Stratigraphic Overview of Palaeogene Tuffs in the Faroe-Shetland Basin, NE Atlantic Margin.

Douglas Watson[1]*, Nick Schofield[1], David Jolley[1], Stuart Archer[2], Alexander J. Finlay[3], Niall Mark[1], Jonathon Hardman[1], Timothy Watton[4]

[1] *Department of Geology and Petroleum Geology, University of Aberdeen, King's College, Aberdeen AB24 3UE, UK*

[2]*Maersk Olie og Gas AS, Esplanaden 50, DK-1263 Copenhagen Ø, Denmark*

[3]*Chemostrat Ltd. 1 Ravenscroft Court, Buttington Enterprise Park, Welshpool, SY21 8SL UK*

[4]*Statoil (UK) Limited, One Kingdom Street, London, W2 6BD, UK*

**Corresponding author (e-mail: douglas.watson@abdn.ac.uk)*

Abstract: Tuffs form key stratigraphic markers which assist with determining the timing of volcanic margin development. A number of laterally extensive tuffs are preserved along the North Atlantic Margin in the offshore Faroe-Shetland Basin (FSB), a product of early Palaeogene volcanism associated with the break-up and seafloor spreading between Greenland and northwest Europe. These tuffs, which are dominantly basaltic in composition, are widely preserved in the contiguous North Sea Basin. However, less attention has been paid to them in the FSB. This study integrates multiple regional datasets, including 3D seismic and released commercial well logs to detail the character and distribution of early Palaeogene tuffs in the FSB. The earliest tuffs are more locally identified by their presence in core, whereas later tuffs are more regionally recognisable, highlighting more widespread volcanism with time. The distribution of tuffs also reveals the timing of formation of the previously enigmatic volcanic centres. Importantly, due to constraints of vertical resolution in well data, we argue the number of tuffs in the North Atlantic Margin is likely underestimated, and biased towards basaltic tuffs which are easier to identify on well logs.

Volcanic tuffs are recognised as an almost ubiquitous component of flood basalt provinces globally (Ross *et al*. 2005), and are invaluable in event stratigraphy and stratigraphic correlation (Fisher & Schmincke 1984). The North Atlantic Margin experienced widespread volcanic activity during the early Palaeogene (66-54 Ma), associated with continental break-up and sea-floor spreading between Greenland and the northwest Europe (Passey & Hitchen 2011). A manifestation of this volcanism was the widespread deposition of basaltic tuffs throughout the offshore basins of northwest Europe. In the Faroe-Shetland Basin (FSB) these tuffs are important in hydrocarbon exploration, as they can form prominent stratigraphic markers that help with regional seismic interpretation and stratigraphic correlation, inform the position of casing points, and can also act as pressure barriers to fluid flow. The early Palaeogene (Palaeocene and Eocene) tuffs preserved in the North Sea Basin are extensively studied (Jaqué & Thouvenin 1975; Knox & Harland 1979; Malm *et al.* 1983; Knox & Morton 1983; Knox & Morton 1988; Morton & Knox 1990). To date though, only isolated stratigraphic units have been characterised in the FSB (e.g. Eidesgaard & Ziska 2015). This study represents the first truly regional stratigraphic appraisal of the tuff horizons throughout the lower Palaeogene stratigraphy of the FSB. We examine the character and distribution of tuffs throughout the FSB Palaeogene stratigraphy, and discuss their likely volcanic sources and the implications for North Atlantic Volcanism.

Classification of tuffs

Tuffs are lithified volcanic ash produced during explosive volcanic eruptions (Fisher & Schmincke 1984). Where ejected material is more buoyant than the surrounding atmosphere it typically forms an eruption plume with ash (angular glass shards) which then rains out, forming *fallout* deposits (Fisher & Scmincke 1984). Fallout deposits can produce a laterally extensive blanket, often over hundreds of kilometres. When ash falls into the water column it is hydrodynamically sorted, forming normally graded beds (Ledbetter & Sparks 1979). Many of the tuffs in the offshore basins of Northwest Europe are regionally extensive (over hundreds of kilometres), thin (cm scale) and normally graded (Knox & Morton 1988), which, in addition to quenched glassy crystals visible in thin section, is why they are widely interpreted as fallout deposits (Malm *et al.* 1977; Knox & Morton 1983; Knox & Morton 1988).

Ash that is moved from its original depositional location before lithification is considered *reworked* (Fisher 1961). Where units contain a mixture of both tuff (>25%) and epiclastic material, they are termed "tuffaceous" (Fisher & Schmincke 1984). Tuffs also fall under the general umbrella term of *volcaniclastics*, clastic material containing epiclastic volcanic grains (Mathisen & McPherson 1991). However, tuffs can generally be distinguished from other volcaniclastics (e.g. clastic units formed of eroded basaltic lavas) due to their unique petrophysical character, detailed in the methodology section of this paper.

Basin Evolution

The Faroe-Shetland Basin (FSB) is located on the NE Atlantic Margin, between Shetland and the Faroe Islands (Fig. 1a). The FSB consists of a collection of southwest-northeast trending sub-basins of Mesozoic to recent basin fill, bounded by intra-basinal highs of Precambrian crystalline igneous and metamorphic basement capped by Palaeozoic and Mesozoic sediments (Lamers & Carmichael 1999). The FSB developed through multiple episodes of extension and subsidence between the Permo-Triassic and Palaeocene (Ritchie *et al.* 2011). The NE-SW basin trend is thought to be inherited from the Caledonian grain (Earle *et al.* 1989). A series of "transfer lineaments" run perpendicular to the main basin trend (Rumph *et al.* 1993; Naylor *et al.* 1999; Ellis *et al.* 2009; Moy & Imber 2009) and appear to have affected sedimentation routes (Larsen & Whitham 2005; Jolley & Morton 2007; Ritchie *et al.* 2011) and in some cases magma emplacement (Archer *et al.* 2005; Schofield *et al.* 2015).

During the Palaeocene and early Eocene large areas of the North Atlantic Margin were significantly affected by flood basalt volcanism due to the impinging proto-Icelandic plume and associated continental breakup between Greenland and Northwest Europe (White & McKenzie 1989). The remainder of the Cenozoic was characterised by post-rift thermal subsidence, punctuated by several inversion episodes in the Oligocene and Miocene (Dore *et al.* 2008). For consistency with previous work, this paper uses the lithostratigraphy of Ritchie *et al*. (2011) and Stoker & Varming (2011), and the sequence stratigraphic subdivision of Ebdon *et al*. (1995), shown in Fig. 2.

Palaeogene Volcanic History

Volcanism in the FSB and North Atlantic margin can be divided into two main categories: (1) volcanism prior to breakup, and (2) volcanism during breakup and subsequent initiation of sea floor spreading which manifested between the Faroes and Greenland. These are outlined as follows:

Phase 1: Pre-continental breakup (62 Ma to 58 Ma)

The earliest volcanic activity in the North Atlantic Margin is recorded by the Eigg Lava Formation, North West Scotland, dated from silicic tuffs near the base of the formation to the early Palaeocene/Danian [61.15 ±0.45 Ma] (Chambers *et al*. 2005). In the FSB, the earliest expression of volcanic activity is recorded in the Mid-Palaeocene/Selandian (*Ca*. 62-59.8 Ma) via basaltic tuffs cored in Sequences T26 and T34, described in this paper. The start of the Thanetian (59.2 Ma) marks a major increase in volcanism, with regional deposition of ash preserved as the Kettla Tuff Member, during Sequence T36 (Jolley & Bell 2002). Aerially restricted subaerial lavas were also erupted at this time, recorded off the flank of Brendan's Volcanic Centre in well 219/21- 1 (Jolley 2009) and in the northern Foula Sub-basin in 208/21-1 (Schofield *et al*. 2015). The Faroe-Shetland Sill Complex, an aerially extensive suite of dolerite sills that preferentially intrude into the Cretaceous shales (Ritchie & Hitchen 1996; Smallwood & Maresh 2002; Schofield *et al*. 2015), was emplaced, at least in parts, during Phase 1 as evidenced by Upper Palaeocene (~58.4-58.1 Ma, Lamba Fm.) sediments onlapping force folds created by underlying sills (Schofield *et al*. 2015).

