The potential role of igneous intrusions on hydrocarbon migration, West of Shetland

Rémi Rateau[1]*, Nick Schofield[2] and Michael Smith[1]

[1]*DONG E&P (UK) Ltd, 33 Grosvenor Place, London SW1X 7HY, UK*
[2]*School of Geography, Earth and Environmental Science, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK*
**Corresponding author (e-mail: RERAT@dongenergy.co.uk)*

ABSTRACT: Numerous challenges for petroleum exploration exist within basins containing sequences of intrusive and extrusive rocks, ranging from seismic imaging to drilling. One poorly understood element in dealing with volcanic-affected basins is assessing the impact magmatism has on the elements of the petroleum system. Within this study we attempt to evaluate the potential impact that the extensive sequence of igneous intrusions of the Faroe–Shetland Basin may have on hydrocarbon migration. Using available well data combined with regional 3D seismic surveys, we show that geometrical relationships between sills location and overlying hydrocarbons shows, together with several cases of gas-charged open fractures in the sills, point toward the recognition of igneous intrusions as a factor in hydrocarbon migration through sill intrusions acting as both barriers or conduits to hydrocarbon migration. We also provide a series of general conceptual models dealing with hydrocarbon migration and igneous compartmentalization within sedimentary basins, which can be applied not just to the Faroe–Shetland Basin, but to other sedimentary basins worldwide if it is found (via well data or other methods) that the intrusions are interacting with a petroleum system.

INTRODUCTION

The novel use of high-quality offshore 3D seismic datasets has allowed insights into the formation of sill complexes and the complex geometry of subsurface magma plumbing systems (Planke *et al.* 1999; Smallwood & Maresh 2002; Thomson & Hutton 2004; Hansen & Cartwright 2006; Thomson & Schofield 2008; Schofield *et al.* 2012*b*). By mapping sills in 3D seismic data it has been found that within sedimentary basins the traditional definition of a 'sill' being concordant with host-bedding does not always apply and sills are often characterized by a broadly concordant inner dish, with a gently inclined, *c.* 20–35° transgressive arcuate rim of dolerite, which cross-cuts stratigraphy and often becomes ragged at its periphery (Bell & Butcher 2002; Smallwood & Maresh 2002; Thomson & Hutton 2004; Cartwright & Hansen 2006; Schofield *et al.* 2012*b*). Individual sills can range anything in size from several hundred metres to *c.* 30 km in diameter, as seen in the Karoo Basin, South Africa (Chevalier & Woodford 1999; Goulty & Schofield 2008; Schofield *et al.* 2010). Pre-existing basin structure and lithology form a major influence on magma flow pathways through a basin by offering paths of least resistance to intruding magma. Commonly intrusions can be seen to exploit and interact with fault planes, exploiting the faults to climb to higher levels in the basin (Thomson 2007; Thomson & Schofield 2008; Magee *et al.* 2013). Increasing evidence would suggest that the rim of a lower sill can feed the base of an upper sill, and that sills can thus feed sills without the need for intervening dykes (Thomson & Hutton 2004; Cartwright & Hansen 2006); this leads to sill complexes forming an interconnected series of intrusions which can permeate extensively through a basin fill over large distances, both vertically and laterally.

Only a few studies have focused on the impact of igneous intrusions on a petroleum system despite the fact that many occurrences world-wide exist of igneous intrusions interacting with operating hydrocarbon systems (Schutter 2003; Jamtveit *et al.* 2004; Archer *et al.* 2005; Holford *et al.* 2012; Witte *et al.* 2012), and none have specifically investigated in detail the impact that igneous sills may have on hydrocarbon migration.

Within this paper, regional mapping of the Faroe–Shetland Basin sill complex, undertaken using a regional seismic and well dataset, has allowed us to identify a possible spatial relationship between the edge of the sill complex and the occurrence of hydrocarbons in the overlying Paleocene sandstones. We investigated the hydrocarbon migration timing information together with the petrophysical characteristics of sills in the Faroe–Shetland Basin in order to identify mechanisms which might potentially explain such a relationship. We also propose several theoretical 'mind-models' dealing with end-member migration scenarios, to allow the occurrence of sill intrusions within sedimentary basins to be properly factored into exploration risk.

GEOLOGICAL SUMMARY: STRUCTURAL AND IGNEOUS HISTORY OF THE FAROE–SHETLAND BASIN

Basin evolution

The Faroe–Shetland Basin (FSB) lies between the Shetland and the Faeroe Islands on the North-West European Atlantic

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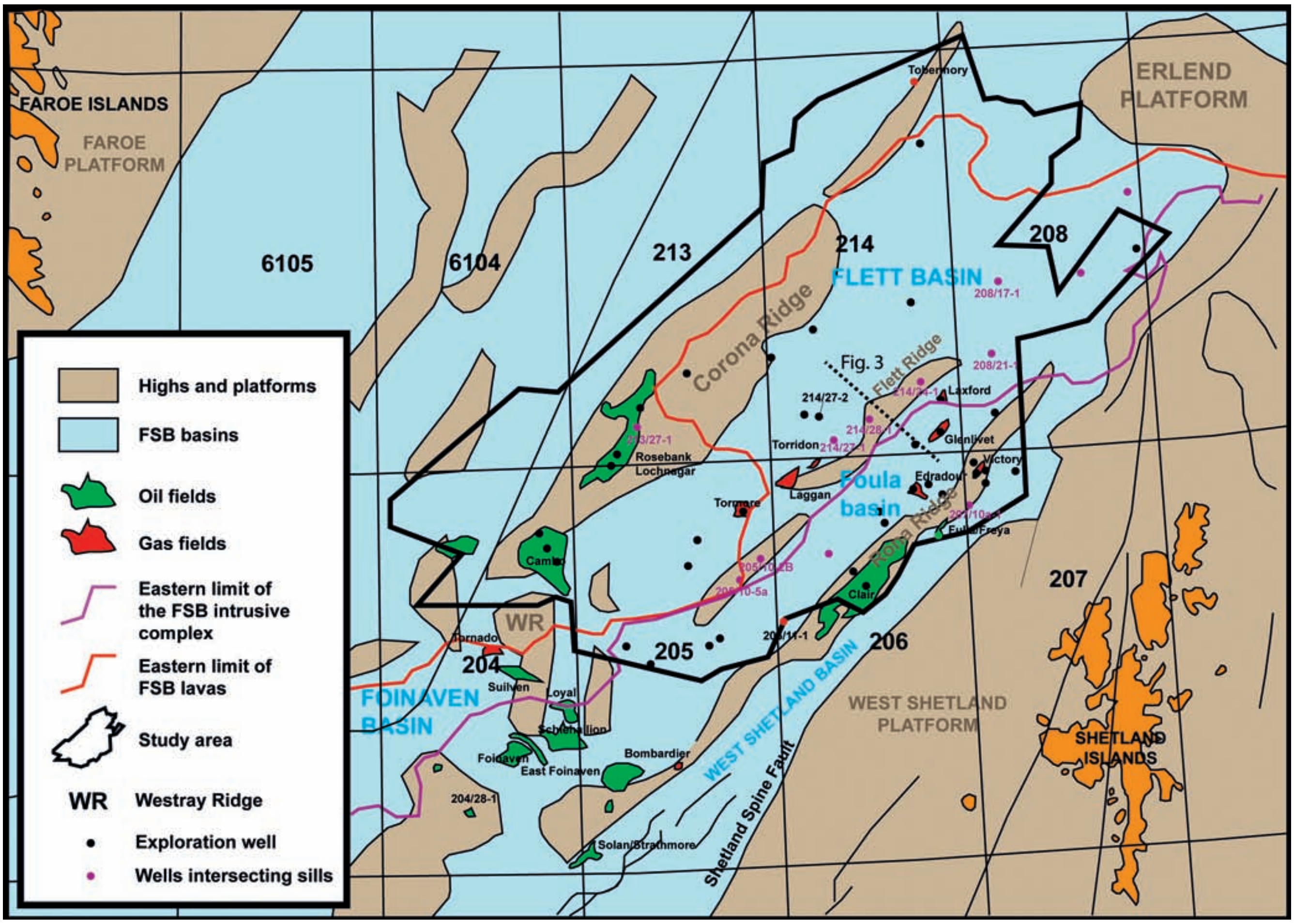


Fig. 1. Seismic and well dataset on structural map of the FSB and main magmatism features (modified after Dean *et al.* 1999 and Ritchie & Hitchen 1996).

margin, in an area commonly referred to as 'West of Shetland' (WoS). The basin is bounded to the SE by the Shetland Spine Fault and the West Shetland Platform, to the NW by the Corona Ridge, to the west by the Westray Ridge and to the NE by the Erlend Platform (Fig. 1). The FSB collectively is comprised of a series of SW–NE-trending sub-basins, separated by Palaeozoic highs (Fig. 1). The region is underlain by Precambrian gneiss, with the complex geological evolution of the region being determined by a succession of rifting, uplift and compressional events, summarized by Dean *et al.* (1999). During the late Palaeozoic, the Caledonian orogeny underwent extensional collapse and erosion, leading to the accumulation of large volumes of continental sandstone, siltstone and shales in parts of the Faroe–Shetland area (Fig. 2). Middle and Late Jurassic E–W extension allowed the deposition of sandstones and shales in some parts of the basin, providing the main source rock to the area (Fig. 2; Scotchman *et al.* 1998). During the Early–Mid-Cretaceous, NW–SE extension along the UK and Norwegian Margin produced major structural relief, coupled with large subsidence rates, which led to the deposition of thick sequences of Cretaceous sediments within the Faroe–Shetland region. Continued subsidence and a worldwide sea-level rise occurred towards Turonian times, leading to a progressive drowning of rift margins and fault blocks, and an Upper Cretaceous section dominated by more mud-rich horizons (Fig. 2; Dean *et al.* 1999). The Cenozoic is dominated by post-rift thermal subsidence, punctuated by episodes of rifting, uplift and compressional events, summarized by Smallwood & Kirk (2005). A further rifting episode is thought to have occurred during the Paleocene, leading to the deposition of deep-water shales and turbidite sands during Paleocene BP sequence T10–T35 time (Ebdon *et al.* 1995). These sequences are of economic importance, forming the main exploration target in the area (Lamers & Carmichael 1999).

