orogeny (ages are based on the timescale of Harland *et al*. 1990). On the mainland in north-west Scotland the Lewisian also has a 'cover' sequence of thick, predominantly fluvial, Torridonian (900-570Ma) sandstones and conglomerates and a much thinner shallow marine Lower Cambrian (570-536Ma) and Lower Ordovician (510-475Ma) quartzites and carbonates (Stoker *et al*. 1993) but their offshore occurrence remains unproven.

Onshore the boundary between the foreland and the mobile belt is the Moine Thrust. Its offshore continuation has been traced north-eastwards (Ritchie *et al*. 1987) such that the NW of the SEA 4 region is underlain by Lewisian whereas the SE of SEA 4 is underlain by Moinian. Examples of both groups have been recovered in commercial wells, BGS boreholes and sea-bed samples. However the Caledonian Front, which supposedly separates the undeformed foreland from the orthotectonic mobile belt, may be west of the offshore Moine Thrust as intra-foreland thrusts (e.g. the Outer Isles Thrust) have been identified from deep seismic data (Brewer and Smythe 1984). The NE-SW structural grain of the Caledonian Orogeny has massively influenced all subsequent tectonic processes in the region including the present orientation of the Faroe-Shetland Channel.

Following the Caledonian Orogeny, local extension or strike-slip tectonism allowed mainly mid-late Devonian (388-362Ma) depocentres to develop, notably in the West Orkney Basin (where former thrusts were reactivated as normal faults) and mainly Middle to Upper Devonian alluvial, fluvial and lacustrine sediments were deposited. In the Clair Basin similar Devonian lithologies are overlain by marine Viséan (348-333Ma) sediments but it is likely that during the Carboniferous most of the SEA 4 region remained an upland area supplying sediments southwards.

Early Permian (290-256Ma) extension and rifting created large and geographically widespread basins which exhibit wedge-shaped packages of sediments dipping into the bounding syn-sedimentary faults (Kirton and Hitchen 1987). The basins dip eastwards in the north of the SEA 4 region but westwards in the south indicating the existence of a major transfer fault cutting the area at this time. Three wells in the region have proved Lower Permian lavas indicating syn-tectonic volcanism at this time. The Late Permian may have been more quiescent as evaporitic units have been drilled at various locations. Red bed deposition continued into the Triassic (245-208Ma). The westernmost half-graben of the West Orkney Basin may contain in excess of 7km of Permo-Triassic sediments (Hitchen *et al.* 1995). Owing to their depth of burial, Permo-Triassic rocks are almost certainly more widely spread across the region than currently proved by exploration drilling.

A connection between the Arctic and Tethys seas (through the Shetland - Faroe Islands gap) may have been established for the first time during the Early Jurassic (Ziegler 1988). However mid Jurassic uplift and erosion removed most Lower Jurassic sediments and caused deposition of mainly shallow marine sandstones. A narrow epicontinental seaway was probably maintained. During the Late Jurassic fault activity declined and coarse-grained sediments are restricted to areas adjacent to existing highs such as the Rona Ridge. Basinal subsidence and rising sea levels led to the deposition of fine-grained clastic sediments which onlapped much of the underlying geology. Restricted circulation during the Kimmeridgian to Ryazanian (154-141Ma) allowed anoxic black shales to accumulate – the major hydrocarbon source sediment for the present day oilfields.

The mid Cretaceous (Aptian-Albian., 124-97Ma) marks the culmination of the major rift event in the SEA 4 region between Shetland and the Faroe Islands. This caused the crust beneath the Faroe-Shetland Basin to be thinned and the margins of the rift zone to be uplifted shedding relatively coarse-grained sandstones and conglomerates into the adjacent West Shetland, Faroe-Shetland and Rona Basins. Some of the structural highs may have been emergent at this time. During the Late Cretaceous active rifting largely ceased and sea level rose. Basins became starved of coarse clastic input and instead collected extensive shale-dominated sequences, with thin limestones and dolomites. By Maastrichtian times (74-65Ma) most of the SEA 4 region was a warm, shallow sea with little or no land.