Phase 2: Syn-continental breakup (56.1 Ma to 54 Ma)

The early Eocene (56-47.8 Ma) marks the main phase of extrusive volcanism in the FSB, with the emplacement of flood basalt lavas of the Faroe Island Basalt Group (56.1-54.9 Ma) over an area at least 40,000 km^2 (Passey & Jolley 2009; Schofield & Jolley 2013). The main phase of emplacement of the Faroe-Shetland Sill Complex is during deposition of Sequence T40, between 56.1-55.2 Ma (Schofield *et al.* 2015). Around 54.9 Ma (upper Sequence T45) the focus of volcanism changed with the cessation of lava eruption in the FSB (Jolley & Bell 2002). During deposition of Sequence T50 it is then postulated that flooding of this nascent rift forming between the Faroes and Greenland led to the interaction between magma and water, resulting in a series of phreatomagmatic eruptions which deposited the fallout tuffs of the Balder Formation (Morton & Knox 1990; Jolley & Bell 2002). Following deposition of the Balder Formation, the dominant expression of igneous activity along the North Atlantic was the emplacement of submarine seaward dipping reflectors (Jolley & Bell 2002).

Methodology

Data

The main dataset used in this study is a collection of over 400 released commercial exploration, appraisal and development wells drilled in and around the FSB (Fig. 1b). Seismic datasets were used to map seismically identifiable tuffaceous units, and to understand the overall basin evolution and stratigraphy. Two 3D seismic surveys were used: the Faroe-Shetland PGS MegaSurvey Plus 3D, covering an area of ~24,000 km^2; and the PGS/TGS MC3D-FSB2012 Geostreamer®, which covers a gap in the MegaSurvey (Fig 1b). In the north of the FSB, 3D seismic datasets are sparse, and the PGS CRRG regional 2D dataset was used (Fig. 1b).

Subsurface Character of Tuffs in the UK Continental Shelf

Micro-scale: core & ditch cuttings

Tuffs are rarely cored in the offshore basins of northwest Europe as they are typically best preserved in non-prospective claystone dominated successions. From the rare instances of Palaeocene to lower Eocene tuffs cored in the FSB, and the more extensive North Sea Basin record, we recognise two distinct types of tuffaceous material (Fig. 3):

- Type 1: Thin, discrete tuff beds (0.2-25 cm thick), typically interbedded with thin claystones, siltstones, sandstones, and limestone stringers (Malm *et al.* 1977; Knox & Morton 1988).
- Type 2: Thicker (5-35 m), generally massive units of sandstone or siltstone containing tuffaceous material.

Most of this tuffaceous material, in both type 1 and 2 tuffaceous deposits, is almost completely altered to varicoloured (green-blue-grey), smectitic or bentonitic clay (Knox & Morton 1988) (Fig. 3), though rare glass shards are identifiable in thin section (Malm *et al.* 1977). Ditch cuttings (the rock fragments brought up to the rig site via drilling mud) are a more widely available source of information regarding tuffs. In the FSB tuffs are commonly described in ditch cuttings as blue-grey, amorphous, with glass shards and/or chlorite (information generally found in composite logs, mud logs and End of Well Reports). An additional way tuffs have been successfully identified in ditch cuttings is through geochemical analysis (Finlay *et al.* 2016), by the fingerprinting of particular elements:

- Ti: Primarily associated with minerals occurring in mafic volcanic rocks such as pyroxene (especially titanaugite), and in mafic volcanic ash deposits.
- Cr: Linked with Cr-spinel and accessory opaque minerals found in mafic igneous material, and also present in trace amounts in pyroxene.

- Th: Associated with heavy minerals such as zircon, apatite, garnet and epidote (confirmed by heavy mineral analysis) and therefore used as a proxy for detrital (non-volcanic) input.

Meso-scale: petrophysical character

Thinly bedded tuffs identified in the Palaeogene of northwest Europe tend be cm-scale, with rare instances of exceptionally thick tuffs (>20 cm) interpreted as reworked debris flow deposits (Malm *et al.* 1977) or an amalgamation of several tuffs (Knox & Morton 1988). The vast majority of these thin cm scale tuffs are therefore significantly below the 40 cm vertical resolution of the wireline gamma ray and density logs (Rider & Kennedy 2011) (Fig. 3). It is thus the grouped response of tuffs interbedded with the surrounding sediments (e.g. a tuffaceous claystone or tuffaceous sandstone) that is generally imaged on well logs, which makes it impossible to determine the thickness of individual ash bands unless the interval is cored (Morton & Knox 1990).

Tuffaceous units of a sufficient thickness have a characteristic petrophysical response in well logs (Fig. 4a), notably: low gamma (15-40 API), high sonic velocity (80-100 US/F) and high resistivity (10-11 Ohm.m). Other lithologies can have low gamma, high sonic velocity and high resistivity (Fig. 4b), such as basaltic lavas, basaltic volcaniclastics (i.e. eroded lavas), limestones and heavily cemented sandstones. However, both types of tuff, interbedded (type 1) and massive, tuffaceous clastic units (type 2) have a characteristic density/neutron response similar to claystone (Fig. 4c), which is unique amongst low gamma lithologies. More specifically this equates to high neutron values (39-30 pu) and moderately low densities (2.15-2.35 g/cm^3). The two distinct types of tuffaceous material can be distinguished from each other most clearly by the gamma ray log, where thinly bedded tuffs (type 1) tend to have a serrated motif (Fig. 4d) due the presence of other interbeds (e.g. claystone and sandstone). Meanwhile, thick massive tuffaceous sandstone or siltstone (type 2), tends to have a blockier gamma profile

(Fig. 4e) and a marginally higher sonic velocity (75 m.s/ft compared to an average of 85 m.s/ft in thinly bedded tuffs) due to the lack of interbeds (Fig. 4f). Due to the high exploration costs associated with offshore drilling, full wireline suites are increasingly only run in reservoir intervals. As the majority of tuffaceous intervals in the FSB are preserved in non-prospective claystone, this can therefore lead to only gamma, resistivity and sonic being run through them, which can be problematic for their consistent identification.

Macro-scale: Seismic

There is generally a significant acoustic impedance contrast between tuffaceous intervals and the surrounding claystone and siltstones, due to the marked increase in sonic velocity going in to the tuffs. Tuffaceous intervals, where sufficiently thick, therefore appear either as seismically identifiable (>12 m) or fully seismically resolvable (>25 m) positive amplitudes ("hard kicks") (Fig. 5) that can be confidently mapped across seismic surveys. Tuffaceous units can also form soft kicks, where the surrounding lithologies are significantly acoustically faster, such as basalt.

Stratigraphy of the tuffaceous sediments in the Faroe-Shetland Basin

Tuffaceous material is reported in six main lithostratigraphic units in the FSB: in the Sullom, Vaila, Lamba, Flett and Balder formations, and in the undifferentiated Stronsay Group. This section will detail the character and distribution of these tuffs throughout the FSB stratigraphy. It should be noted that a number of tuffs reported in previous literature appear to have been identified based on either limited evidence (i.e. lack of well penetrations) or misinterpretation of petrophysical logs, which shall also be addressed below. For reference, tuffaceous sediments present within the Sullom, Vaila and Lamba formations are equivalent to Knox & Morton's (1988) North Sea Phase 1 pyroclastic sediments (in the Lista, Maureen and Ekofisk formations), while tuffs in the Flett and Balder formations fall within Phase 2 (Forties, Sele and Balder formations) (Fig. 2).