During the latest Paleocene (sequence T36–T45), regional uplift led to the deposition of major deltaic formations and culminated with a regional unconformity in Balder times. The Eocene and Neogene are dominated by post-rift thermal subsidence and deep-water sediments, with episodic compressional events during the Eocene, Oligocene and Miocene, which created basin-scale inversion structures (Fig. 2; Smallwood & Kirk 2005).

Igneous activity

The region experienced considerable igneous activity associated with the onset of ocean-floor spreading in the NE Atlantic Ocean and presence of the proto-Icelandic plume (Naylor *et al.* 1999), although global plate reorganization has been proposed as an alternative (non-plume) trigger (Hansen *et al.* 2009). Despite this controversy, the first phase of volcanism in the North Atlantic is thought to have occurred around 62 Ma (White & Lovell 1997), this was followed with the eruption of the Faroes flood basalts around 61–57 Ma ago (Passey & Jolley 2009).

The intrusive and extrusive sequences in the FSB are comparable in form and age to onshore equivalents located around the NW European margin and North Atlantic, including the British

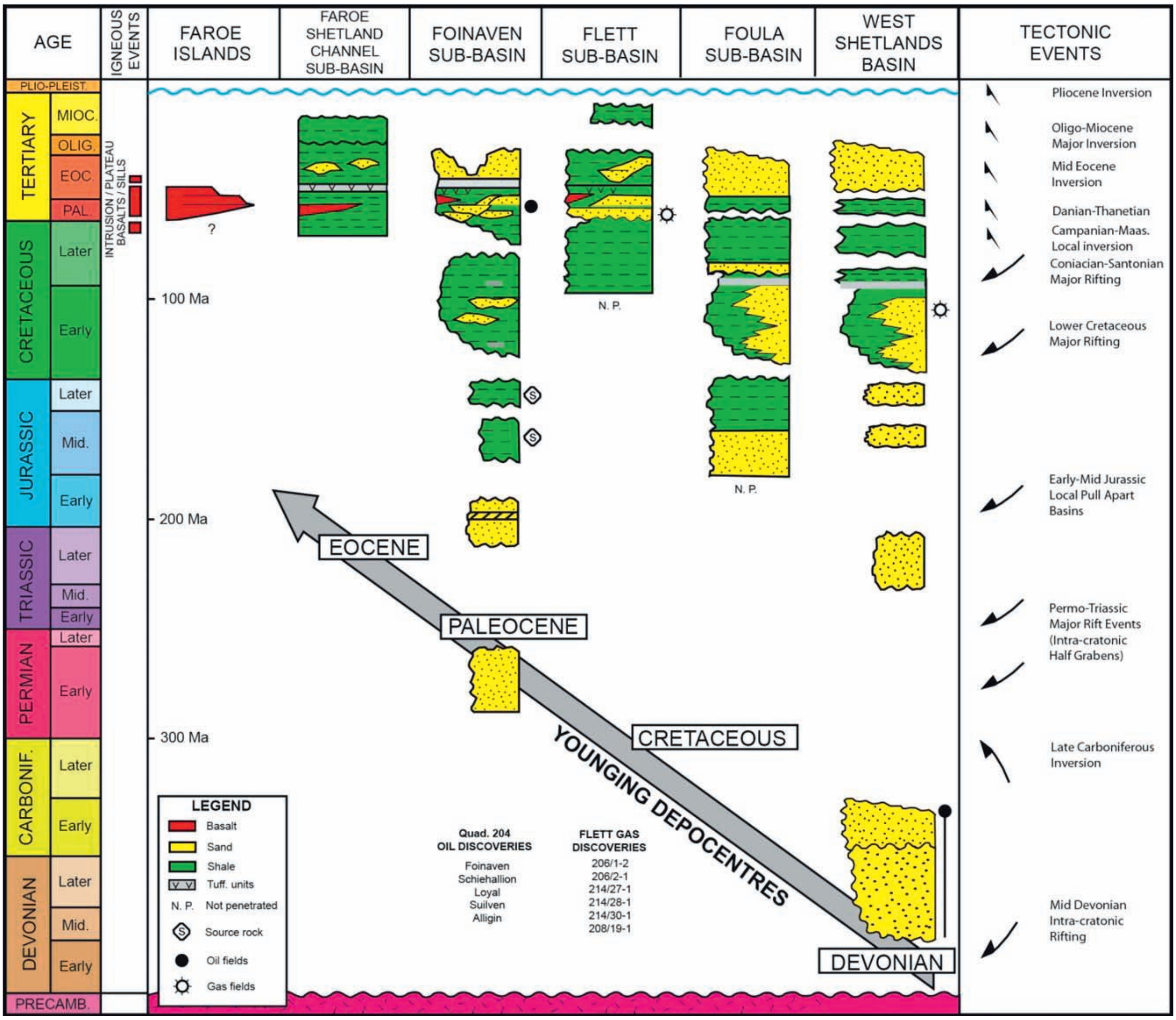


Fig. 2. Lithostratigraphy of the FSB (modified after Lamers & Carmichael 1999). The Flett and Foula basins are dominated by Cretaceous and Lower Paleocene deep-water shales and sandstones, followed by shallow-water deposits during the Late Paleocene and Early Eocene. The main economic reservoirs located in the FSB are the deep-water turbidites from the Lower Paleocene.

Paleogene Igneous Province (BPIP) and also East Greenland, and represent the initiation of volcanism and the onset and progression of seafloor spreading between NW Europe and East Greenland. Within the FSB, the resultant volcanism resulted in a thick flood basalt sequence covering an area of at least 40 000 km^2 (Fig. 1; Naylor *et al.* 1999).

Despite varying thicknesses of extrusive basalt within the various sub-basins forming the FSB, all of the basins contain an extensive intrusive suite of dolerite and olivine–dolerite sills and dykes (Gibb & Kanaris-Sotiriou 1988; Stoker *et al.* 1993), which are thought to have intruded between 55 and 53 Ma (Ritchie & Hitchen 1996).

The sills, which form an aerially extensive suite of intrusions, extending outwith of the basalt cover as far as, in some cases, the Shetland platform (Fig. 1; Naylor *et al.* 1999), appear to preferentially intrude mainly the Upper Cretaceous shales and the lower part of the Paleocene, possibly the result of preferential exploitation of water-rich shale horizons (Thomson & Schofield 2008; Schofield *et al.* 2012*a*).

DATASET AND METHODS

The project database consists of a 3D seismic cube covering *c.* 18 500 km^2 across the Flett Basin and of 13 wells which intersect igneous intrusions within the FSB (Fig. 1). The 3D seismic cube is part of the PGS Faroe–Shetland MegaSurvey, with 25 m line spacing and a positive reflection coefficient represented by positive amplitude and a black peak. Well reports, composite and CPI logs, as well as time–depth data, were available for all the wells. Out of the 13 wells, 7 have cores in sills.