Differential subsidence and minor faulting associated with the intra-basinal highs in the Faroe-Shetland Basin resulted in over 3000m of mostly Upper Paleocene (60.5-56.5Ma) sandstones and shales accumulating in the Flett sub-basin (Hitchen and Ritchie 1987, Mudge and Rashid 1987). This depocentre is offset to the south-east from the underlying area of maximum Cretaceous thickness. Some of the sandstones are gas-bearing whereas others contain producing oilfields (see below). Towards the end of the Paleocene and into the Eocene (57-54Ma) the whole region was affected by the Iceland plume and continental break-up NW of the Faroe Islands. Massive volcanism resulted in lavas being extruded over much of the north and west of the SEA 4 region. Several central igneous centres and numerous smaller intrusive bodies were emplaced and magma was underplated on the base of the crust enhancing the thermal uplift effect (Ritchie *et al.* 1999). Consequently much of the area became emergent and large volumes of sediment were removed from the Orkney-Shetland platform area.

The initiation of sea-floor spreading to the NW of the Faroe Islands at the end of the Paleocene placed the SEA 4 region in a compressive buffer zone between the spreading axis to the west and the Africa-Europe convergence zone to the south-east (Knott *et al.* 1993) thus making it susceptible to subtle changes in plate movement and rates of spreading which in turn affect uplift/subsidence and water circulation patterns (Stoker *et al.* 2002).

During the Early Eocene rifting and volcanism waned. Under the influence of passive thermal subsidence shallow water sandstones and lignites were succeeded by finer-grained siltstones and shales of the Middle and Upper Eocene (50-35Ma) as fully marine conditions became re-established. Wells in the southern Møre Basin have proved the Eocene succession here to be hundreds of metres thick. At the end of the Eocene (35Ma), a minor plate reorganisation caused a vigorous bottom-current circulation to develop which caused erosion over a wide area and an angular unconformity with the overlying Oligocene successions which are relatively thin in the SEA 4 region.

During the early Miocene, the distant effects of the Alpine Orogeny (20-16Ma) caused renewed intra-plate stresses in the region. Subsequently, in the mid-Miocene (16-10Ma), the Wyville-Thomson Ridge became submerged and an existing exchange of water between the Norwegian Sea and the northern Rockall Trough was further enhanced. The Late Oligocene to Early Miocene Unconformity (‘LOEMU’) was created at this time. In the Faroe-Shetland Basin the Miocene thickness, which ranges from 50 to 400m, appears to be constrained by former current strengths and palaeo water depths with the thickest preserved succession in a mid slope setting in the north-east. Sediments on the shelf are shallow-water glauconitic sandstones whereas sediment drifts dominate the slope. The early Pliocene saw a regional uplift of the Atlantic margin resulting in the Intra-Neogene Unconformity (‘INU’) in the Faroe-Shetland Basin. This marks the onset of shelf-margin progradation that produced a Pliocene to Holocene lowstand prograding wedge in an outer shelf to mid slope setting. The wedge, which ultimately migrated the shelf break 40km seawards, contains the Glacial Unconformity (‘GU’) which separates interdigitating downslope/alongslope sediments from overlying mud-prone glacigenic sediments. The latter mark the onset of widespread glaciation on the West Shetland margin (Stoker *et al.* 2002). The nature of the West Shetland margin during the Neogene to Holocene, with its various unconformities developed by uplift and erosive bottom currents, means that in places the LOEMU, INU and GU unconformities are composite surfaces.

Post-glacial Holocene sediments form a widespread veneer across the SEA 4 region largely recording the effects of reworking during the early post-glacial marine transgression of the shelves. Since this rise in sea level the shelves have been starved of sediment but in the deeper-water areas the change from glacial to interglacial conditions appears to have corresponded with fluctuations in bottom-current velocity resulting in erosion and resedimentation of the slope and basin-plain deposits.

3 Petroleum Geology

The first well in the region (206/12-1) was spudded in 1972 but drilling activity has always continued at a low level here compared to the North Sea. This is due to a combination of factors including the deep water, complex geology (with added complications due to the early Palaeogene volcanism), lack of offshore infrastructure, and the short Summer weather window.

The organic-rich Kimmeridgian to Ryazanian Kimmeridge Clay Formation is the principal source rock in the SEA 4 region. TOC values up to 11.2% have been recorded in the south-western end of the West Shetland Basin. Other Jurassic, Cretaceous and Cenozoic shales generally lack sufficient organic content of the right type or are immature. There is a wide variety of potential trapping mechanisms and stratigraphic seals. However the timing of source rock maturation, and particularly hydrocarbon migration, is not well understood due to the effects of the Palaeogene volcanism and Cenozoic uplift events.

A small number of fields, and significant other discoveries, has been made in the region and these are described below. They are all to the west or north-west of Shetland. Nothing of significance has yet been discovered north of 62°N or west of Orkney. It is unlikely that hydrocarbons will be discovered in the extreme north of the SEA 4 region until techniques are developed to improve seismic resolution beneath the Palaeogene lavas.