Sullom Formation (T10-T22) (66 Ma to 62.9 Ma)

Misreported tuffs

Naylor *et al*. (1999) identify several wells (204/19- 2, 204/20- 1 and 204/24- 1A) in the Foinaven Sub-basin containing thin tuffaceous units in the Sullom Formation, which they link to the supposed presence of two nearby Palaeocene volcanic centres: the "Judd" and the "Westray". Both of these "volcanic centres" were identified based on circular positive gravity and magnetic anomalies (Fig. 6), though in 1999 neither structure had been tested by an exploration well. Subsequently, the crest of the "Judd Volcanic Centre" was penetrated by 204/10-1 (drilled in 2002) and at 2484 m (measured depth below the rotary table [MDBRT]) Devonian granodiorite was encountered, confirmed by numerous side-wall cores. The "Westray Volcanic Centre" was penetrated by 204/15-2 (drilled in 2001) and encountered Pre-Cambrian granite at 3788 m (MDBRT). The homogeneous seismic character and well data of both testifies to them being ancient acidic plutonic bodies and not related to Palaeocene volcanism. In the wells listed by Naylor *et al*., we recognise no petrophysically identifiable tuffaceous units, nor is there any description of tuffaceous material from the ditch cuttings, side-wall cores, mud log, composite log or End of Well Report. The lack of any petrophysically identifiable tuffaceous units means that any hypothetical tuffaceous material identified in cuttings cannot be proven as *in-situ*, and could be from cavings from higher in the well bore, or transported via recirculated or re-used drilling mud. We therefore conclude there is, at present, in the 400 wells studied, no clear evidence of tuffaceous material or volcanism in the FSB during deposition of Sequences T10-T22.

Vaila Formation (T25-T35) (62.9 Ma to 58.7 Ma)

T25-T28

Character & distribution of tuffs

Morton *et al*. (1988) identify one single tuff horizon (1 cm thick) within a claystone succession at 22.7 m depth from BGS shallow borehole 82/12 core, in the Papa Basin, located on the extreme south eastern edge of the FSB (see Fig. 7a for location of borehole, and all other wells henceforth referred to). We have re-examined the palynofloras from this borehole which contain common *Palaeocystsodinium bulliforme* with abundant *Palaeoperidinium* pyrophorum. This indicates an age equivalent to Sequence T26. Morton *et al*. note the 82/12 tuff is composed of pale yellow, angular, vitric shards with high TiO_2 and a tholeiitic character, and identify further tuffaceous material in 204/30-1 and 205/30-1, though no petrophysically identifiable tuffs are recognised within these two wells. Further tuffaceous material is reported in Sequences T25-T28 [unit V2 of the Vaila Fm.] in the FSB by Sørensen (2003) and Stoker & Varming (2011). However, thin T28 tuffaceous mudstones identified in the Foinaven sub-basin in wells 204/20-3 and 204/20-4 (Stoker & Varming 2011) have exceptionally low resistivity (0.6 Ohm.m) and high density values (2.55 g/cm^3) relative to tuffs, petrophysically more consistent with thin beds of porous sandstone. Sørensen (2003) meanwhile does not refer to any specific wells. Similar Sequence T28 thin beds are identified in the Marjun well log (6004/16-1z), in the Faroese portion of the Judd Sub-basin. However, these low gamma thin beds, located around 3530 m (MDBRT), are likely limestone, due to their moderately high densities (2.5-2.65 g/cm^3).

T31-T34

Character & distribution of tuffs

Stoker & Varming (2011) recognise several 1-2 cm, normally graded, green tuff bands in core from the Flett sub-basin in the Laggan Discovery well (206/01-2). A similar tuff is present in the nearby 206/01-3 well, and is characterised as chlorite-rich, with an extremely low quartz content and relatively high proportions of Ti, Mg and Co (Hillier 2006), consistent with a mafic tuff. In both wells, these tuffs are too thin to enable a petrophysical expression, meaning their identification is therefore based purely on their visibility in core. Tuffaceous siltstone is also cored in the Longan Well (6005/15-1) overlying the Sjúrður High, located at the southwestern end of the FSB in the Faroese sector. The cored section is between 3508-3514 m, and in thin section mainly consists of a mixture of glassy volcanic grains and detrital quartz and feldspar, suggesting reworking (Nils Einar Aase pers. comm 2016). The interval has a distinct petrophysical response, exhibiting a moderately low gamma (40-45 API) with a serrated motif (suggesting an interbedded character, typical of type 1 tuffaceous deposits), and high resistivity (10.5-11 Ohm.m). Geochemical analysis has not been conducted on this tuff. In all of the quoted wells there is an abundance of *Glaphyrocysta ordinata* at the depths these tuffs are present, which is characteristic of Sequence T34 within the basin. The cored T34 tuffs in the Flett Sub-basin cannot be correlated to offset wells due to the lack of a petrophysical expression. Meanwhile, the petrophysically imaged Longan tuffs do not correlate to any offset wells in the Judd or Foinaven sub-basins. At present, thickness trends therefore cannot be determined for Sequence T34 tuffs.

T35

Character & distribution of tuffs

Stoker & Varming (2011) also identify Sequence T35 [unit V4 of the Vaila Fm.] tuffaceous sediments in wells 204/19-2 and 205/9-1, on the Westray Ridge and in the Flett Sub-basin (Fig. 7), respectively. However, we recognise no cuttings descriptions, side-wall cores or petrophysically identifiable tuffaceous intervals in Sequence T35 in either well, though Sequence T36 (Kettla Tuff Mb.) tuffs are present. There is, however, a 22 m thick tuffaceous siltstone interval interbedded within "clean" siliciclastic sandstones identified in well 204/17-1 in the Foinaven Sub-basin (Fig. 7a). This tuffaceous unit is described from sidewall cores as greenish grey, with abundant dark grey lithic fragments and poor visible porosity. Petrophysically the unit has a relatively blocky, low gamma profile, a blocky high resistivity and exhibits a density/neutron response typical of claystone (Fig. 8). The blocky gamma and resistivity of this tuff imply a lack of interbeds, typical of type 2 tuffaceous deposits. This 22 m thick tuffaceous unit is also relatively laterally discontinuous in nature, pinching out before 204/18-1, <9 km to the north east.

Lamba Formation (T36-38) (58.7 Ma to 56.1 Ma)

T36

Character of tuffs

The Kettla Tuff Member, henceforth referred to as "Kettla", is a prominent stratigraphic marker, found near the base of Sequence T36 (Lamba Fm.), characterised by a mixture of siliciclastic and volcaniclastic material which contains tuffs (Eidesgaard & Ziska, 2015). At a microscopic scale degraded volcanic ash is recognised in the member (Jolley *et al*. 2005), and ditch cuttings are generally described as pale grey-blue, mottled with glass shards and abundant white clay (e.g. 205/5a-1, Flett Sub-basin). Geochemically the Kettla is regionally characterised by a relatively high Cr/Th and TiO_2/Th content (Fig. 9a) (Chemostrat 2013; Finlay *et al*. 2016). When the immobile elements are plotted on a geochemical discrimination diagram (e.g. Winchester & Floyd 1977), the Kettla lies in the andesite field (Fig. 9b), significantly more evolved than the older tuffs we have described.

Petrophysically the Kettla is often characterised by a double gamma peak and sharp increase in sonic velocity, as well as an intra-Kettla high gamma spike (Stoker & Varming 2011), interpreted as marine claystone largely devoid of tuff. However, the petrophysical character of the Kettla exhibits significant lateral variability, in places showing a blockier gamma (representing type 2 tuffaceous deposits), for example in well 6004/17-1 in the Judd Sub-basin (Eidesgaard & Ziska 2015). Locally the Kettla grades into tuffaceous sandstone (e.g. seen in core in 205/09-1, Flett Sub-basin). This cored interval in 205/09-1 is composed of a fine-medium grained sandy matrix, with glassy shards and very fine-grained porphyritic igneous lithoclasts (5-10 mm), and exhibits a lower gamma and higher sonic velocity than in offset wells (Fig. 10). The unit is interpreted as a debrite, not a typical fallout tuff, and is occasionally misattributed to Sequence T35/Vaila Fm. (e.g. see Stoker & Varming 2011), though seismic horizon mapping shows it be the same reflector as the prominent Kettla in well 214/28-1, Flett Sub-basin (Fig. 10). On a macro-scale, the Kettla forms a prominent, though laterally restricted seismic marker, the amplitude of which generally dims as the unit thins.