The igneous intrusions have been interpreted via normal picking over the area. The manual interpretation, in comparison to the volume rendering or geobodies extraction techniques, allows a better quality control on the interpretation, particularly with the large number of interpreted sills (>200). The main objective of the mapping of the intrusions was to get a detailed overall view of the distribution of the intrusions in the basin, as well as their stacking patterns, sizes and shapes (Fig. 3). In conjunction with the seismic study, an integrated study of the well

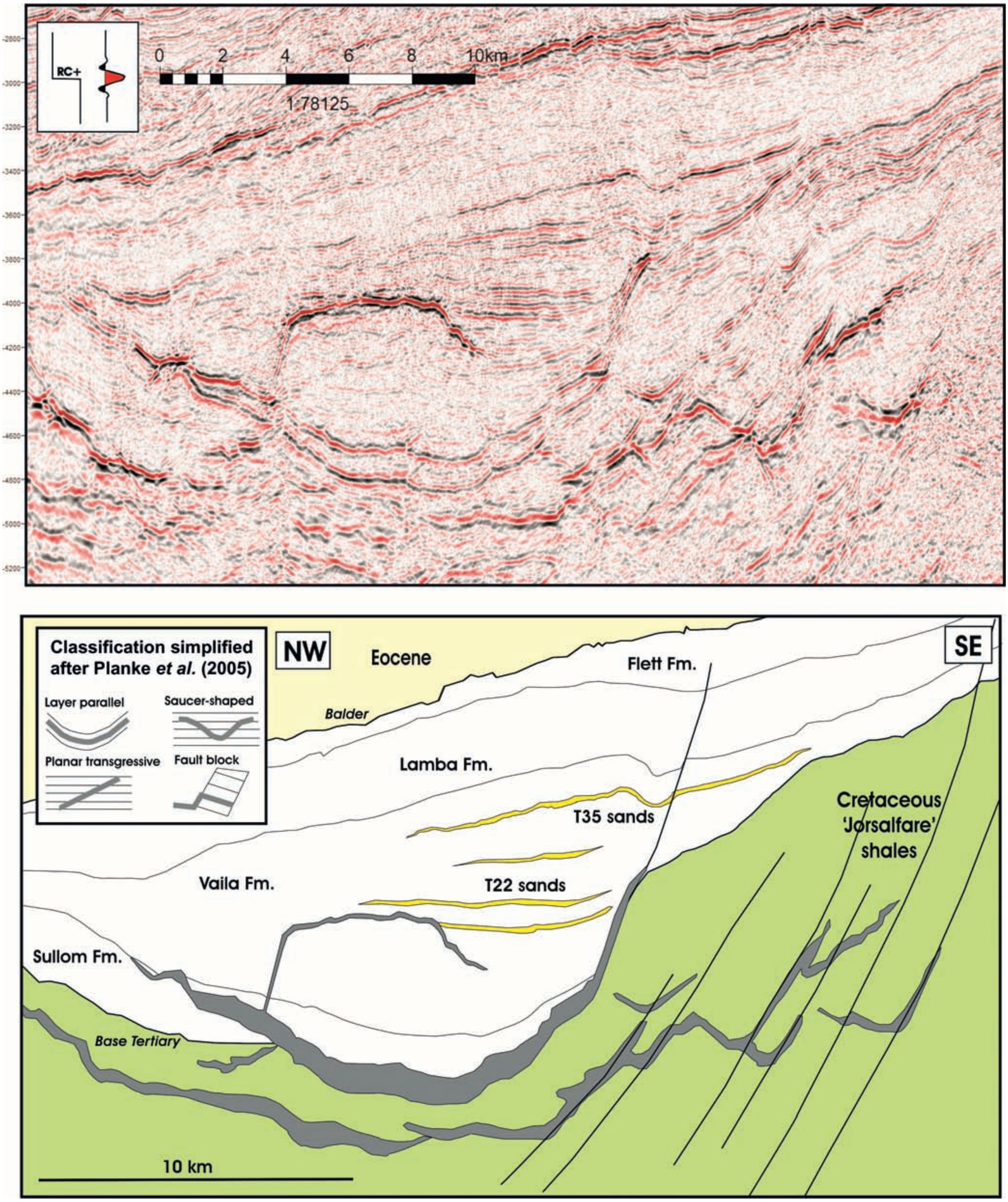


Fig. 3. Seismic line and geoseismic interpretation through Eocene–Cretaceous section within the FSB (see Fig. 1 for location). Of particular prominence are the sills in the Flett Basin, which are often saucer-shaped, stacked and thick (in this case, the top and base of the main sill are visible and the extremities are tuned). In the SE part of the basin, sills are more fault-block in shape and thinner. Within the FSB as a whole, the Jurassic source-rock sequences are often physically located below the sill complexes (aside from where uplifted on basin highs), while the Lower Paleocene reservoirs (T-sequences) are most often physically located in sequences above the sill complexes.

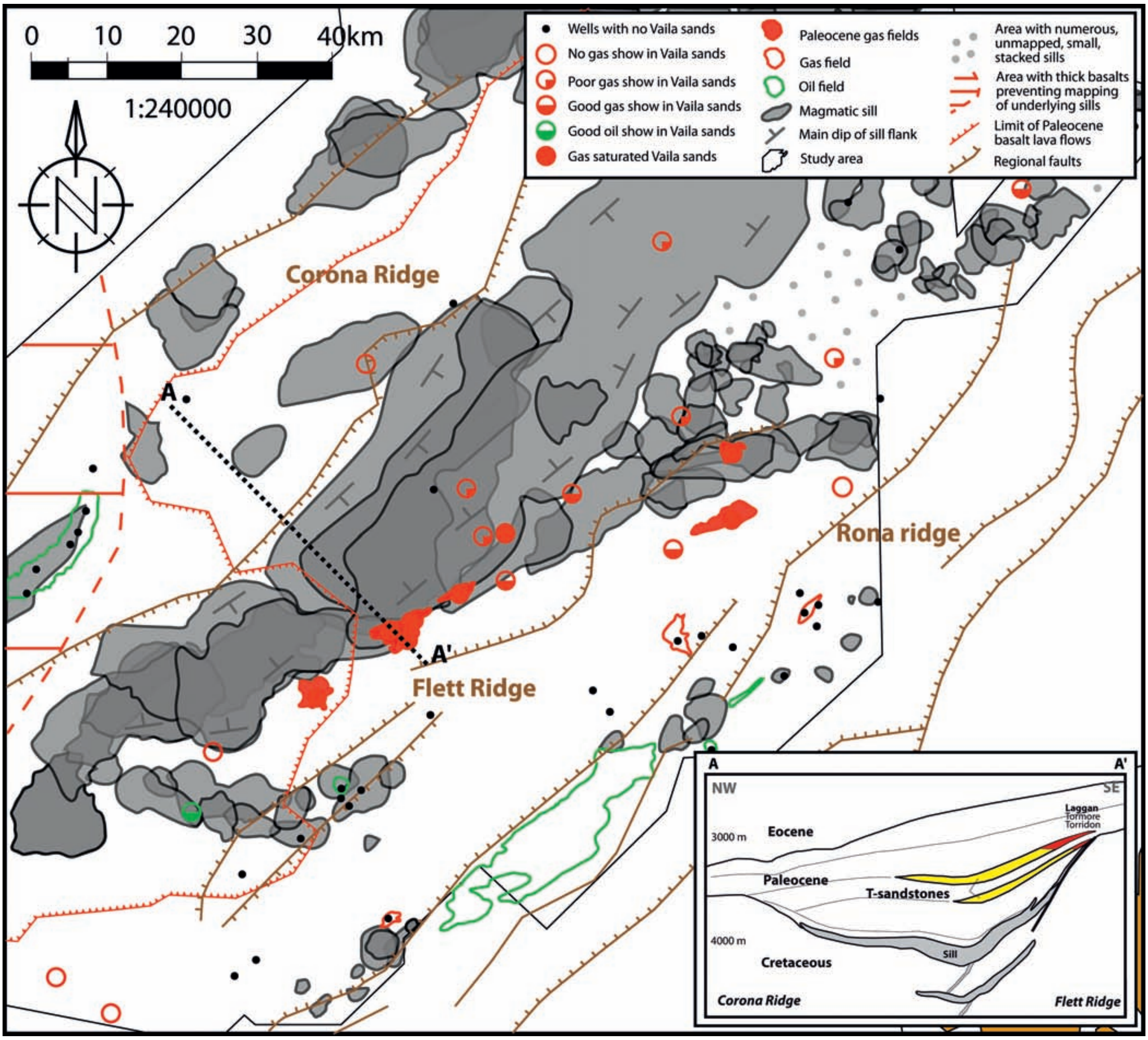


Fig. 4. Map showing overall sill distribution within the FSB against Paleocene Vaila reservoir gas shows. The map shows the distribution, shape, size, flanks' dip and degree of stacking of the sills in the FSB. The wells which have drilled through the Lower Paleocene Vaila reservoirs are highlighted by a red circle. The filling of the circles gives an evaluation of the gas shows in the reservoirs (from no shows to gas-saturated reservoirs). It can be noticed that most of the good gas shows and Vaila gas reservoirs are located at the edges of the sills and sill complexes while the wells with no show or poor shows are either above the central part of sills or over areas without any sills below. Although the distribution of gas shows is certainly related to the main structures in the basin (like the Flett Ridge), a relationship between the areal distribution of the sills and the gas occurrences cannot be ruled out: sills might impact hydrocarbon migration in the basin.

data, including composite and CPI logs, geological reports, mud log and drilling reports, was carried out in order to identify the role of the intrusions on hydrocarbon migration in the Faroe–Shetland area.

THE HYDROCARBON SYSTEM AND SILL INTRUSIONS IN THE FSB

Distribution of sills and Paleocene gas shows: A relationship?

The detailed mapping of more than 200 igneous sills in the FSB (Fig. 4) shows that sills do not occur randomly and tend to have coherent characteristics within specific areas of the basin. The Flett Ridge seems to separate a NW province with few, large (>10 km), stacked saucer-shaped sills from a SE province, leading on to the Shetland Platform which is relatively devoid of sills. Towards the northeastern part of the area (quadrant 208 and northern part of quadrant 214), small (<10 km) sills and sill-exploiting stacked fault blocks are dominant (Figs 3 and 4).