The Clair oilfield was discovered in 1977 by well 206/8-1A (Coney *et al.* 1993) and it is the largest oilfield under development on the UK continental shelf with possible reserves up to 4.0 x 10^9 barrels. The principal reservoir comprises Devono-Carboniferous continental clastics, with very variable facies types, but oil also occurs in fractures within the underlying Lewisian metamorphic basement. The oil is heavy, at a shallow structural level and contained in a complex series of irregular fault blocks on the crest of the Rona Ridge. Appraisal drilling (including the sub-horizontal well 206/7a-2), well stimulation tests, a 3D seismic survey and computer modelling have resulted in a Phase I development plan whereby an estimated 2.5 x 10^6 barrels of oil will be recovered from the central area of the field with first production in late 2004.

The Foinaven oilfield, discovered by well 204/24a-2 in 1992, was the first deep-water discovery west of Shetland and the first field from the region to be developed. The reservoir is Upper Paleocene deep-water sandstones which are segmented in a broad, faulted anticline above the Westray Ridge within the Faroe-Shetland Basin (Lamers and Carmichael 1999). Production started in late 1997 and recoverable reserves are estimated at 200 x 10^6 barrels. Development has been by subsea wells to manifolds at two drilling centres. Thereafter the oil reaches the surface through rigid flowlines and flexible risers to a floating production, storage and offloading vessel (FPSO) permanently stationed above the field (Cooper *et al.* 1999).

The adjacent Schiehallion and Loyal oilfields (the ‘Schiehallion development’) were discovered in late 1993 (well 204/20-1) and late 1994 (well 204/20-3) respectively. The reservoir is Upper Paleocene turbiditic, channelized submarine slope sands. Both fields are segmented by faults which, combined with up-dip pinch-out of the reservoir and structural closure, define the limits of the field. Development drilling began in 1996 and production commenced in 1998. It is estimated that 425 x 10^6 barrels will be recoverable using a FPSO facility (Leach *et al*. 1999).

Other hydrocarbon fields, for which there are no immediate development plans, have also been discovered in the SEA 4 region. The Triassic Strathmore field was discovered by well 205/26a-3 in 1990 and the partially overlapping Jurassic Solan field by well 205/26a-4 in 1991. These fields are unlikely to be commercially viable unless better flow rates can be achieved from the low-permeability Otter Bank Sandstone reservoir of the Strathmore field in order to recover a higher proportion of the 200 x10^6 barrels of oil in place (Herries *et al*. 1999). The Victory gas field, discovered by well 207/1-3 in 1977, occurs in Aptian-Albian, shallow to marginal marine, high-quality reservoir sandstones originally deposited as fan-deltas but subsequently reworked into transgressive shoreface deposits. The sandstones are currently within a tilted fault block structure on the Rona Ridge. The field contains an estimated 250-350 x 10^9 SCF gas in place (Goodchild *et al*. 1999).

4 Seismicity

Understanding the seismicity of an offshore area is harder than dealing with onshore areas because of the practical limitations on the availability of data. This is particularly the case in an area like the British Isles, where, for assessment of seismic hazard, the dependence is on good historical records to counterbalance the inherently low rate of earthquake occurrence and few data for analysis. In the case of the SEA 4 region this is complicated by the inherently low seismicity of the area. The number of known earthquakes in SEA 4 is 25, over an area of more than 90,000 sq km, and the largest is only 3.1 ML in size.

4.1 CONSTRAINTS ON SEISMICITY DATA

In a region with apparently no earthquakes the question is whether the absence is due to lack of earthquakes, no research or lack of resolution. A case in point is the Faroe Islands where a few years ago no information existed on historical seismicity because the subject had not been studied. A joint project involving the British Geological Survey and the Faroese Natural History Museum initiated a search of historical materials to look for reports of Faroese earthquakes and proved that that absence of earthquakes in the Faroes is real (Musson et al., 2001).

The SEA 4 region is divided into two: a small area in the south and south-east including the coasts of Sutherland, the Orkneys, Shetland and the remaining offshore area.

Considering the offshore area first, the detection of historical earthquakes is unlikely. A magnitude 5.5 ML earthquake occurring in the northern part of the area would probably (assuming average UK attenuation) be felt weakly over the Shetlands and Faroes at intensity 3 EMS (European Macroseismic Scale) and be almost imperceptible elsewhere (intensity 2 EMS in the Orkneys, N Scotland and W Norway). Thus the documentation for such an earthquake, if any existed at all, would most likely consist of one or two descriptions of weak shaking in Shetland, which one might well interpret as a small local event rather than a relatively large earthquake at some distance. There are a small number of such reports from Shetland in the latter part of the 19th century, mostly from lighthouses. It is impossible to make any locations from such reports as they may also be due to earthquakes occurring in the Viking Graben area of the northern North Sea.