Distribution of tuffs

The Kettla is identified by its distinct petrophysical and seismic character against the background sediments, produced due to the presence of tuffaceous material. The distribution of Sequence T36 tuffaceous material is therefore predicated on the distribution of the Kettla as whole. Eidesgaard & Ziska (2015) identify a southern (in the Foinaven and Judd sub-basins) and central Kettla depocentre (Flett Sub-basin) (Fig. 7b). There is an additional (3) northern Kettla depocentre in the western edge of the Møre Basin (Fig. 7b), out with the study area of Eidesgaard & Ziska (2015). In the southern depocentre the Kettla generally thickens towards the northwest, away from structural highs (16 m thick overlying the Westray Ridge in 204/15-2) towards basin lows (42 m in the Judd Basin, 6004/16-1z). In the central depocentre the

Kettla thins to the northeast, from 56 m in the southern end of the Flett Sub-basin (in 205/09-1) to 9 m in the northern end (214/19-1). In the northern depocentre the Kettla is only clearly identifiable in three wells in the western Møre Basin, appearing too thin to the south, from 25 m thick in 219/28-2z to 5 m thick in 219/28-1, 2km to the south. This thinning also corresponds to a dimming in amplitude of the Kettla seismic horizon in the northern depocentre.

T38

Character & distribution of tuffs

A 92 m thick volcaniclastic sandstone is penetrated in the south of the FSB, on the margin of the Judd High in well 204/22-1 (Fig. 7b). The interval has a prominent petrophysical character, exhibiting a low gamma (15-20 API) with a "cleaning upwards" profile (gamma decreases), and a high sonic velocity (70-80 ms/ft). The unit is interpreted as volcaniclastic due to its significantly lower gamma and higher sonic velocity relative to all other sandstone units penetrated in the well. The unit is described as tuffaceous from ditch cuttings, though we argue it cannot be confidently classified as tuffaceous as density and neutron tools were not run in the well. The volcanicastic unit is relatively laterally discontinuous, present in 204/22-1 (overlying the Judd High) and pinching out before 204/22-2, 8 km further northwest in the Judd Sub-basin. The palynological assemblage (*Alisocysta margarita*) through the interval is typical of sediments throughout the mid-late Palaeocene (Sequence T36-T40). Through examination of the seismic section (Fig. 11) the volcaniclastic unit is clearly younger than the underlying Kettla Tuff Mb. and older than the T38/T40 regional unconformity in the south of the FSB, which places it around Sequence T38.

Flett Formation (T40-T45) (56.1 Ma to 54.9 Ma)

Both type 1 and type 2 tuffaceous deposits are recognised within Flett Formation sediments (Sequences T40-T45) in the FSB. There is also a third, more ambiguous category of tuffaceous material present in intra-basaltic sediments, addressed in its own right. All tuffaceous sediments within Sequences T40-T45 are equivalent to Knox & Morton's (1988) phase 2a (Fig. 2) (Forties and Dornoch formations) in the North Sea Basin.

T40

Character & distribution of tuffs

Sequence T40 fallout tuffs are recognised by Fitch *et al.* (1988) through examination of sidewall cores in wells 219/28-1 & 219/28-2z, in the western Møre Basin. Fitch *et al.* describe these tuffs, as well as the overlying Balder Formation tuffs, as basaltic lithic-vitric (glass) rich, and partially degraded to palagonite and chlorite. Petrophysically, the package of tuffs is characteristic of tuffaceous claystone, with a low, serrated gamma typical of type 1 tuffaceous deposits (22-29 API) and a density/neutron response akin to claystone (Fig. 12). We also recognise a 15 m thick tuffaceous interval in the Flett Sub-basin (in wells 205/9-1 & 205/9-2). Neutron logs were not run through the unit, though a bell-shaped low gamma and high sonic velocity are similar in pattern to the motif seen in the Balder Fm. (Fig. 4). This tuffaceous unit pinches out before 205/08-1, 6 km further southwest in the Flett Sub-basin.

Tuffaceous intervals are also recognised further north, around the Erlend Volcanic Centre (e.g. in 209/4-1A, Fig. 7c), where a 95 m thick tuffaceous siltstone is described as pale green, soft to firm and sticky from cuttings. The unit has a low gamma (15 API), high sonic velocity (90 m.s/ft), high neutron (averaging 30 pu) and moderately low density (2-2.15 g/cm^3) typical of tuffs. The gamma motif is blocky, typical of type 2 tuffaceous deposits, and the unit is interbedded within terrestrial lava flows (Jolley & Bell, 2002). A laterally discontinuous tuffaceous unit is also identified in the released composite well logs of 204/26-1A & 204/27a-

1 (Fig. 7c), preserved in southern margin of the FSB, overlying the Judd High. On the released composite logs the unit is placed within the Balder Formation (Sequence T50), though the palynological assemblage (*Apectodinium* species and *Peterospermella*) indicate an age equivalent to Sequence T40. This "tuff" has a blocky, low gamma (15-20 API), though it has an extremely low sonic velocity (170-110 m.s/ft), and a resistivity lower than most of the sandstones penetrated in the well. Density/neutron logs were not run until deeper down in the well, but the acoustically slow and conductive nature of the unit suggests it is unlikely to be a tuff.

T45

Character & distribution of tuffs

There is a conspicuous dearth of petrophysically identifiable Sequence T45 tuffaceous intervals. However, discrete cm scale tuffs may be present that are too thin to be detected using common downhole tools, for example near coeval lavas around the Corona Ridge.

Intra-basaltic volcaniclastics- tuffaceous component (T40-T45)

Intra-basaltic volcaniclastic sediments in the FSB are best developed around the Erlend Volcanic Centre (in Sequence T40), and on the Corona Ridge (Sequence T40-T45), for instance in the Rosebank discovery well (213/27-1z). Petrophysically these sediments are distinct, generally exhibiting significantly higher density (2.45-2.75 g/cm^3) and a lower, blockier gamma motif than tuffs. From examination of outcrop on the Faroe Islands, we recognise tuffaceous material (in the form of angular glassy shards) in volcaniclastic siltstone in coeval lava interbeds (Fig. 13). Ultimately many of the finer-grained volaniclastic sediments in the FSB within sequence T40-T45 are likely composed of a complex assemblage of epiclastic basaltic, siliciclastic and fine-grained tuffaceous material, much of which is degraded to palagonite or smectite in the subsurface.

Balder Formation (T50) (54.9 Ma to 54.3 Ma)

Character of tuffs

The Balder Formation is divided into two members: the lower section (Balder Tuff Member) has an abundance of tuffs interbedded with claystones, silts and sands, and is equivalent to Knox & Morton's (1988) Phase 2b. The upper Balder Fm. (Balder Claystone Member) is similarly interbedded, though with proportionally less tuffs, and is equivalent to Knox & Morton's Phase 2c. This decrease in abundance in tuffs toward the top of the Balder Fm. is also exhibited in outcrop, in Sequence T50 sediments near Thanet in the southeast of England (Fig. 14). Balder tuffs have not been cored in the FSB, though are clearly correlatable to the Central Graben, North Sea, where they are cored (e.g. in well 29/05a-7). In these cored intervals there are hundreds of individual tuff beds (0.5-4.5 cm thick), potentially representing hundreds of separate ash forming eruptions (Knox & Morton 1988). The tuffs are generally blue to green and normally graded, interbedded with claystone, siltstone and thin sands. These normally graded tuffs are interpreted as the fallout of ash, deposited into water (Knox & Morton 1988). In the FSB the Balder tuffs are described in ditch cuttings as blue-grey to pale green, soft, crumbly, occasionally calcareous, generally of clay grade though occasionally silty (e.g. towards the Corona Ridge). Morton & Knox (1990) note the Balder tuffs in the North Sea are regionally characterised by an intra-plate tholeiitic basaltic composition. More recent analysis from samples in the FSB show Balder tuffs regionally marked by a high Ti, Fe and Mg and low Cr (Fig. 9a), typical of a mafic magma source (Finlay *et al*. 2016). When the immobile elements are plotted on a geochemical discrimination diagram, the Balder tuffs lie in the alkali basalt field (Fig. 9b) (Chemostrat 2013).