When compared with the distribution of gas shows in the overlying Paleocene reservoirs of the area, it can be seen that most of the gas fields and good gas shows are located on the edges of the main sill complexes, while the absence of shows or poor shows are either above an area without sills or above the central part of large sills (Fig. 4).

This correlation may be explained partly by the genetic dependence between regional fault and sill terminations:

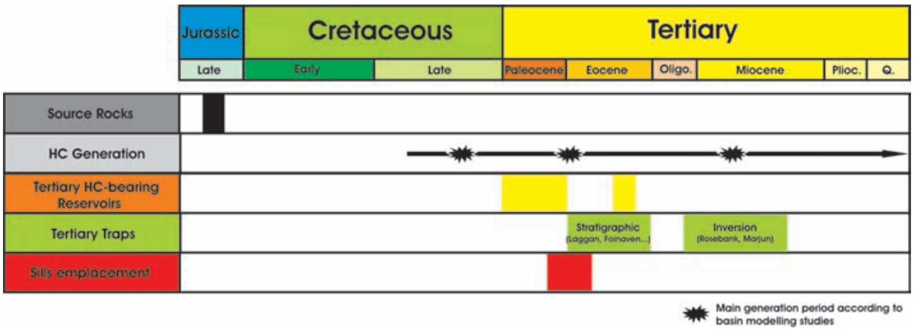


Fig. 5. Timing chart showing main elements of the petroleum system within the FSB. Part of the hydrocarbon migration from the Jurassic source rock occurred during and after the intrusion of the sills (Paleocene–Eocene boundary times) and continues to the present day. On top of the regional basin modelling results, the existence of a Late Paleocene and Eocene gas-bearing reservoir, as well as the existence of traps formed during the Eocene and during the Oligo-Miocene inversion, prove that some significant hydrocarbon migration occurred after the emplacement of the sills in the basin.

migration through the Flett High boundary faults would lead to a similar shows pattern in this part of the basin. However, the presence of igneous intrusions in the basin and apparent correlation cannot be totally ignored, and the potential role that the sills may play in acting as ‘barrier and baffles’ to hydrocarbon migration needs to be assessed.

Timing of hydrocarbon migration and igneous intrusions

To assess the possibility that sill complexes may have played a key role in hydrocarbon migration within the FSB, it is first critical to understand the timing of emplacement of the intrusive complex compared with hydrocarbon migration timing. For the intrusions to act as possible ‘barriers and baffles’ to migration, the intrusive complex would need to be ‘in-place’ before migration of the hydrocarbons took place into rock sections and traps overlying the sill complex.

The age of emplacement of the FSB sills is determined by a combination of radiometric (Hitchen & Ritchie 1993) and seismic-stratigraphic techniques (Smallwood & Maresh 2002; Trude *et al.* 2003; Hansen 2006), which indicate that their emplacement occurred between the Late Paleocene and the Early Eocene (Fig. 5).

The timing of hydrocarbon expulsion and migration in the FSB (Fig. 5) is far less understood. The main source rock in the FSB is the Upper Jurassic Kimmeridge Clay equivalent formation (Scotchman *et al.* 1998). Most of the basin modelling studies have focused on the Foinaven sub-basin or East Solan basin and a conundrum is recognized in the main FSB (Carr 1999; Iliffe *et al.* 1999; Lamers & Carmichael 1999; Scotchman & Carr 2001; Carr & Scotchman 2003; Scotchman *et al.* 2006). Traditional basin modelling predicts a Late Cretaceous generation of hydrocarbons, with the present-day basin regarded as mature for gas or overmature (Iliffe *et al.* 1999; Carr & Scotchman 2003). However, oil seems to be the main phase in most of the basin, with some post-Paleocene hydrocarbon charge in some reservoirs (Scotchman & Carr 2001; Scotchman *et al.* 2006). This mismatch between observed and modelled data has been explained by several models. Carr (1999), Carr & Scotchman (2003) and Scotchman *et al.* (2006) invoke a delayed generation of hydrocarbons due to overpressure in the Kimmeridge Clay equivalent formation, with a final generation during the Oligo-Miocene inversion. Others invoke a delayed migration with temporary stockage (‘Hydrocarbon Hotel’ model) in Lower Cretaceous sandstones and then re-migration to Paleocene reservoirs through burial/overpressure-induced fractures in the Upper Cretaceous shales (Doré *et al.* 1997; Lamers & Carmichael 1999; Iliffe *et al.* 1999). Despite these models, the overall lack of well data and seismic data at the source-rock level, coupled with the complex thermal history of the basin (rifting, inversion, igneous activity) means that getting a totally clear theoretical understanding of the timing of hydrocarbon generation and migration is still troublesome.

However, as gas has been found in Mid-Eocene turbidites in the Tobermory Field (indicating a syn- or post-Eocene migration), coupled with the sizeable Rosebank and Cambo oil fields (Fig. 1), which possess Late Paleocene reservoirs that are hosted in Oligo-Miocene related structural traps, this implies that hydrocarbon migration into these Late Paleocene reservoirs certainly occurred during or even after the Miocene. Therefore, it would appear that a reasonable quantity of hydrocarbons has migrated from the Jurassic source kitchen (below the main occurrence of sills within the basin), toward stratigraphically higher sediments, after the emplacement of the sill complex had taken place and, therefore, based on timing alone, it can be suggested that the sill complex within the FSB had the potential to affect hydrocarbon migration pathways within the basin to some degree.

SILLS IN PROSPECTIVE SEDIMENTARY BASINS: POTENTIAL EFFECTS ON MIGRATION PATHWAYS

In order to estimate the potential role of igneous sills on hydrocarbon migration, it is critical to understand the petrophysical characteristics of these bodies and their potential behaviour with fluids in sedimentary basins. Different examples in the world show that igneous sills can act both as a barrier for fluid or, on the contrary and more counter-intuitively, as conduits.

‘Barriers and baffles’

Dolerite and, more generally, igneous rocks are traditionally viewed as impermeable (Schutter 2003). Indeed, documented examples in the literature have shown that magmatic sills can act as effective barrier/seals to fluids. Coal-bed methane deposits in the Gunnwedah Basin, Australia, have been sealed by sills which have acted as impermeable barriers (Gurba & Weber 2001). The Phetchabun Basin, Thailand produces oil from a reservoir situated in an open anticline formed by a laccolith-like dolerite body, with the seal being provided by a dolerite sheet (Schutter 2003). In the Solimões Basin, Brazil, the intrusion of a dolerite dyke is thought to have acted as a side-seal preventing horizontal movement of oil (Filho *et al.* 2008). Therefore, as the above examples illustrate, within prospective sedimentary basins, the potential does exist for sill intrusions to act as impermeable barriers to hydrocarbon migration.

Conduits

Permeability in sills can be created by formation of cooling joints, fractures and, in very shallow-level intrusions, by the