Instrumental data are identified with similar problems. Prior to the 1970s, instrumental monitoring of earthquakes largely consisted of a few stations equipped with instruments whose primary purpose was to record large earthquakes occurring worldwide. The closest station to SEA 4 was the one at Edinburgh, 300 km from the closest point of SEA 4 and 850 km away from the furthest point.

Two benchmarks can be cited. The Inverness earthquake of 1901, which had an estimated magnitude of 5.0 ML based on macro-seismic data was not recorded by the instrument then operating at Edinburgh; nor anywhere else. The Viking Graben event of 1927 (5.7 ML) was recorded throughout Europe; the number and quality of instruments had improved significantly in the intervening 26 years. It is probably reasonable to suggest that any earthquake in SEA 4 exceeding 5.5 ML would have been detected in the period 1920-1970, and between 1900-1920 a magnitude 6.0 ML event would have been detected.

After 1970 a network of short-period seismometers ideal for recording British earthquakes was installed around Edinburgh and this was expanded throughout the 1980s and 1990s to cover the whole country, including the Shetlands and further north west in the Faroes. After 1970 it is likely that any event above 4.0 ML would have been detected within SEA 4. The present network is capable of locating any event in SEA 4 above 3.0 ML and at times of low background noise and in areas of favourable geometry relative to stations, earthquakes >2.0ML (Walker, 2002).

The same statistics apply to the coastal and nearshore areas of SEA 4, but there is better information about historical events. A study by Musson (1998) concluded that historical documentation for the Shetlands, Orkneys and E Sutherland/Caithness was surprisingly good, given the remoteness of the area, and that, by making comparison with records of other natural phenomena, it is likely that no earthquake was felt with intensity 6 EMS or higher as far back as 1600. Before 1600 data are insufficient for any speculation. The completeness of earthquakes producing only moderate intensities (4 or perhaps 5 EMS) is uncertain.

The earliest earthquake positively identified in the SEA 4 region was an event near Thurso in 1862 (2.5 ML). A Shetlands earthquake in 1755 that appears in some catalogues (Milne 1842-4, Davison 1924) is shown by Musson (1998) to be spurious. The historical record is thus demonstrably capable of preserving information on small events (~3 ML) after 1850. Continuous local newspaper publication in the area started in 1836. One conjecture is that the record should be complete for Shetland, Orkney and the N coast of Scotland for magnitude 4 ML and over after this date.

4.2 DISTRIBUTION OF SEISMICITY

The seismicity of the SEA 4 area and the region around it is shown in Figure 1. These data are drawn from the UK seismicity database and do not include a small earthquake sequence in the Faroes in 1967 (maximum magnitude 2.2 ML). The data are almost entirely derived from the post 1970 period, with the exception of small events on the N coast of Scotland in 1862 and 1887, and two events near Unst in 1886, which have been given notional epicentres just offshore (the spatial parameters of these events are highly uncertain).

Epicentres of the smallest earthquakes in the area (< 1.5 ML) are naturally confined to the near shore areas where the recording stations are located. Otherwise, the few events are more or less randomly distributed; a statistical test shows that the spatial distribution of epicentres for events > 1.5 ML within the bounds of SEA 4 is not significantly different from random. The only possible exception is that a few events in the extreme NE appear to be associated with the fringes of the high activity zone of the southern Møre Basin.

The largest recorded event is 3.1 ML in size. This event occurred on 17 January 1980 in the northern part of SEA 4. It can be taken for granted that, considering that this event was located on the basis of data recorded around the Scottish Lowlands, the position of the epicentre is very poorly constrained (>±10km).

A larger earthquake occurs just outside the boundary of SEA 4. This is the 9 February 1973 Fair Isle earthquake (3.4 ML), which can be considered to be the largest known regional event east of the Møre Basin-Viking Graben active area, and north of Caithness/Sutherland. The very limited felt information in the BGS archives comes only from Fair Isle itself, and suggests the intensity did not exceed 4 EMS (if that). None of the other instrumentally detected earthquakes within SEA 4 were reported as felt.