The Balder Tuff Mb. has a distinct petrophysical character manifested in a serrated, low gamma motif (22-40 API), with significant increases in resistivity and sonic velocity, and a density/neutron response typical of claystone/shale. The Balder Claystone Mb. has a similar character, though due to fewer tuffs present, gamma is slightly higher (30-46 API) and resistivity and sonic velocity are marginally lower. The serrated gamma motif of both the Balder Tuff and Balder Claystone members represents type I tuffaceous deposits, corroborated by core (Fig. 3) and outcrop (Fig. 14). The top of the Balder Formation is regionally marked by a high-gamma spike, interpreted as the basal Eocene transgressive maximum (Mudge 2014). At a macro-scale, the Balder Fm. produces a prominent, generally fully resolvable, "hard kick" seismic horizon. This seismic horizon, commonly though erroneously referred to as "Top Balder", "Balder Tuff", or "Top Palaeocene" generally represents the acoustic impedance contrast of the entire Balder Fm. with the surrounding sediments.

Distribution of tuffs

Tuffs are recognised in the Balder Fm., and its lithostratigraphic equivalent, throughout the offshore basins of north-western Europe (Knox & Morton 1983). In the FSB the Balder Fm. equates to Sequence T50, which is a transgressive system tract near the top of the basin fill, accounting for its widespread distribution. The preservation of tuffaceous material in Sequence T50 shows significant variation in the FSB, particularly with respect to marginal/non-marine depositional settings compared to the marine realm.

Marine (below the wave-base) preservation of tuffs

In the FSB the tuffs of the Balder Fm. are best preserved in claystone/siltstone lithologies which were deposited in an inner-outer neritic shelf setting, such as the Corona Ridge, Flett Sub-basin and parts of the Sissal Basin (Fig. 7d). These marine sediments are demarked by the Sequence T50 palaeo-coastline, which trends northwest-southeast across the Foinaven Sub-basin between the Westray and Cambo highs, curving round in a southwest-northeast trend, parallel with the Flett Ridge (Fig. 7d). There are rare instances of poor tuff preservation in Sequence T50 marine sediments, such as the Tobermory Discovery (214/4-1) in the Sissal Basin, where a weak petrophysical and seismic character (more akin to a non-tuffaceous claystone/siltstone succession). The northern extent of Balder tuffs (Quads 216, 217 & 218) in the FSB is unclear, as the amplitude of the Balder Fm. seismic marker becomes weaker and more difficult to map. In the single well penetration in the far north of the FSB, the Lagavulin well (217/5-1), the first return of ditch cuttings was not until Sequence T40, and only gamma was run in the overlying section, therefore the Balder cannot be confidently identified. The Erlend and Brendan volcanic centres are interpreted to be subaerial structures during deposition of Sequence T50, as evidenced by the absence of Balder Fm. sediments in nearby wells 209/3-1A and 219/21-1, respectively. The thickness of the Balder Fm., and therefore the abundance of tuffs, is controlled mainly by the accommodation space available during deposition of Sequence T50, with thickening generally toward basin lows (e.g. 35 m thick in 213/23-1 on the Corona Ridge, compared to 62 m thick in 213/28-1 in the Flett Sub-basin). The Balder Tuff Mb. is typically 10-35 m thick, with the Balder Claystone ranging between 8-25 m.

Marginal marine to non-marine preservation

In marginal and non-marine settings, proximal to and up dip of the Sequence T50 palaeo-coastline, the preservation of tuffs is more limited, appearing as relatively discontinuous tuffaceous claystone packages (2-12 m thick) interbedded with sandstone, siltstone and coals (e.g. 204/20-2). Tuffaceous material is also commonly described in ditch cuttings within a 15-25 m thick, coal package. The interval is seismically resolvable, and, due to the acoustically slow nature of the coals, appears as a soft-kick which can be mapped over a ~35 km^2 area around the Foinaven Sub-basin and Westray Ridge. The exact nature of this lithologically complex interbedded succession of tuffs and coals remains enigmatic as it has never been cored in the FSB. Further north in the FSB a similar depositional setting is present in the Erlend sub-basin (quads 208 & 209) where a Sequence T45/T50 deltaic succession exhibits limited preservation of tuffaceous material (e.g. 208/15-1A). The total thickness of Sequence T50 tuffaceous intervals in marginal to non-marine sediments varies from 0 m (i.e. no tuffaceous material identified petrophysically) to 20 m.

Stronsay Group (T60) (54.3 Ma to 48.6 Ma)

Character & Distribution

Tuffaceous material is commonly identified in ditch cuttings in the Stronsay Group, described as varicoloured, mottled, black specked, soft, friable, amorphous with abundant dark coloured lithics and rare glassy shards. Typically there is no distinct petrophysical expression associated with these purported tuffs against the surroundings sediments (generally claystones and siltstones). In rare instances where cuttings are described as tuffaceous (e.g. 208/17-1 Foula Basin, northern FSB) and conform to low gamma (20 API)/high sonic velocity (95 m.s/ft) beds (akin to tuffs), moderate densities (2.45 g/cm^3) recorded are more typical of limestone stringers. Low gamma (averaging 17 API) tuffaceous claystone is identified on the released well log in the Ben Nevis Prospect (219/21-1), located on the Brendan Platform in the far north of the FSB. However, density/neutron and sonic logs were not run in the well until the underlying Lamba Formation, meaning this interval cannot be confidently interpreted as tuffaceous. On the released well log these low gamma sediments are marked as belonging to the Moray Group (SequencesT40-T50). However, a palynoflora assemblage of *Caryapollenites veriptes* (frequent) and *Thomsonipollis magnificoides* corresponds to Sequence T60 and the Stronsay Gp. (Jolley 2009).

As Sequence T60 is widely considered unprospective in the FSB, there is ultimately no core or side-wall cores to prove the presence of tuff. The strongest evidence for the presence of Sequence T60 tuffs in the FSB is the pervasiveness of its identification in cuttings by mud loggers, from south to north: in the Foinaven Sub-basin (204/18-1), overlying the Westray (204/15-2) and Corona Ridges (213/25c-1), in the Flett (205/09-1), Foula (208/17-1) and Corona sub-basins (214/4-1, Tobermory) and in the More Basin (219/28-1 & 219/28-2: Fitch *et al.* 1988).

Discussion

Derivation of Lower Palaeogene tuffs in the FSB and its Implications for North Atlantic Volcanism

Danian (Sequence T10-T20, 66 Ma to 61.6 Ma) - We recognise no evidence of tuffs or volcanism during the Danian (Sequences T10-20 sediments). Within the wider North Atlantic Margin during the Danian, volcanic activity was occurring in the Inner Hebrides, in the form of localised lava flows of the Eigg Lava Fm. (Chambers *et al.* 2005). The absence of Danian tuffaceous material, or Danian igneous activity in general in the FSB is therefore likely due to volcanism being confined to other regions on the Atlantic Margin at the time (e.g. Inner Hebrides).

Selandian (Sequence T22-35, 61.6 Ma to 59.2 Ma) - We note several distinct episodes of Selandian ash fallout deposition, during Sequence T26, T34 and finally in T35 (summarised in Fig. 15, together with all other tuffs identified in the FSB). There is considerable uncertainty in determining the extent and derivation of these events as the cm thickness of the Sequence T26 and T34 tuffs is below wireline vertical resolution and therefore prevents correlation away from the wells they are recognised in from core. Morton *et al.* (1988) discount the

British Palaeogene Igneous Province (e.g. the coeval Rum Igneous Centre) as a source of the earlier Sequence T26 tuff because of a scarcity of high-Ti tholeiites, which they argued makes an East Greenland or Faroe volcanic province origin more plausible. However, the onshore Faroe Islands and East Greenland lava fields are erupted after deposition of Sequence T35 (Passey & Jolley 2009), discounting them as a source, leading Jolley & Bell (2002) to suggest an, as yet, unidentified igneous centre in the offshore northeast Atlantic.

Sequence T34 tuffs are preserved overlying the Sjúrður High in the south of the FSB, and in the Flett Sub-basin in the centre, again pre-dating the East Greenland and Faroes lavas. In addition to Sequence T35 tuffs recognised in the Foinaven Sub-basin, there is a 30m thick package of Sequence T35 basaltic volcaniclastic sandstones (containing no quartz) intruded by sills, penetrated further north on the East Faroe-High in the Brugdan-2 well (6104/21-2). These volcaniclastic sediments were deposited in a shallow-marine environment, and contain a pollen and spore flora typical of those described as being sourced from the western side of the Faroe-Shetland Basin (Jolley & Morton 2008). The Munkegrunnar Volcanic Province (MVP), which includes the Fraenir Volcanic Centre, is to the west-south west, and is therefore a possible source of these volcaniclastics. Assuming the MVP was active during deposition of Sequence T35, it therefore could feasibly have sourced the Sequence T35 tuffs encountered in the Foinaven Sub-basin, and other Selandian-aged tuffs.