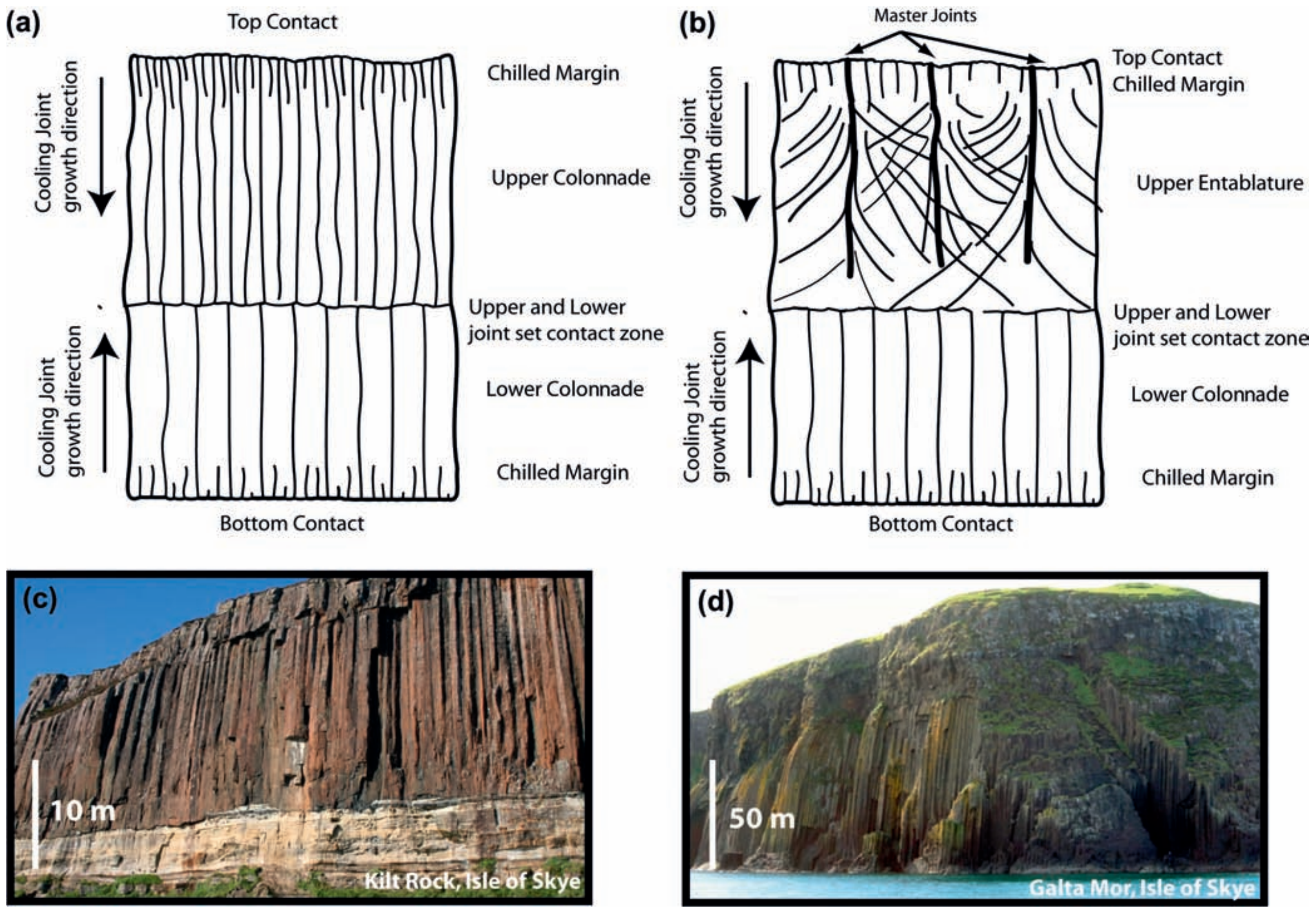


Fig. 6. (**a**) Idealized style of columnar joints across a volcanic body, illustrating the growth of columns away from the contact, and the discontinuity produced when columns meet, which tends to inhibit the connectivity of joint sets across the body (after Grossenbacher & McDuffie 1995). (**b**) The development of irregular jointing within a volcanic body, as a result of ingress of available fluids into master joints early after emplacement (after Lyle 2000). (**c**) Kilt Rock, Trotternish Peninsula, Isle of Skye, showing a sill which has undergone even and slow cooling across the intrusive body leading to the development of a well-formed set of vertical columnar joints; such a strong anistropy in the joints may lead to increased vertical permeability through the sill when compared to connectivity horizontally. (**d**) A sill (despite appearances of a lava) at Galt Mora, Trotternish Peninsula, Isle of Skye, which has undergone highly irregular cooling on its top surface, similar to that in (b). In such a scenario the upper part of the sill has a highly irregular cross-cutting series of joints. One may expect increased permeability in the upper part of the sill due to the high degree of interconnectivity of joint sets.

occurrence of interconnected gas vesicles. However the interplay of these processes during cooling of magma and its impact on the petrophysical properties of dolerite is often complex and variable. In this respect, often only generalities can be applied when dealing with sheet intrusions in sedimentary basins.

Columnar (cooling) joints represent the main method in which permeability can be created in an intrusion (Fig. 6). They form when magma is cooled and occurs layer by layer as a result of cooling stresses which occur behind the main solidification front as it moves through the cooling magma (DeGraff & Aydin 1993). Cooling fractures, in general, will grow perpendicular from the bottom and top contacts of a sill simultaneously. As a result the zone in which the two column sets meet tends to form a discontinuity, in which joint sets do not interconnect (Fig. 6a, Grossenbacher & McDuffie 1995). The non-connectivity of cooling joints (and low permeability) throughout sills is confirmed by Matter *et al.* (2006), who found the vertical conductivity of fluid through the *c.* 100 m thick, laterally extensive Palisades Sill, New York State, to be poor, even at the base of the sill, where the amount of sub-vertical fracture sets was three times greater than in the central portion. Importantly, the test of permeability conducted by Matter *et al.* (2006) was on a sill currently exposed at the surface; critically, in this situation the cooling joints will have undergone further opening due to removal of overburden loading before exposure. In a subsurface situation, such as in the sills within the FSB, where unloading-related opening of cooling joints has not taken place, permeability through cooling joints is likely to be reduced even further.

However, in situations where irregular cooling takes place laterally over a sill (Fig. 6b), possibly the result of uneven cooling, the resulting set of cooling joints can form a complicated set of interference patterns as a result of interaction between different joint sets (Lyle 2000). In such a circumstance the overall permeability of a sill is likely to be increased, as a function of increased connectivity of the separate cross-cutting joint sets.

Aside from cooling fractures, which can be viewed in terms of primary permeability pathways within a sill, several factors can act to create secondary permeability of a sill post-emplacement, including hydrothermal and diagenetic alteration and tectonic fractures. Within the Ayukawa oil field in Japan, the main reservoir is formed from dolerite. This has resulted as the originally impermeable dolerite underwent extensive metasomatism, which dissolved the pyroxenes in the dolerite (Hoshi

& Okubo 2010), creating secondary permeability and porosity within the dolerite.

Secondary permeability can also be created within an intrusion post-emplacement, as most magmatic rocks, due to their brittle nature, are liable to fracture when subjected to tectonic stresses (Schutter 2003). Therefore, any major tectonic event post-emplacement of a sill/sill complex (e.g. basin inversion events within the FSB) is liable to act to increase secondary permeability through a sill by creation of tectonic-related fracture sets. In the Northern Neuquén Basin, Argentina, both cooling and tectonic fractures due to a Miocene–Pliocene inversion are recognized in the sills and are thought to play an important role in allowing the transmission of hydrocarbons through the sills, which act as main oil-producing intervals within the basin (Witte *et al.* 2012).

Additionally, if basin tectonism occurs which is sufficient to lead to uplift (and erosion) of the basin sequences, then this may likely lead to increased fracture porosity and permeability within intrusions emplaced within the basins as a result of expansion of cooling joints sets within the intrusions as a result of unloading.

In conclusion, though igneous sills have zero matrix porosity originally, several parameters, such as early cooling fractures or later tectonic fractures, diagenesis, weathering and hydrothermal alteration, can create effective large-scale permeability in the sills which, in a basin setting, will mean that certain sills will be impermeable while others will be permeable.

IGNEOUS INTRUSIONS IN THE FSB: ‘BARRIERS AND BAFFLES’ OR CONDUITS?

Within the previous section, it has been seen that sheet intrusions have the ability to behave as both ‘barriers and baffles’ or carriers/reservoirs for fluids. The parameters controlling these two end-members are the presence or absence of: (1) connected genetic pores, such as vesicles; (2) hydrothermal alteration; and (3) open or cemented set of fractures (either cooling- or tectonically related). The following section will review each of these parameters for the dolerite sills intersected in wells within the FSB.

1. *Vesicles*. Vesicles have been documented in sidewall cores and cores from sills in wells 205/10-5A, 205/10-2B and 208/21-1 (Fig. 7). In wells 205/10-2B and 208/21-1, vesicles are low in frequency and sometimes cemented to form amygdales. A higher frequency of vesicles and amygdales occurs within the porphyry sill intersected within well 205/10- 5A (Fig. 7), which is possibly the result of a shallow/er emplacement below the paleo-seabed. Available well data suggests that no porosity or permeability has been measured on any of these cores. The low frequency of vesicles observed in samples, together with the absence of any lost circulation in wells 205/10-5a, 205/10-2b and 208/21-1 (Fig. 7), suggests that vesicles are not an important mechanism in creating effective porosity of permeability in the sills within the FSB.
2. *Hydrothermal/diagenetic alteration*. High degrees of metasomatic alteration of the dolerite witnessed within the Japanese Ayukwa oil field can be observed on logs as a continuous transition from the encasing mudstones to the fresh dolerite (Hoshi & Okubo 2010). In contrast to this, the logs of dolerite sills in the FSB area show a sharp transition, with a blocky shape to the logs (e.g. well 208/17-1, Fig. 7), suggesting that both the host rock–sill contact is one which is sharp and relatively unaltered, and that the sills themselves are relatively homogenous in nature. Although log responses from sills penetrated within the FSB do not appear to record any large degree of alteration, available cores and sidewall core data do show some weak hydrothermal-related alteration of the plagioclase and ferromagnesium minerals into various clays and oxides (e.g. wells 205/10-2B, 208/17-1, 214/28-1, Figs 7 and 8). However, the weak nature of hydrothermal alteration/metasomatism seen in the FSB sills is unlikely to create any substantial secondary porosity and permeability, such as that seen within the Ayukawa oil field, Japan (Hoshi & Okubo 2010).
3. *Open/cemented fractures*. Both open and cemented fractures are present in the well data over the study area. Cores and cuttings show numerous examples of fractures cemented mainly by calcite and quartz (e.g. well 208/21-1 and 214/28-1, Figs 7 and 8) and sometimes by various silicates (e.g. well 214/28-1, Fig. 8).

   Both open and closed fractures are recognized in the core from well 208/26-1 (Fig. 8). A series of mainly vertical open fractures are present; these fractures do not show any sign of movement in contrast to other fractures which are cemented and show evidence of shear-fracturing, with slickensides, granulation and smearing of quartz (Fig. 8). Although the exact origin of the fracture sets in 208/26-1 is unknown, they are likely related to magma cooling, with a possible degree of post-emplacement tectonism leading to shear fracturing and cementing along the cooling joints.