It is debatable how reliable it is to extrapolate from a small number of earthquakes recorded over a 30-year period to the recurrence times of larger events. Nevertheless, these are all the data available on which to base such estimates, and it is certainly the case that elsewhere in the UK 30-year rates are usually fairly representative of longer-term seismicity rates (with a few notable exceptions, such as SW Wales). If such an extrapolation is made the recurrence rate of seismicity within SEA 4 can be expressed as

$$\text{Log } N = 1.20 - 0.85\, M$$

where N is the cumulative number of events exceeding magnitude M (local magnitude, i.e. ML). From this one can infer that the return period of a magnitude 4.0 ML earthquake within SEA 4 is 163 years, or, taking estimates of uncertainty into account, between 79 and 336 years.

Estimates of focal depth for earthquakes in the region vary from approximately ≤5 to 15 km, and are certainly not likely to be very accurate. However, it is quite possible that some or all these events are occurring at depths below those shown in the geological profiles shown in Figure 2, and it would be unwise to match any of the epicentres with the geological structures illustrated on figures 1 and 2. Comparing the seismicity to the generalised geological structural framework shows that epicentres are evenly distributed between basement highs and basins and there is no correlation with basin margins.

This diffuse seismicity is typical of random reactivation of old weaknesses under the influence of the regional stress regime. Information about stress directions in this area is limited, but what data are available (from breakouts) suggest a NW-SE to N-S direction of maximum compressive stress (Reinecker et al 2003). If the direction is more N-S, the conditions would be suitable for reactivating the NW-SE trending transform features shown in Figure 1.

4.3 SEISMIC HAZARD

Given that the seismicity of the area is very low, inevitably the seismic hazard, expressed in terms of the probability of ground shaking, will also be low. Regional hazard maps for the UK offshore territory are presented in Musson et al (1997). These show that, within SEA 4, the expected peak ground acceleration with annual probability of 10^{-3} is less than 0.05 g, and the corresponding value for 10^{-4} annual probability is between 0.05 and 0.1 g. Although this study is more than ten years old (the publication date is misleading) these figures are still valid.

There remains to discuss the possibility of an unexpectedly large earthquake in the area. A study by Johnston et al (1994) sought to find common factors in the occurrence of large (>6) earthquakes in areas of low seismicity ("stable continental regions" or SCR). The conclusion of the study was that large SCR earthquakes seem to occur usually either in association with failed rifts (the N Sea central grabens provide an example of a failed rift) or passive margins. The edge of the modern continental shelf running SW-NE through SEA 4 is an example of a passive margin, albeit one complicated here by internal patterns of basins and ridges.

One therefore needs to consider the possibility of an event similar to the 1929 Grand Banks earthquake, which occurred east of Nova Scotia and south of Newfoundland, in an area otherwise almost devoid of seismicity. This earthquake had a moment magnitude (Mw) of 7.4 according to Johnston et al (1994), and was associated with a tsunami, a sediment slump and turbidity current. There were 27 fatalities.

Johnston et al (1994) found a strong correlation within SCR between the occurrence of earthquakes and recently extended crust, i.e. Mesozoic-Palaeogene. This correlation was strengthened when considering the larger SCR events. From this one can conclude that if an uncharacteristically large earthquake (more than 6 and up to 7.7 Mw) is possible at all in the UK area, it is more likely to be possible along the passive margin (SEA 4 being one instance of such) than in some other area (e.g. onshore UK). However, it does not necessarily follow that because large earthquakes are more likely to occur on passive margins, all passive margins are likely to have large earthquakes. Other factors may also be involved; there may be a distinction, unknown at present, between passive margins capable of hosting such events and other passive margins that are not. "A … problem … presently unanswered, is why huge stretches of SCR passive margins appear to be aseismic while other segments are among the most seismogenic portions of SCR crust" (Johnston et al 1994).

Therefore, all one can say is that the probability of an abnormally large earthquake occurring at some time within SEA 4 is unknown, and while it may be very low, it is not zero. The complexity of the passive margin in this area may be a factor in making a large earthquake more, rather than less, likely, but this is presently open to speculation.

The largest of the historical passive margin events, including the 1929 Grand Banks earthquake, have tended to occur along the continent-oceanic boundary, which in the case of NW Europe, is NW of the Faroes. However, inboard passive margin events have been observed up to 7.1 in magnitude.

The effects of such an event would be considerable. The Grand Banks earthquake caused massive turbidity currents on the continental slope and at least 22 submarine cable breaks were reported.