Thanetian (Sequence T36-T38, 59.2 Ma to 56 Ma) - The start of the Thanetian marks a significant escalation in volcanism, manifested in the first emplacement of lavas (initially submarine, then subaerial e.g. in 219/21-1) in the FSB, and regional deposition of the Kettla (Sequence T36) (Fig. 15). Eidesgaard & Ziska (2015) suggest the Corona Ridge as a source of the tuffaceous and volcaniclastic material present within the Kettla. However, there is no evidence of Sequence T36 volcanics either in the 10 well penetrations or in the 3D seismic in and around the Corona Ridge (Schofield & Jolley 2012; Schofield *et al*. 2015; Poppitt *et al*. 2016). Jolley & Morton (2007) note two different source areas, one to the south and another from the north, for the palynology and sediments in the Kettla, suggesting the idea of different volcanic sources. Multiple sources could explain why the three Kettla depocentres each have unique thickening orientations. The Kettla is stratigraphically equivalent to the volcaniclastic Glamis Tuff (Knox & Holloway 1992; Mudge & Bujak 2001) in the North Sea Basin, which Knox & Morton (1988) interpret as penecontemporaneous reworking of pyroclastic material. As the Glamis Tuff is confined to the Outer Moray Firth in the North Sea, the source, and therefore predominant wind direction are interpreted from the west to east (Knox & Morton 1988). In particular, Knox & Morton favour an Inner Hebrides derivation; The Skye Main Lava Series, for instance, is biostratigraphically dated as equivalent to Sequence T36 (Jolley 1997). The immobile trace element chemistry associated with the Kettla in the Flett Sub-basin (the central depocentre) suggests a more intermediate (andesitic) chemical composition relative to the earlier basaltic tuffs of Sequence T26 and T34 in the FSB, and to the basaltic Glamis Tuff. Further geochemical studies, particularly from the southern and northern Kettla depocentres in the FSB, will be important to ground truth both the andesitic composition and multiple source theory related to the Sequence T36 Kettla.

Ypresian (Sequence T40-T60, 56 Ma to 47.8 Ma) - The start of the Ypresian marks the onset of flood basalt volcanism in the FSB (Fig. 15). Sequence T40 tuffs are all located close to known volcanic centres or edifices: Møre Basin tuffs proximal to volcanic edifices mapped near Brendan's Dome (Hodges *et al.* 1999; Mclean et al. 2017), Erlend Sub-basin tuffs adjacent to the Erlend Centre, and Flett Sub-basin tuffs close to both the Erlend Centre and nearby coeval lavas on the Corona Ridge (Schofield & Jolley 2013). Generally these Sequence T40 tuffs are interpreted as reworked, laterally discontinuous tuffaceous units, produced from various volcanic centres and edifices throughout the FSB. Thick, petrophysically identifiable tuffs are conspicuously absent in T45 sediments, which is coincident with a change from classic tabular lavas to compound flows in the Faroe Island Basalt Group (Passey & Jolley 2009), and the initiation of seaward dipping reflector emplacement along the North Atlantic Margin, off Eastern Greenland (Larsen & Saunders 1998).

Sequence T50 clearly represents the acme of ash deposition in the North Atlantic Margin (Fig. 15), with hundreds of individual tuff beds recognised in the Balder Fm. (Knox & Morton 1988). Each tuff bed may not necessarily equate to an individual eruption, with reworking or amalgamation potentially serving the function of increasing or decreasing, respectively, the number of observed tuff beds. Regardless, the exceptional thickness and distribution of Sequence T50 tuffs (relative to all other tuffaceous intervals throughout the FSB stratigraphy) suggest a relatively prolonged, yet explosive phenomena (Knox & Morton, 1988). Knox & Morton (1988) identify a northerly increase in the number of tuffs in Sequence T50 core in the North Sea Basin, implying a source to the north. Sequence T50 tuffs consistently exhibit an intra-plate tholeiitic basaltic geochemical signature in samples throughout the North Sea Basin, which is interpreted as evidence of a common source (Morton & Knox 1990). Deposition of Balder tuffs is immediately preceded by sea-floor spreading during Chron 24r (Jolley & Bell 2002). Repeated flooding of the nascent rift would enable interaction between groundwater and basaltic magma giving rise to phreatomagmatic eruptions (Jolley & Bell 2002; Jolley & Widdowson 2005). In particular, edifices fed from the proto-Icelandic plume along the nascent rift is favoured as the source. This would imply a north-westerly prevailing wind direction (Morton & Knox, 1990). At present it is unclear whether ash continued to be supplied to the FSB during deposition of Sequence T60 sediments, though this material would have to be sourced from outside the FSB, for example from coeval basaltic lavas of the Irgtetiva Formation, East Greenland (Jolley & Bell 2002).

Volume of tuff underestimated in the Faroe-Shetland Basin & biased towards basaltic tuffs

Petrophysical detectability in subsurface well data is a key issue with tuffs, as the cored tuffs throughout the UKCS tend to be thin, cm-scale beds, and therefore identifiable on a wireline log scale only when present as a collection of tuffs. Thinner tuffaceous intervals, in particular those cored in the Vaila Fm., may have been penetrated by a number of wells, though their thinness prevents log detectability. Many of the tuffs identified within this paper are mafic in composition, however, identifying more evolved silicic tuffs in offshore data is particularly challenging. The presence of more evolved intrusive igneous lithologies identified in the FSB (e.g. quartz porphyry sills in 205/10-5A, Flett Sub-basin, and dacite sills in 209/3-1A, Erlend Volcanic Centre) suggests that nearby silicic pyroclastic eruptions may have occurred during the early Palaeogene.

However, the more distal, fallout products of silicic eruptions tend to form thin, discrete beds which would likely be below the vertical resolution of the gamma ray and density tools. Additionally, the increased quantities of potassium and thorium expected (from minerals such as potassium feldspar) would generate gamma ray values similar to claystone, the lithology we have shown to be most conducive to tuff preservation in the FSB. This inability to accurately identify both thin and silicic tuffs means there may be a significant underestimation of the amount of tuffs contained not only in the FSB but globally in offshore basins.

Ultimately, one of the most significant implications of underestimating the volume of tuffs present in the FSB and UKCS as a whole, could be the underestimation of the volume of magma erupted during the formation of these tuffs. For instance, if the estimated figure of 6000 km^3 of magma erupted during formation of the Balder tuffs (Knox & Morton 1988) was even greater, the volume of ash injected into the atmosphere therefore could have been greater too. This may help contextualise the cooling event which proceeds deposition of the Balder tuffs (Jolley & Widdowson 2005).

How the misidentification of tuffs in the FSB can help tuff characterisation in other basins globally

This paper presents examples throughout the FSB lower Palaeogene stratigraphy of tuffaceous material described both in the literature and in mud logs (e.g. in Sequence T10, T35, T40 and T60 sediments), however petrophysically resolvable tuffaceous units are absent and the intervals in which the tuffs have been recorded as being present have not been cored. In such circumstances the identification of tuffs appears to have been based on a misinterpretation of wireline logs, or on its apparent presence in ditch cuttings. Geochemical analysis of cuttings can be used to identify tuffs, though the absence of a petrophysical response (usually when tuffaceous material is too thin to detect) ultimately means any tuffs cannot be proven as *in-situ* in the absence of core/side-wall core.

The historical misinterpretation of both tuffs and "volcanic centres" in the FSB highlights the importance of integrating multiple regional datasets- including 3D seismic, petrophysical logs and biostratigraphy reports- which has important implications for other volcanic margins globally. In the drive to cut costs when undertaking hydrocarbon exploration in these basins, a reluctance to acquire core and run a full wireline suite in intervals deemed non-prospective is clearly problematic for the identification and characterisation of tuffs for several reasons:

- Thin (cm scale), sparsely spaced tuffs are only reliably identifiable through core.
- Thicker, petrophysically resolvable tuffaceous intervals (> meter scale) require not only the basics of gamma-resistivity-sonic for identification, but crucially require density/neutron to differentiate from tight sands, limestones and other volcaniclastics (e.g. eroded basalts).