   The occurrence of open fractures set within sills is highlighted in wells 208/15-1A and 214/27-1, where loss of circulation while drilling through sills is reported to have occurred, suggesting interconnected sets of open and permeable fractures (Fig. 7). It should be noted that the loss of circulation experienced in well 208/15-1A occurred at *c.* 2000 mTVDSS, while the three loss-of-circulation events in well 214/27-1 occurred at depths close to 5000 mTVDSS. These instances of loss of circulation of the drilling mud, combined with observations from core and sidewall plugs, illustrate that significant permeable open fracture sets can occur in sills within the FSB even at depths greater than 4000 mTVDSS. Therefore, such fractures could potentially have the ability to act as large-scale effective permeability pathways in the dolerite sills, even at present-day burial depths.

Strikingly, four wells in the area mention gas shows associated with sills (Figs 7 and 8). The well report for 214/27-1 states that ‘whilst drilling through the igneous intrusion … circulation was lost several times. This is attributed to a series of fracture zones … these fractures consistently provided high gas values …’ (Fig. 7). Similarly, the well report for 214/28-1 describes some ‘gas charged, fractured dolerite sills’ (Fig. 7). In the ‘Hydrocarbon Indications’ section of the geological report of well 205/10-2B, BP indicates that ‘gas peaks were associated with … and on entering an igneous body at 10480 ft BKB’ (Fig. 7). All these gas shows are visible on the mud logs of these wells.

The gas seen in the fractures might originate from deeper levels and have migrated upwards and into the sill fracture network. If true, the presence of gas in the sills reinforces the fact that at least part of the migration of hydrocarbons occurred after the emplacement of the magmatic intrusions within the FSB and that the sill intrusions do play some role in the migration of hydrocarbons. However, it is possible that all, or some, of the gas originated from local maturation of organic-rich shales surrounding the magmatic intrusions. Present-day data do not allow an easy evaluation of the later hypothesis. Although the number of sills penetrated by wells within the Faroe–Shetland Basin is limited, the examples explored within

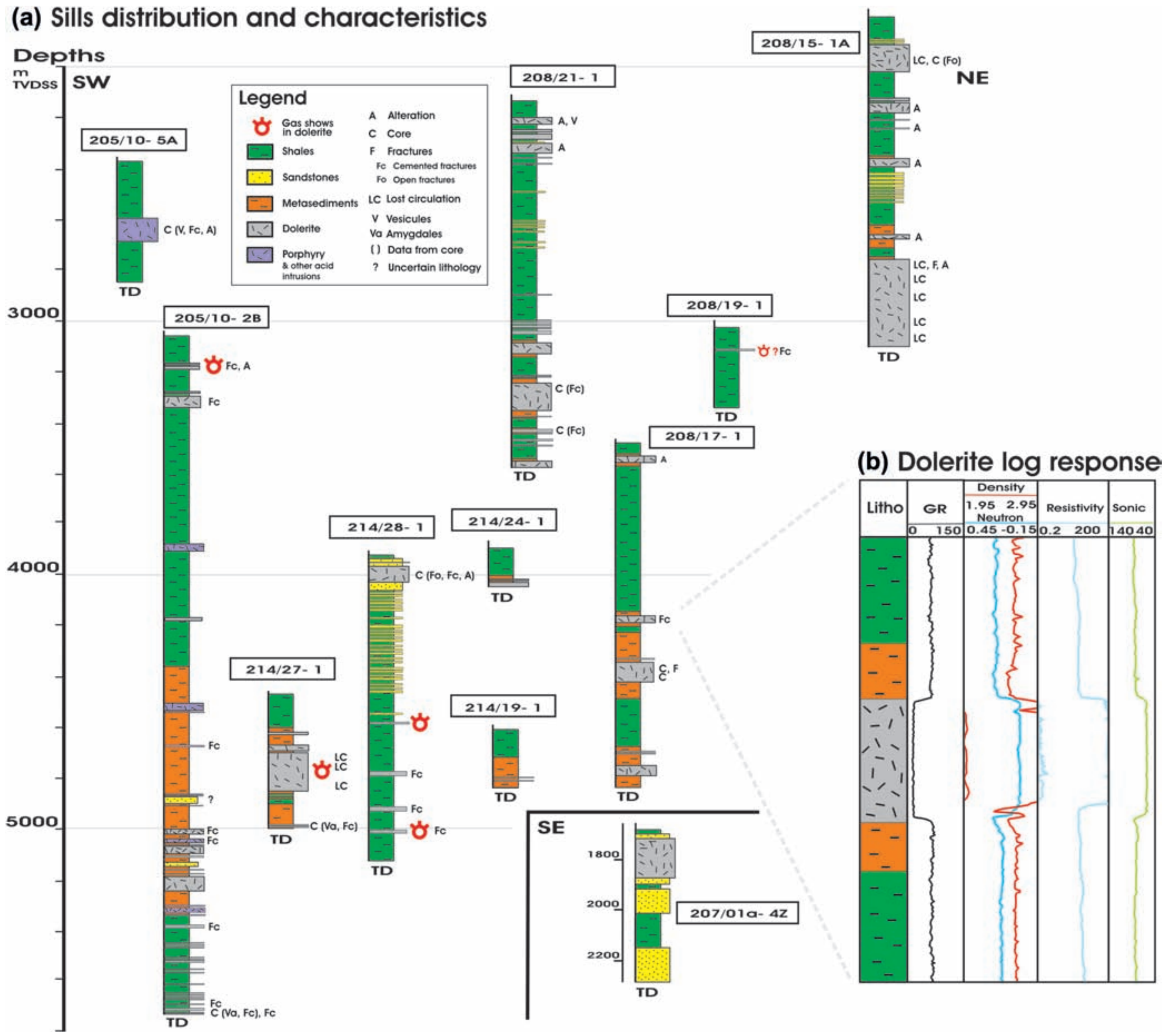


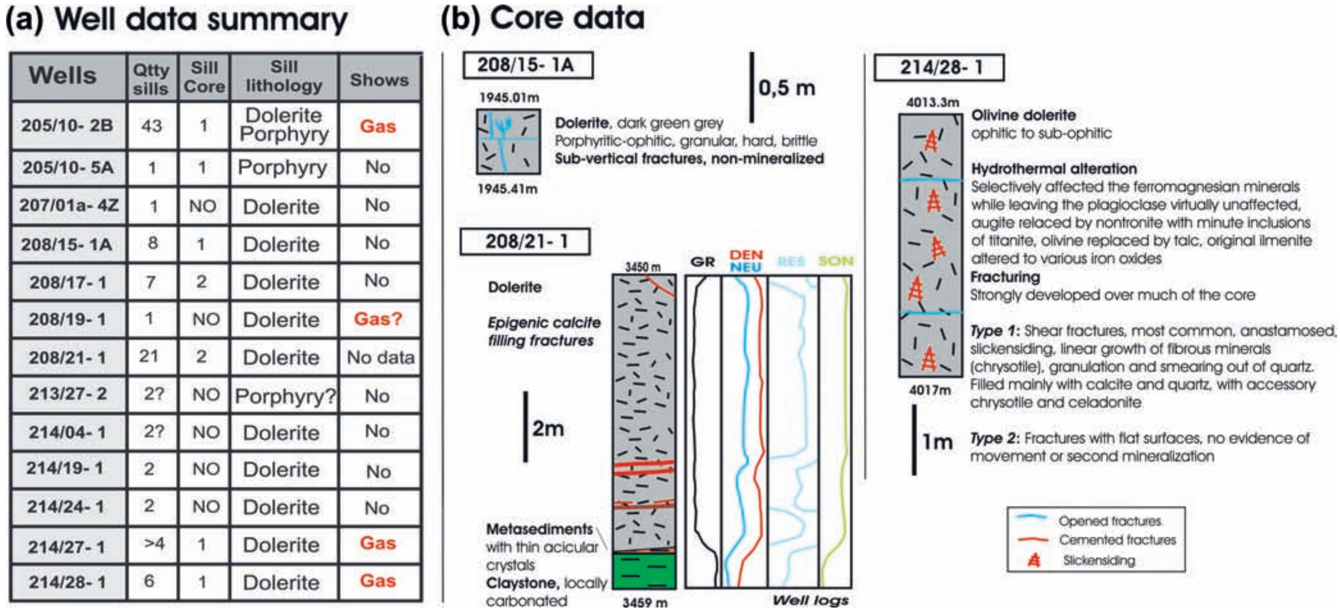
Fig. 7. Well data on sills in the FSB. (**a**) Vertical distribution, depth, thickness and characteristics of the sills in the Foula and Flett basins. (**b**) Typical log response of a magmatic sill, encasing shales and metasediments.

this paper provide information about the petrophysical behaviour of sills in the basin. Two end-member behaviours appear to be present within the basin, where the sills have the ability to act as either barriers or carriers to fluid. At one end-member, the lack of any large-scale hydrothermal alteration of sills combined with the cementation of fractures within the sills could lead to highly impermeable bodies of rock, which act as ‘barriers and baffles’ to hydrocarbon migration in the basin. At the other end-member, large sets of open fractures in some sills (genetic cooling joints or tectonically related), even at great depths, may provide an important pathway for fluid flow and hydrocarbon migration.