The occurrence of slides at various points along the continental slope in NW Europe, notably the three massive Storegga slides, could be taken as possible evidence of passive margin seismicity in the past. Jansen et al (1987) suggest that the Storegga slides are most likely to have been triggered by earthquakes. Dawson et al (1988) estimate the magnitude of the triggering event of the second Storegga slide to have been 7. Analysis of the Trænadjupet Slide, further to the north and east along the continental margin, suggests that the slide could have been triggered by a single earthquake of magnitude 5.8, or cyclic loading due to several earthquakes (Leynaud and Mienert, 2003). Some other examples in the UK sector are discussed by Long and Holmes (2001), with reference to the possibility of seismic triggers.

It can also be debated as to how much influence the release of gas hydrates had on the occurrence of these slides, or whether they had triggers other than earthquakes. If slopes are very unstable, a slide may be triggered by only weak shaking from a small earthquake. Equally, they may be triggered without any earthquake. A historical observation of an underwater slump near Fetlar (Shetlands) in 1768 was not associated with any felt earthquake (Low, 1879).

A further consideration, when discussing possible palaeoseismic evidence, is whether the seismicity of the UK continental shelf was enhanced by rapid isostatic change after the last main deglaciation, compared to the present day. It seems plausible that it should have been, in which case evidence of magnitude 7 earthquakes 7000 years BP is not necessarily an indication that they are still likely to occur in present day conditions.

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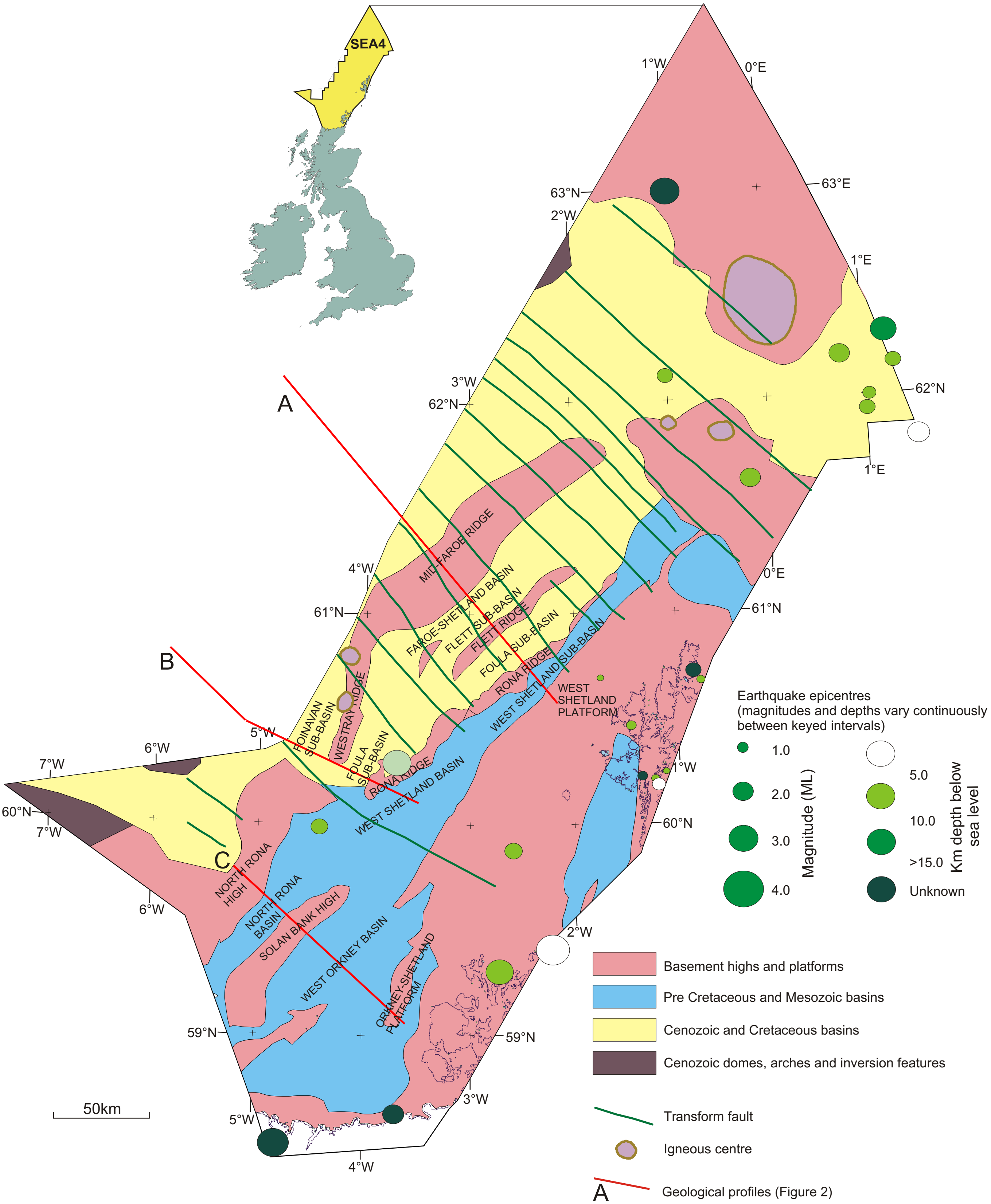