- Aside from Erlend and Brendan's, there is a dearth of geochemical and well data relating to volcanic centres throughout the North Atlantic Margin, making interpretation of each tuff's likely derivation highly challenging- of key hydrocarbon exploration relevance when active volcanic centres can expel material detrimental to reservoir quality.

When identifying tuffs in offshore basins, emphasis should therefore be placed on key wells which have broader suite of wireline data and/or core/sidewall core to calibrate to, which can then be used to correlate to offset wells. This could be important when dealing with tuffaceous intervals that are too thin to detect, though still may have practical implications such as associated swelling clays balling the drill bit (Millet *et al*. 2016).

Conclusions

We have detailed a comprehensive stratigraphic overview of all the identifiable tuffaceous intervals within the lower Palaeogene of the FSB, the first basin scale stratigraphic review of tuffs anywhere in the UKCS since 1988. By integrating petrophysical logs from over 400 released wells, available core, and seismic horizon mapping we have been able to detail the character and distribution of these tuffs through space and time, and suggest their geographical volcanic derivation.

The majority of tuffaceous intervals in the FSB are identified due to a distinct, petrophysical log motif of relatively low gamma, high resistivity and sonic velocity, and density/neutron response typical of claystone. From the geochemical evidence available, these tuffs are mainly basaltic in composition, which is consistent with both the extrusive lavas in the region, and their low gamma character.

A number of units have incorrectly been interpreted as tuffaceous in previous studies, the most significant of which is the absence of any Sequence T10 tuffs in the FSB, which helps demonstrate that volcanism was confined to the Inner Hebrides during the Danian. The earliest tuffs identified, deposited during the Selandian (Sequences T26 and T34, 62 Ma to 59.8 Ma), are known only through serendipitous coring, and represent the earliest recorded manifestation of volcanism in the FSB. The greatest accumulation of tuffs is represented in Sequences T36 (Kettla Tuff Member, 58.4 Ma) and T50 (Balder Formation, 54.9 to 54.3 Ma), which form important seismic and stratigraphic markers. Ultimately though, the amount of explosive volcanic activity, evidenced by tuffs, is likely underestimated in the FSB due the limited vertical resolution of downhole tools. This issue may be further exacerbated in future exploration by the desire to reduce costs, manifested in a limited array of tools deployed very rarely in intervals deemed non-prospective, in lithologies such as claystone which are most favourable for tuff preservation.

Acknowledgments

This work is part of DW's PhD research, which is funded by a University of Aberdeen College of Physical Sciences Scholarship. We are very grateful to PGS for generously donating seismic datasets. Seismic interpretation was carried out using IHS Kingdom software, and wells were downloaded from the UK Oil & Gas Common Data Access. Well log interpretation was conducted using Schlumberger Techlog software. DW would also like to thank Christine Telford for insights regarding the identification of tuffs in ditch cuttings, and Total (UK) for material concerning the Vaila Formation. Attendees of VMRC workshops from academia and industry provided important insights into the stratigraphy of the FSB. Finally, DW would like to acknowledge the late Robert Knox, without whom our knowledge of North Atlantic explosive volcanism would be considerably poorer. The reviews of P. Reynolds and J. Ólavsdóttir greatly improved the manuscript.

References:

Archer, S.G., Bergman, S.C., Iliffe, J., Murphy, C.M. & Thornton, M. 2005. Palaeogene igneous rocks reveal new insights into the geodynamic evolution and petroleum potential of the Rockall Trough, NE Atlantic Margin. *Basin Research*, **17**, 171–201.

British Geological Survey 2016a. Offshore Hydrocarbon Wells. www.bgs.ac.uk/data/offshoreWells/wells.cfc?method=searchWells

British Geological Survey 2016b. Offshore Geoindex. www.mapapps2.bgs.ac.uk/geoindex_offshore/home.html

Chambers, L. M., Pringle, M. S. & Parrish, R. R. 2005. Rapid formation of the Small Isles Tertiary centre constrained by precise 40AR/39Ar and U-Pb ages. *Lithos*, **79**, 367-384.

Chemostrat. 2013. Report NE 118 Integrated Stratigraphic and Provenance Study undertaken on the Lower Palaeocene Successions (T10 - T38) within the Faroe-Shetland Basin.

Dore, A. G., Lundin, E. R., Kusznir, N. J. & Pascal, C. 2008. Potential mechanisms for the genesis of Cenozoic domal structures on the NE Atlantic margin: pros, cons and some new ideas. *In*: Johnson, H., Dore, A. G., Gatliff, R. W., Holdsworth, R. W., Lundin, E. & Ritchie, J. D. (eds) *The Nature of Compression in Passive Margins*. Geological Society, London, Special Publications, **306**, 1-26.

Earle, M. M., Jankowski, E. J. & Vann, I. R. 1989. Structural evolution of the Faroe-Shetland Channel and northern Rockall Trough. 461-489. *In*: Tankard, A. J. & Balkwill, H. R. (eds) *Extensional tectonics and stratigraphy of the North Atlantic margins*. American Association of Petroleum Geologists Memoir, 46. Tulsa, Oklahoma, 461-489.

Ebdon, C. C., Granger, P. J., Johnson, H.D. & Evans, A. M. 1995. Early Tertiary evolution and sequence stratigraphy of the Faroe-Shetland Basin: implications for hydrocarbon prospectivity. *In*: Scrutton, R. A. Stoker, M. S., Schimmield, G. B. & Tudhope, A. W. (eds) *The Tectonics, sedimentation and Palaeoceanography of the North Atlantic Region*. Geological Society, London, Special Publications, **90**, 51-69.

Eidesgaard, O. R. & Ziska, H. 2015. The Kettla Member An overview from the Faroe-Shetland Basin. *In*: Eidesgaard, O. R. & Ziska, H. (eds) *Faroe Islands Exploration Conference: Proceedings of the 4th conference*. Annals Societatis Scientiarum Faerensis, Supplementum. **64**, 26-44.

Ellis, D., Jolley, D. W., Passey, S. R. & Bell, B. R. 2009. Transfer zones: The application of new geological information from the Faroe Islands applied to the offshore exploration of intra basalt and sub-basalt strata. *In*: Varming, T. & Ziska, H (eds) *Faroe Islands Exploration Conference: Proceedings of the 2nd conference*. Annals Societatis Scientiarum Faerensis, Supplementum. **50**, 205-226.

Finlay, A. J., Roach, C., Morgan, T., Pearce, T. 2016. A new stratigraphy for the Rockall and Faroe-Shetland Basin Petex 2016.

Fisher, R. V. 1961. Proposed classification of volcaniclastic sediments and rocks. *Geological Society of American Bulletin*, **72**, 1409-1414.

Fisher, R.V. & Schmincke, H.-U. 1994. Volcaniclastic sediment transport and deposition. *In*: Pye, K. (ed.) *Sediment Transport and Depositional Processes*. Blackwell Scientific, Oxford, 351–388.

Fitch, F. J., Heard, G. L. & Miller, J. A. 1988. Basaltic magmatism of late Cretaceous and Palaeogene age recorded in wells NNE of the Shetlands. 253-262. *In*: Morton, A. C. & Parson, L. M. (eds). *Early Tertiary volcanism and the opening of the NE Atlantic*. Geological Society, London Special Publications, **39**, 253-262.

Hodges, S. Line, C. & Evans, B. 1999. The Other Millennium Dome. Offshore Europe Oil and Gas Exhibition Conference, 7-10 September. Society of Petroleum Engineers.

Hillier, S. 2006. Detailed Mineralogical and Geochemical Study of Diagenetic Chlorite in Sandstones, Shale and Tuff from the Laggan Field, West of Shetland. The Macaulay Institute.

Jaqué, M. & Thouvenin, J. 1975. Lower Tertiary tuffs and volcanic activity in the North Sea. *In*: Woodland, A. W. (ed). *Petroleum and the Continental Shelf of North west Europe*. Applied Science Publishers, London, 455-465.

