Introduction

Within many volcanic basins globally the modelled critical moment, depicting the generation-migration-accumulation of most hydrocarbons, disagrees with the observations from actual discoveries (e.g. Bohai Bay Basin). One such basin is the Faroe-Shetland Basin (FSB), located within the West of Shetlands region of the United Kingdom Continental Shelf.

The FSB is an area of active petroleum exploration with discovered resources estimated at 1.6 billion boe, including the Schiehallion and Rosebank fields (Figure 1). Oil generation from the main source rock, the Upper Jurassic Kimmeridge Clay Formation (KCF), has previously been thought to have started by the mid-Cretaceous in previous models due to rapid Cretaceous basin subsidence. But this timing significantly predates the deposition of Paleocene and early Eocene reservoirs and seals in the area and the development of structural traps during Miocene inversion along faults at ca.16 Ma, providing a discrepancy between the apparent timing of petroleum generation and trap formation. This has previously been explained by invoking either overpressure delaying the critical moment of petroleum generation (Carr & Scotchman, 2003) and/or transitory hypothesized reservoirs (“Motels”) operating between the source rock and reservoir which temporarily host migrating petroleum before more recent re-migration into Paleocene reservoirs (Lamers & Carmichael, 1999).

Importantly, large areas of Cretaceous and lower Paleocene sediments across the FSB are intruded by a subsurface sill complex emplaced between 58 – 55 Ma (Schofield et al., 2015). Although previous work has investigated the direct heating effects of intrusions on source rocks within basins (Peace et al., 2015), few have quantitively considered the additional effects that intruding up to 2 km of igneous material into the overburden above a source rock has on petroleum generation.

Figure 1 Top Kimmeridgian source rock depth map (m) derived from seismic interpretation, including the Judd and Flett sub-basins and showing location of 1-D models.

Here we demonstrate using 1-D and 3-D basin modelling that properly estimating the thickness of igneous intrusions within the overburden atop the KCF and emplacing this at the correct time at ca.58 – 55 Ma results in a later onset of oil generation than previously predicted. Crucially, when used in conjunction with a lithospheric thermal model which incorporates the “old and cold” Neoarchean basement typical of the FSB, our model delays the critical moment of petroleum generation locally until after Paleogene reservoir and seal strata are deposited, removing the need to rely completely on complex re-migration modelling such as the “Motel” and “Whoopie Cushion” models by Lamers & Carmichael (1999) and Iliffe et al. (1999), respectively.
Time discrepancy in previous petroleum systems modelling

The timing conundrum between the onset of petroleum generation, charge timing and reservoir/trap availability has been previously explained by Iliffe et al. (1999) and Lamers & Carmichael (1999), who inferred the storage of petroleum in deep Cretaceous reservoirs prior to geologically-recent re-migration into Paleogene reservoirs. However, the presence of Cretaceous sandstones with porosity and permeability remains unproven (Scotchman et al., 2016), and there is little evidence of widespread oil staining or fluid inclusions within Cretaceous strata in the basin (Doré et al., 1997).

Carr & Scotchman (2003) provided an alternative mechanism to delay the onset of oil generation until the Cenozoic by invoking the overpressure of the source rock to retard kerogen transformation. However, the quantitative impact of overpressure on kerogen maturation remains a subject of debate. In addition, the magnitude of overpressure varies markedly across the FSB (Iliffe et al., 1999), questioning the viability of employing this model regionally. Mark et al. (2018) suggests that the removal of igneous intrusions and restoration of original basin sedimentary thickness may lead to later burial and onset of oil generation within the FSB than previously assumed, but this was not quantified.

Inclusion of igneous material in Cretaceous sequences in the FSB

Cretaceous thickness within the FSB, previously assumed to be of sedimentary origin, is often a combined thickness of both Cretaceous sedimentary material and a substantial thickness of Paleogene aged sills, producing an “overthickening” of the Cretaceous sequences post-deposition. Crucially, this forms a significant proportion of the overburden above the Jurassic source rock(s). Imagined and unimaged igneous intrusions can locally have a cumulative thickness totalling 1 – 2 km (out of a typical 3 – 5 km thick Cretaceous section), which needs to be removed to restore the Cretaceous section to its original depositional thickness. The major implication of removing igneous material is that Jurassic source rocks were significantly shallower than previously considered, and thus colder, until ca.58 – 55 Ma.

As ca. 91% of measured intrusions in FSB wells are <40 m in thickness and typically basaltic in nature (Mark et al., 2018), our models suggest geologically-rapid cooling of intrusions (in the order of ca.10^2 years) due to the large contact area with surrounding country rock sediments and the relatively rapid heat conduction associated with thin intrusions (Peace et al., 2015).

The Cretaceous sediments within the FSB are primarily shales and other fine-grained rocks, which typically have low thermal conductivities, averaging ca.0.8 - 1.5 W/mK globally. This results in a relatively high geothermal gradient (>35 °C/km), with a shallow depth (<2.5 – 3.0 km) to the oil generation window (90 – 140 °C) in the FSB. In contrast, crystalline igneous material is an efficient conductor of heat, with thermal conductivities of dolerite ranging from ca.2.1 – 2.5 W/mK.