Figure 1 Generalised structural geological framework and natural seismicity
Structure adapted from BGS Passive Margins Modelling Project (Gatliff, *pers comm.*2003).
The inset map shows a complex boundary to the NW limits of data in SEA4 and this boundary has been excluded for purposes of clarity.

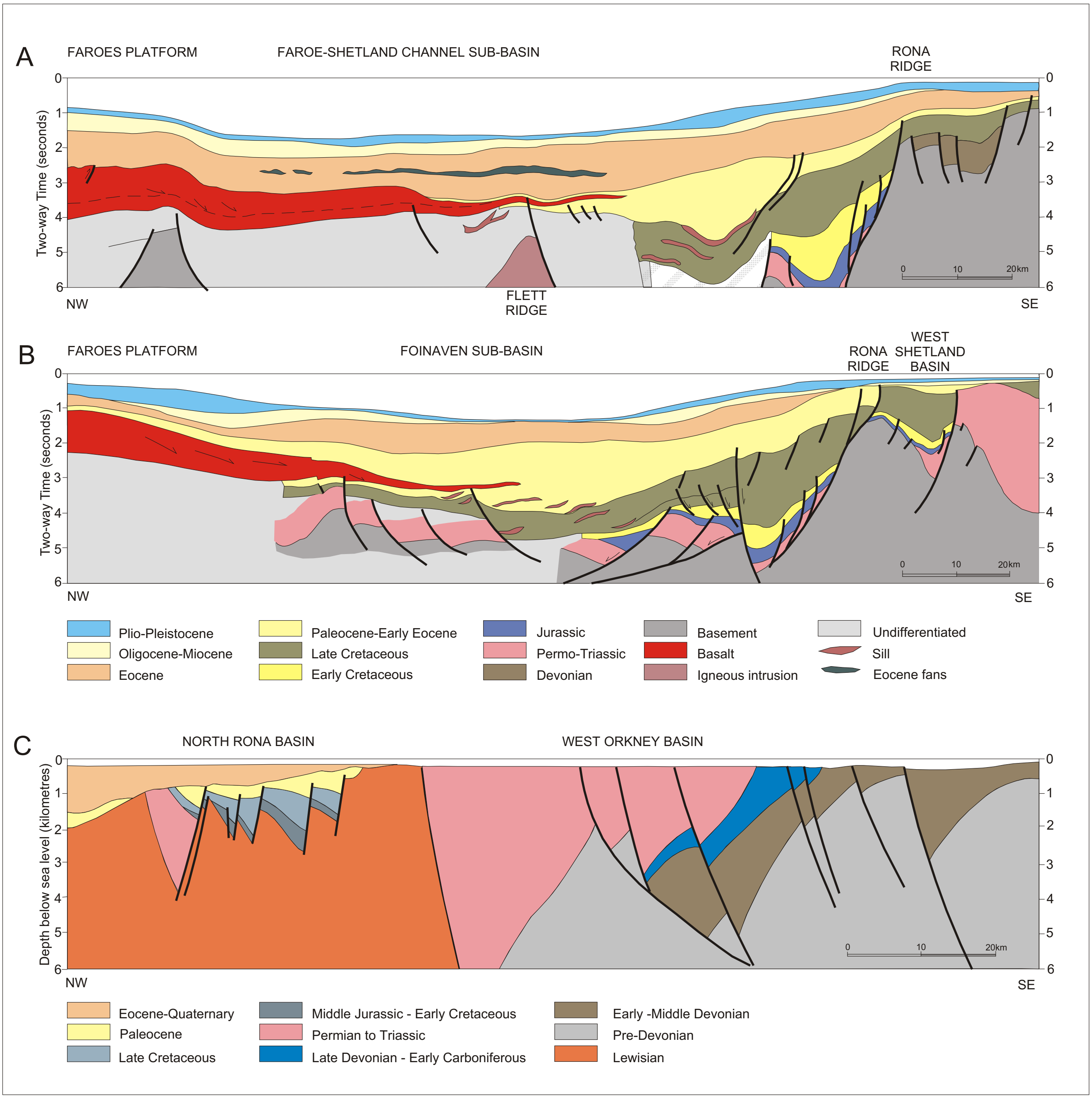

Figure 2 Geological profiles

For locations see Figure 1. Modified from Lamers and Carmichael (1999) and Stoker *et al. (1993).*