DISCUSSIONS

It appears that igneous sills within the FSB may have had the ability to interact with large-scale petroleum system in the basins. In particular, in terms of hydrocarbon migration, the sills may have acted as either barriers to, or – more surprisingly – as carriers for, hydrocarbon migration. The main mechanism of modification of the petrophysical characteristics of the sills has been recognized as the fracturing of the dolerite through genetic cooling processes or post-emplacement tectonic stresses. Although the number of wells and shows is not sufficient to draw firm conclusions, it seems that in the Flett Basin the migration of the gas in the Paleocene reservoirs could be affected to some degree by the magmatic intrusions. For example, we can tentatively suppose that charging of fields, such as Laggan and Tormore, might have been facilitated, to some degree, by the presence of large saucer-shaped sills whose edges are located just below the fields (Fig. 4). On the other hand, those same sills might have prevented the migration of gas in the sandstones located just above their most central part, as in wells 214/27-2 (Fig. 1).

However, we strongly emphasize that the impact of sills on hydrocarbon migration within the FSB (and in a wider context) is still not well understood, mainly due to lack of available data. Within this paper we have simply tried to highlight the



(a) Well data summary

Wells	Qtty sills	Sill Core	Sill lithology	Shows
205/10- 2B	43	1	Dolerite Porphyry	Gas
205/10- 5A	1	1	Porphyry	No
207/01a- 4Z	1	NO	Dolerite	No
208/15- 1A	8	1	Dolerite	No
208/17- 1	7	2	Dolerite	No
208/19- 1	1	NO	Dolerite	Gas?
208/21- 1	21	2	Dolerite	No data
213/27- 2	2?	NO	Porphyry?	No
214/04- 1	2?	NO	Dolerite	No
214/19- 1	2	NO	Dolerite	No
214/24- 1	2	NO	Dolerite	No
214/27- 1	>4	1	Dolerite	Gas
214/28- 1	6	1	Dolerite	Gas

(b) Core data

208/15- 1A

Dolerite, dark green grey
Porphyritic-ophitic, granular, hard, brittle
Sub-vertical fractures, non-mineralized

214/28- 1

Olivine dolerite
ophitic to sub-ophitic

Hydrothermal alteration
Selectively affected the ferromagnesian minerals while leaving the plagioclase virtually unaffected, augite relaced by nontronite with minute inclusions of titanite, olivine replaced by talc, original ilmenite altered to various iron oxides
Fracturing
Strongly developed over much of the core

Type 1: Shear fractures, most common, anastamosed, slickensiding, linear growth of fibrous minerals (chrysotile), granulation and smearing out of quartz. Filled mainly with calcite and quartz, with accessory chrysotile and celadonite

Type 2: Fractures with flat surfaces, no evidence of movement or second mineralization

Fig. 8. Well data summary table and core descriptions. (**a**) Table of wells penetrating magmatic sills. Qtty sills: Quantity of sills drilled; Sill Core: Quantity of cores taken in magmatic sills; Shows: Absence ('No') or presence ('Gas') of gas shows in the sills, or lack of documents to evaluate the absence/presence of shows ('No data'). (**b**) Examples of core descriptions with sills. Both open and cemented fractures are visible in the core. 208/21-1 shows that, in some cases, fracture location might be resolved with the resistivity logs when cores are not available.

potential interaction that sills may have with the petroleum system within the FSB.

Importantly, the factors which control the barrier or carrier behaviour of individual sills are not well understood. Depth of burial, intensity of faulting and diagenesis, and thickness of the magmatic body are all elements which control this behaviour but further studies need to be undertaken to improve the understanding of the mechanisms involved. Sills complexes in the Norwegian margin, offshore Australia and onshore Argentina, all in prospective basins, could provide good well and seismic datasets for such research. Additionally, field-based studies (e.g. East Greenland) looking at porosity and permeability around intrusions, plus the effect of fault inversion on faults containing feeder dykes, could be undertaken to provide valuable 'hard' data to allow de-risking of prospect in basins containing intrusions.

Despite uncertainties, we do tentatively suggest that the role of dolerite sills in hydrocarbon migration in the FSB (and further afield) may have been underestimated and intrusions should, in some degree, be integrated into future migration models in the FSB. It is, therefore, important to understand the end-member scenarios of hydrocarbon migration in basins with igneous intrusions compared to that of an 'ideal' prospective sedimentary basin without intrusions (Fig. 9). This is particularly applicable in basins covered by thick extrusive basalt sequences, where the formulation of strong subsurface conceptual models is needed due to the poor quality of seismic imaging. On this basis, a series of end-member scenarios is presented below and, based on these models, a method is proposed to integrate sills into the exploration workflow.

Basin compartmentalization: Sills acting as barriers to fluid migration

Within this scenario all the large igneous intrusions present in the sedimentary basin are assumed to be impermeable and act as barriers to fluid flow (Fig. 10).

Source rock. In the deeper part of the basin, intrusions may pervasively invade source-rock regions and create compartments (Fig. 10). Part of the subsequent hydrocarbons generated by the source rock and, in particular, any oil phase might in turn be trapped close to source. This will impact migration efficiency by reducing the quantity of hydrocarbons migrating into shallower reservoirs, in addition to creating the potential of a 'shadow zone' of hydrocarbon migration in sequences above the intrusions as a result of hydrocarbons being unable to migrate up fault sets.

Such a scenario is possibly the most troublesome that may occur in a volcanic-affected sedimentary basin, as it has the potential to severely affect migration pathways and efficiency. If an overlying sill suite or lava sequence is present, then seismic imaging may have degraded to such an extent at source-rock levels that identification of sills and sill geometries may be challenging in source-rock intervals. This very aspect occurs in the FSB, where confidently imaging the Jurassic source-rock regions is troublesome due to the occurrence of sills in the Cretaceous and Paleocene sections and, therefore, assessing the potential and severity of compartmentalization of source rocks within the FSB by intrusions is difficult.

Reservoir rock. In the shallower part of the basin intrusions permeate pervasively through the basin fill (Fig. 10), occurring through several stratigraphic levels. In this circumstance the possibility of compartmentalization of reservoir sequences occurs. Magma-exploiting fault sets may have the ability to form laterally extensive 'screens', further affecting migration efficiency and routes to reservoirs. The screens may also have the ability to act as side-seals or create overpressure compartments.

Basin compartmentalization: Sills acting as carriers to fluid migration

Within this end-member scenario all the igneous intrusions present in the sedimentary basin are permeable and act as carriers to fluid flow (Fig. 11).

In this case the hydrocarbons will preferentially migrate through the sills in comparison to the surrounding impermeable shales. Therefore, the 'shadow zone' effect will still be present;

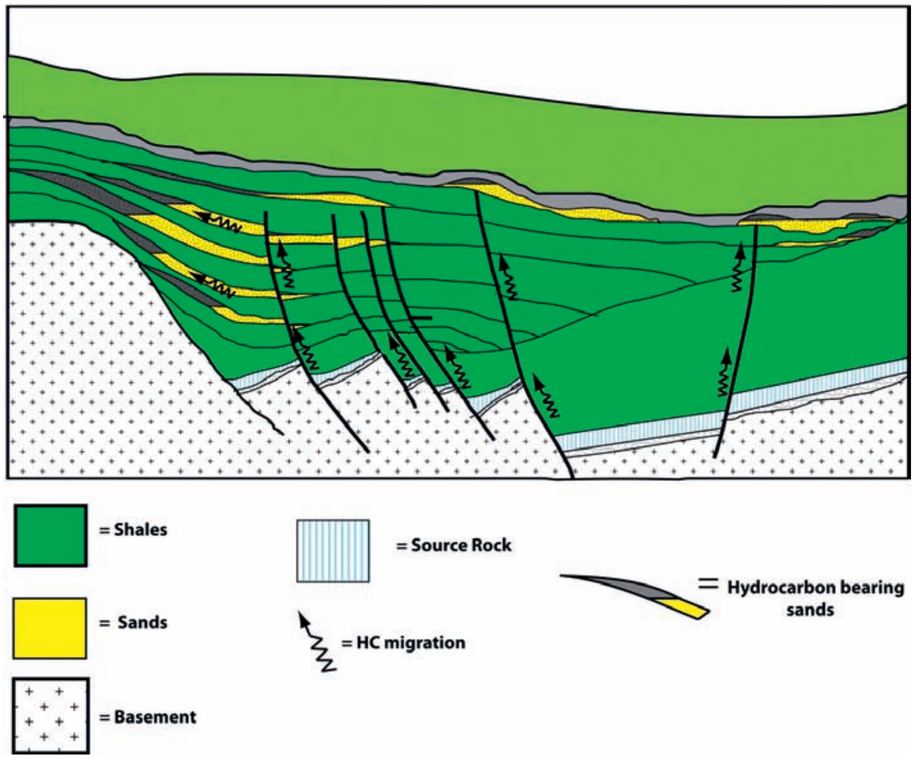


Fig. 9. Schematic of an 'ideal' petroleum-bearing basin with migration of hydrocarbons up major fault sets into reservoirs.