We estimate that including crystalline igneous material may result in up to a 36% increase in the net thermal conductivity of the Cretaceous overburden above the KCF (based on 100% sediment vs. 50% sediment and 50% igneous material), invoking a reduction of up to ca. 8% in the geothermal gradient of the Cretaceous package wherever intrusions are thickest, reducing the present-day temperature of the underlying KCF. Where the top KCF is overlain by up to 7 km of overburden, this may amount to a reduction of up to 20 °C at the top KCF level at the present day compared to sedimentary overburden alone in our model.

The model indicates that in the centre of the Judd Sub-basin, KCF oil generation begins as early as ca.90 Ma when modelling the total Cretaceous thickness, because of the implied thick, poorly-thermally conductive Cretaceous (i.e. mud-rich) overburden (Figure 2). However, by emplacing the 1,190 m thickness of Paleogene intrusions predicted in this location by Mark et al. (2018) at the correct time (58 – 55 Ma), the thinner overburden during the Upper Cretaceous above the KCF would reduce the source rock palaeo-temperature, with the predicted onset of petroleum generation in the late Campanian (73 Ma), some ca.17 Myr closer to the present-day than previous models (Figure 2). Interestingly, the relatively high thermal conductivity of crystalline igneous rocks in comparison to mud-rich sediments within the overburden atop the KCF is predicted to have a significant influence on
maturation history, resulting in up to a 7% decrease in the geothermal gradient at present day where intrusions are thickest.

However, even after including 1,190 m of intrusive material, the model suggests oil generation in the centre of most sub-basins in the FSB would still begin within the Cretaceous. This implies that additional processes must be considered to allow oil expulsion to begin in the Cenozoic.

Inclusion of Neoarchean basement
Lithospheric composition and structure acts as a primary control on the thermal regime in sedimentary basins, with up to 50% of surface heat flow originating from radiogenic heat production (RHP) from the upper crystalline crust and basin infill. The RHP from “typical” Phanerozoic continental crust (including the North Sea) ranges from 2.5 – 3.2 μW/m³, with default values of upper crust RHP in most basin modelling software set at ca. 2.8 – 3.2 μW/m³ (e.g. Genesis®, PetroMod©).

The basement underlying the FSB is composed of Neoarchean (ca.2.7 – 2.8 Ga) orthogneisses (Holdsworth et al., 2018) which typically contain low concentrations of heat-producing radionuclides $^{40}$K, $^{232}$Th, $^{235}$U and $^{238}$U which, together with the prolonged time for radiogenic decay, are expected to result in cold (reduced RHP) basement at the time of petroleum generation.

To test this, RHP was calculated using K, Th and U concentrations following the method of Turocotte & Schubert (2014) from 3 basement samples from wells in the study area (204/10-1, 205/16-1 and 214/9-1). The result is a mean RHP of 1.6 μW/m³ ($\sigma = 0.74$), a reduction of up to 50% in comparison to a “typical” North Sea value of 3.2 μW/m³.

Without incorporating igneous intrusions, this “cold” basement results in a mean present-day surface heat flow of 51.6 ± 2.5 mW/m² and geothermal gradient of 30.7 ± 2.8 °C/km across the FSB, a decrease of ca.10% in comparison to a “typical” North Sea RHP model. This “cold” basement model suggests that the onset of oil expulsion will occur later than previously predicted by up to 30 Myr in the centre of the Judd Sub-basin and up to 22 Myr in the centre of the Flett Sub-basin.

Figure 2 Cartoon modified from Mark et al. (2018) of “overthickening” of a sedimentary section by igneous intrusions and the need to add igneous intrusions into the overburden atop source rocks at the correct time (58 – 55 Ma). B) Predicted oil expulsion history from the Kimmeridgian source rock in a 1-D pseudowell model assuming a net thickness of 1,190 m of igneous intrusions within the Cretaceous and Paleogene overburden, with both the “Typical RHP” (2.8 μW/m³) and “Cold RHP” (1.6 μW/m³) crust of the North Sea and Neoarchean orthogneiss basement in the FSB, respectively. C) The relationship between net igneous intrusion thickness and the time difference of the onset of oil expulsion for the 14 1-D pseudowell models shown in Figure 1.
Discussion: Motel models, overpressure, basement composition or igneous overthickening?
We have demonstrated that by considering an appropriate basement composition, in conjunction with both the post-deposition thickening and increase in thermal conductivity of the Cretaceous overburden by Paleogene igneous intrusions, that the onset of KCF oil expulsion may begin up to 40 Myr later than previously modelled (Figure 2), within the isotopic age range of oils.

However, as demonstrated by Mark et al. (2018), the presence and thickness of Paleogene intrusions is highly variable across the FSB, from as much as 2 km in the Nuevo Sub-basin to 200 m locally in the Flett Sub-basin, some 30 km away. We therefore argue that no one unifying mechanism across the basin can solely explain the time discrepancy between basin models and actual timing of petroleum charge. Rather, the mechanisms outlined in this paper, combined with previous models (e.g. overpressure retardation and “Motel” models) or some hitherto unrecognised factors, might all operate across the FSB to some degree. Our model cannot account for very recent charge (since 20 Ma) seen in many fields within the FSB, based on the modelled biodegradation rate of oils and reservoir temperature histories. On this basis, re-migration of oil from basin sands or long-lived open fracture systems in the basement (Holdsworth et al., 2019) could provide the source of oil required for recent replenishment of oil fields/discoveries in the basin margins. Igneous intrusions may act as migration barriers within the heavily intruded sections of the basin, providing a complex migration route to accumulations on the basin margins.

References