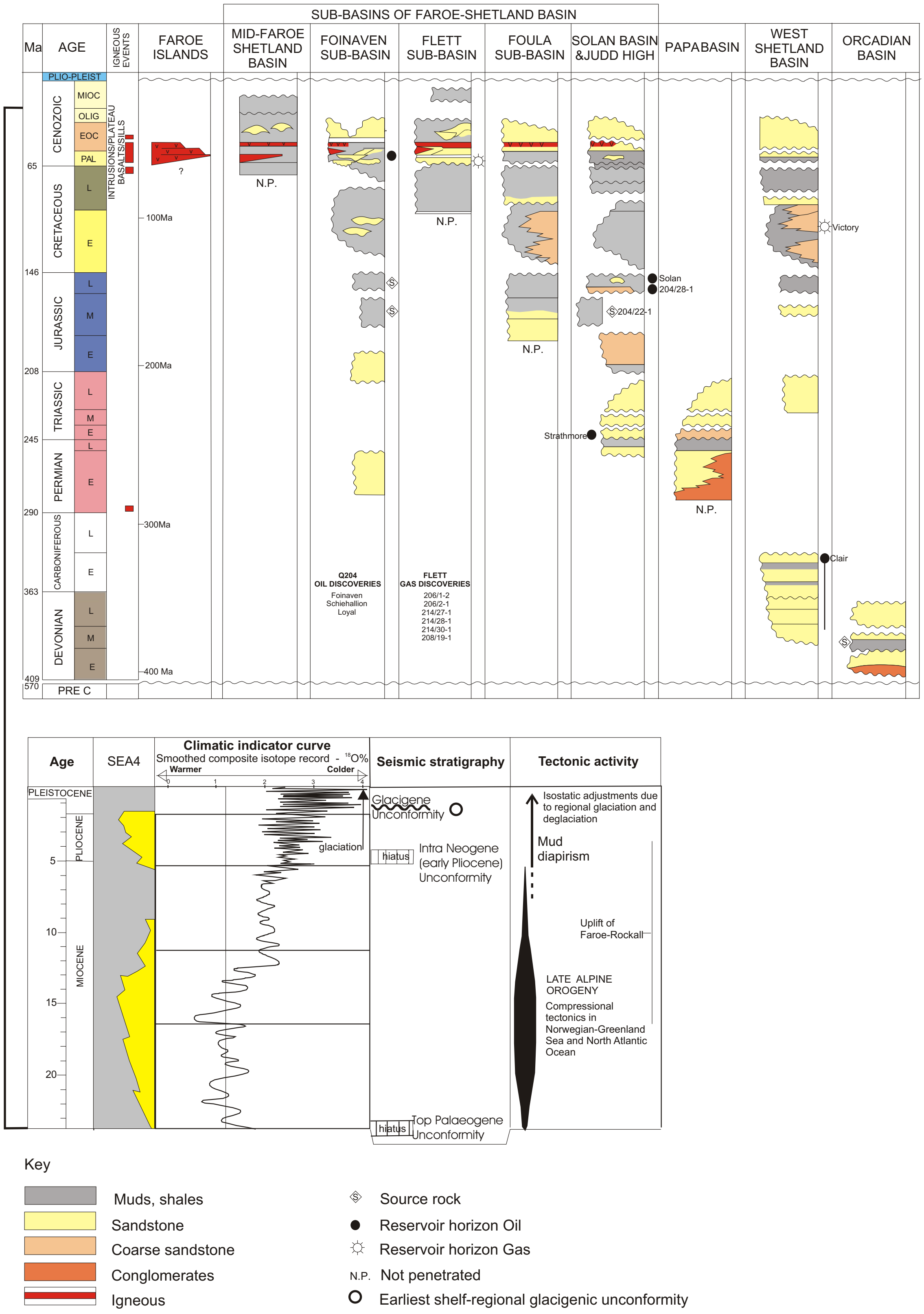

Figure 3. Lithostratigraphy 409Ma-10Ka and tectono-stratigraphical development 24Ma-10Ka

Modified from Lamers and Carmichael (1999). Ages from Harland *et al.* (1990).