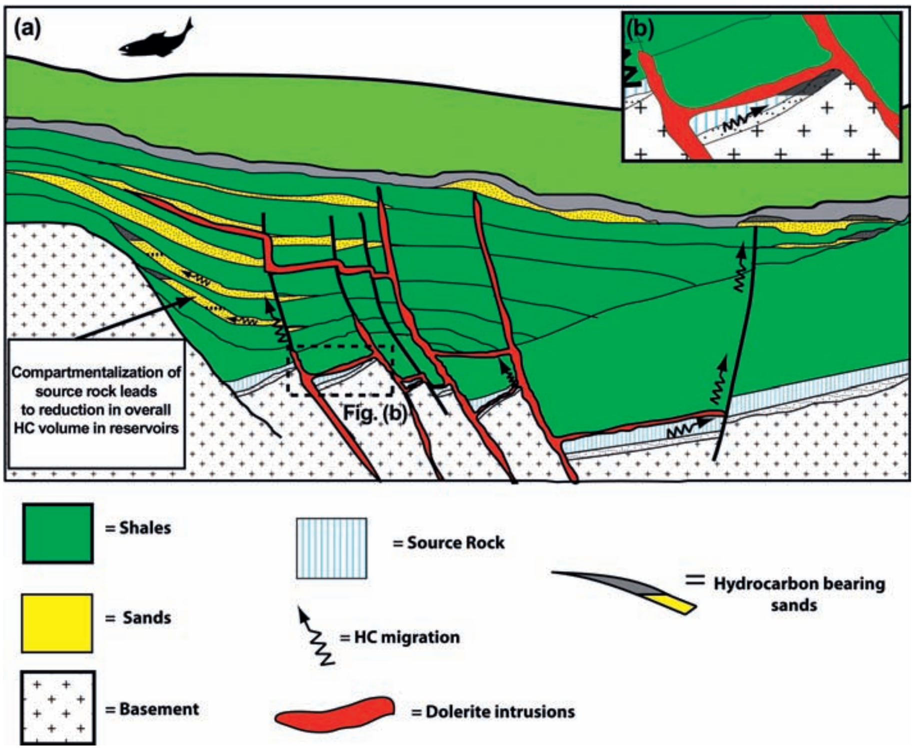


Fig. 10. (**a**) End-member scenario of igneous compartmentalization showing sills acting as impermeable 'barriers and baffles' to hydrocarbon migration, both within source-rock and reservoir intervals. Within such a scenario migration pathways up faults and through sandbodies may be inhibited, leading to certain reservoirs not being charged. The compartmentalization of source rock may lead to hydrocarbons becoming trapped close to source (**b**), leading to a reduction in the size of the kitchen which can be sourced by the reservoir and, therefore, to smaller charged volumes.

however; migration will be focused greatly on the edges of the sills. This scenario might be slightly or greatly altered, depending on the importance of faulting in the basin and the behaviour of these faults in regard to hydrocarbon migration.

This 'baffled migration' is possibly the case in the FSB where hydrocarbons might have exploited open fracture sets in large saucer-shaped sills to migrate from the deep Jurassic source rock, through a thick and relatively impermeable Upper Cretaceous shale sequence (into the Paleocene reservoirs).

Prospect risking in basins containing igneous sheet intrusions

It has been shown that in certain circumstances igneous intrusions may have an influence on hydrocarbon migration in sedimentary basins by either preventing or facilitating fluid flow. If such a behaviour is recognized in a basin, then the evaluation of the chance of success of charge of any prospect in this basin should take into account the intrusions. We propose here a simple

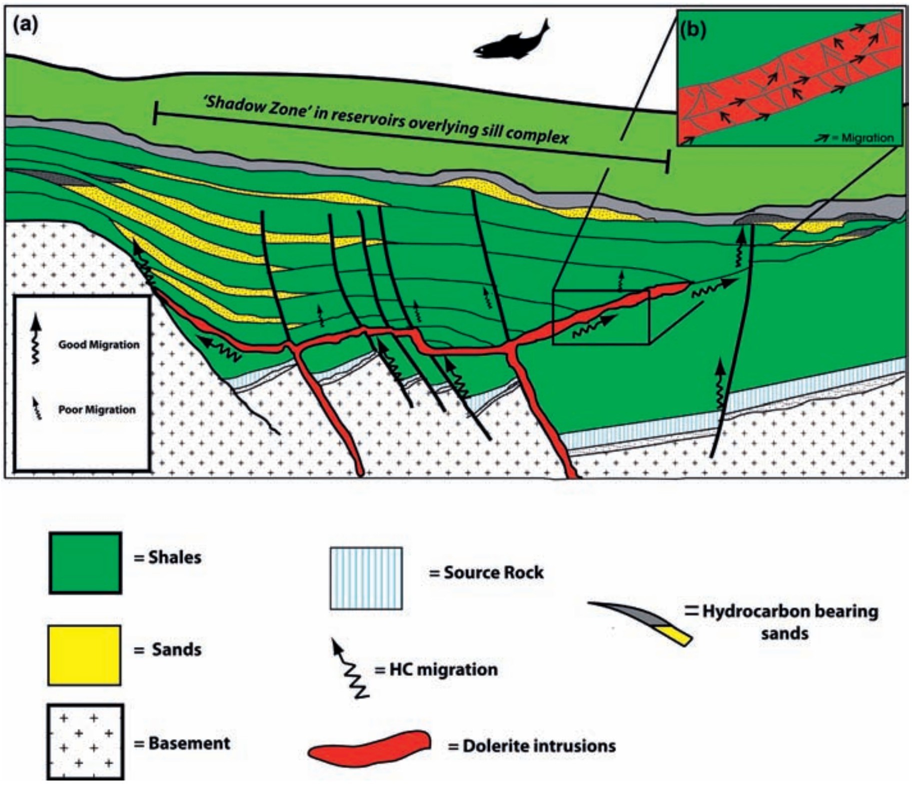


Fig. 11. (**a**) End-member scenario of igneous compartmentalization showing sills acting as carriers. Within such a scenario, open fractures in the sills create a high permeability pathway in the basin in comparison to the encasing shales. Most of the hydrocarbons from the source rocks will migrate through the sills (**b**) and escape at the edges of the main sill complexes. This type of migration scenario will create an area of poor migration, a 'shadow zone', in sequences overlying the sills, in addition to an area of focused migration above the edges of the sills.

method to incorporate sills in the process of prospect risking during the exploration phase.

Due to their lithology, sills in sedimentary basins are easily mappable on seismic sections. Two-dimensional maps of stacked sills in basins can be created in a small amount of time (e.g. Fig. 4). Using the models presented earlier, the maps can then be used to identify areas of 'concentrated migration', migration 'shadow zones' and areas of 'traditional migration' where there are no sills (Figs 9, 10 and 11). A prospect in a 'shadow zone' would see its charge risk increased, while a prospect in a 'concentrated migration zone' would see its charge risk decreased. In sedimentary basins that have undergone a tectonic event (e.g. basin inversion) post-emplacement of the intrusions (e.g. the FSB), prospects located above inverted faults can be assigned a decreased risk, as in this circumstance impermeable intrusions which have exploited, or cut across, faults are likely to have been fractured, causing fracture permeability and thus curtailing the ability of the intrusions to act as impermeable barriers to hydrocarbon migration.

This model is based on simple assumptions that sills are acting as barriers and/or conduits and that hydrocarbon migration is taking place post-emplacement of the sills. Each case should be evaluated with caution, but it may be a quick method that enables the incorporation of a potentially major factor in hydrocarbon migration, which has been overlooked until now. A more complex version could be created by incorporating the sills into traditional 3D basin modelling software.

CONCLUSIONS

Within this paper we have tried to evaluate the possible impact of magmatic intrusions on hydrocarbon migration in the FSB. Analysing the spatial relationships between sills and hydrocarbon occurrences, as well as recognizing the presence of gas-charged fractured sills and understanding the different processes which control the petrophysical characteristics of sills, led to a number of conclusions.

1. Magmatic intrusions in the FSB may act both as barriers and/or carriers for fluid flow/hydrocarbon migration.
2. The presence of open fracture sets within sills, even at deep levels of >4000 mbsf, appears to be a major factor in controlling if a sill is permeable. The origin of these fractures may be both primary, relating to cooling processes of the intrusion, or created by secondary tectonic events post-emplacement. Cementation by secondary minerals (e.g. calcite) sometimes destroys fracture permeability.
3. Hydrocarbon migration in areas with saucer-shaped sills may result in a concentration of migration above the tips of the sill, while above the central portion no or little migration may occur ('shadow zone'). This pattern seems to be visible in the FSB when analysing the location of sills and occurrences of gas fields and gas shows, although this relationship is also partly explained by the location of regional faults in the basin.
4. In basins with sills acting as 'barriers', both the source- and reservoir-rock intervals may be compartmentalized by the sills. In both cases, sills may impede hydrocarbon migration, leading to poorly charged traps (impact on prospect volume) or absence of charge (impact on prospect risking).
5. We tentatively suggest that the role of dolerite intrusions (sills and dykes) on hydrocarbon migration in sedimentary basins may have been underestimated. The models described here may be used for exploration purposes by identifying areas of concentrated migration and areas of 'shadow migration' as well as by using sills as input in 2D and 3D basin modelling.

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