Jolley, D. W. 2009. Palynofloral evidence for the onset and cessation of eruption of the Faroe Islands lava field. *In*: Varming, T. & Ziska, H (eds) *Faroe Islands Exploration Conference: Proceedings of the 2nd conference*. Annals Societatis Scientiarum Faerensis, Supplementum. **50**, 156-173.

Jolley, D. W. & Bell, B. R. 2002. The evolution of the North Atlantic Igneous Province and the opening of the NE Atlantic rift. *Geological Society, London, Special Publications*, **197**, 1-13.

Jolley, D. W. & Morton, A. C. 2007. Understanding basin sedimentary provenance: Evidence from allied phytogeographic and heavy mineral analysis of the Paleocene of the NE Atlantic. *Journal of the Geological Society*, **164**, 553-563.

Jolley, D. W. & Widdowson, M. 2005. Did Paleogene North Atlantic rift-related eruptions drive early Eocene climate cooling? *Lithos*, **79**, 355-366.

Knox, R. W. O'B. & Harland, R. 1979. Stratigraphical relationships of the early Palaeogene ash-series of NW Europe. *Journal of the Geological Society, London*. **136**, 463-470.

Knox, R. W. O'B. & Holloway, S. 1992. Lithostratigraphical Nomenclature of the UK. North Sea. 1. Paleogene of the Central and Northern North Sea. In: Knox, R. W. O'B. & Cordey, W. G. (eds) Lithostratigraphic Nomenclature of the UK North Sea. British Geological Survey, Keyworth.

Knox, R. W. O'B. & Morton, A. C. 1983. Stratigraphical Distribution of Early Palaeogene Pyroclastic Deposits in the North Sea Basin. *Proceedings of the Yorkshire Geological Society*. **44**, 355-363.

Knox, R. W. O'B. & Morton, A. C. 1988. The record of early Tertiary N Atlantic volcanism in sediments of the North Sea Basin. *In*: Morton, A. C. & Parson, L. M. (eds). 1988. *Early Tertiary Volcanism and the opening of the NE Atlantic*. Geological Society Special Publications, **39**, 407-419.

Lamers, E. & Carmichael, S. M. M. 1999. The Paleocence deepwater sandstone play West of Shetland. *Petroleum Geology Conference series* **5**, 645-659.

Larsen, H. C. & Saunders, A. D. 1998. Tectonism and volcanism at the southeast Greenland rifted margin: a record of plume impact and later continental rupture. In: Saunders, A. D. et al. (eds) *Proceedings of the Ocean Drilling Program, Scientific Results*. Ocean Drilling Program, College Station, Texas, **152**, 503-533.

Larsen, M. & Whitman, A. G. 2005. Evidence for a major input point into the Faroe-Shetland basin from the Kamgerlussuaq region of southern East Greenland. *In*: Dore´, A. G. & Vining, B. A. (eds) *Petroleum Geology: North–West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference*. Geological Society, London, 913–922.

Ledbetter, M. T. & Sparks, R. S. J. 1979. Disruption of large-magnitude explosive eruptions deduced from graded bedding in deep-sea ash layers. *Geology*, **7**, 240-244.

Loizou, N. 2014. Success in exploring for reliable, robust Paleocene traps west of Shetland. *In*: Cannon, S. J. C. & Ellis, D. (eds). *Hydrocarbon Exploration to Exploitation West of Shetlands*. Geological Society, London, Special Publications, **397**, 59-79.

Mathisen, M. E. & McPherson, J. G. 1991. Volcaniclastic deposits: implications for hydrocarbon exploration. *Sedimentation in Volcanic Settings, SEPM Special Publications*, 45, 27-36.

McLean, C. E., Schofield, N., Brown, D. J., Jolley, D. W. 2017. 3D seismic imaging of the shallow plumbing system beneath the Ben Nevis Monogenetic Volcanic Field: Faroe–Shetland Basin. *Journal of the Geological Society*, first published online, https://doi.org/10.1144/jgs2016-118.

Millett, J. M., Wilkins, A. D., Campbell, E., Hole, M. J., Taylor, R. A., Healy, D., Jerram, D. A., Jolley, D. W., Planke, S., Archer, S. G. & Blischke, A., 2016. The geology of offshore drilling through basalt sequences: Understanding operational complications to improve efficiency. *Marine and Petroleum Geology*, **77**, 1177-1192.

Morton, A. C., Evans, D., Harland, R., King, C. & Ritchie, J. D. 1988. Volcanic ash in a cored borehole W of the Shetland Islands: evidence for Selandian (late Paleocene) volcanism in the Faroes region. *In*: Morton, A. C. & Parson, L. M. (eds). *Early Tertiary volcanism and the opening of the NE Atlantic*. Geological Society of London Special Publications, **39**, 263-269.

Morton, A. C. & Knox, R. W. O'B. 1990. Geochemistry of late Palaeocene and early Eocene tephras from the North Sea Basin. *Journal of the Geological Society, London*. **147**, 435-437.

Moy, D. J. & Imber, J. 2009. A critical analysis of the structure and tectonic significance of rift-oblique lineaments ('transfer zones') in the Mesozoic–Cenozoic succession of the Faroe–Shetland Basin, NE Atlantic margin. *Journal of the Geological Society, London*. **166**, 831–844.

Mudge, D. C. 2014. Regional controls on Lower Tertiary sandstone distribution in the North Sea and NE Atlantic margin basins. *In*: McKie, T. Rose, P. T. S. Hartley, A. J. Jones, D. W. & Armstrong, T. L. (eds) *Tertiary Deep-Marine Reservoirs of the North Sea Region*. Geological Society, London, Special Publications, 403, 17-42.

Mudge, D. C. & Bujak, J. P. 2001. Biostratigraphic evidence for evolving palaeoenvironments in the Lower Palaeogene of the Faroe-Shetland Basin. *Marine and Petroleum Geology*. **18**, 577-590.

Naylor, P. H., Bell, B. R., Jolley, D. W., Durnall, P. & Fredsted, R. 1999. Palaeogene magmatism in the Faroe-Shetland Basin: influences on uplift history and sedimentation. *In*: Fleet, A. J. & Boldy, S. A. R. (eds). *Petroleum Geology of northwest Europe, proceedings of the 5th conference*, 545-558.

Passey, S.R. & Jolley, D.W. 2009. A revised lithostratigraphic nomenclature for the Palaeogene Faroe Islands Basalt Group, NE Atlantic Ocean. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, **99**, 127–158.

Passey, S. & Hitchen, K. 2011. Cenozoic (igneous). *In*: Ritchie, J. D., Ziska, H., Johnson, H. & Evans, D. (eds) *Geology of the Faroe-Shetland Basin and Adjacent Areas*. British Geological Survey, Nottingham, UK. 317 pp (RR/11/001).

Rider, M. & Kennedy, M. 2011. *The Geological Interpretation of Well Logs*. 3rd Edition. Rider-French Consulting Ltd, Glasgow.

Ritchie, J. D. & Hitchen, K. 1996. Early Paleogene offshore igneous activity to the northwest of the UK and its relationship to the North Atlantic Igneous Province. *In*: Knox, R. W. O'B., Corfield, R. M. & Dunay, R. E. (eds) *Correlation of the Early Paleogene in Northwest Europe*. Geological Society, London, Special Publications, **101**, 63-78.

Ritchie, J. D., Ziska, H., Johnson, H. & Evans, D. (eds) 2011. *Geology of the Faroe-Shetland Basin and Adjacent Areas*. British Geological Survey, Nottingham.

Ross, P. –S., Ukstins Peate, I., McClintock, M. K., Xu, Y. G., Skilling, I. P., White, J. D. L. & Houghton, B. F. 2005. Mafic volcaniclastic deposits in flood basalt provinces: A review. *Journal of Volcanology and Geothermal Research*, **145**, 281-314.

Rumph, B., Reaves, C. M., Orange, V. G. & Robinson, D. L. 1993. Structuring and transfer zones in the Faeroe Basin in a regional tectonic context. *In*: Parker, J. R. (ed) *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*. Geological Society, London, 999-1010.

Schofield, N. & Jolley. D. W. 2013. Development of intra-basaltic lava-field drainage systems within the Faroe-Shetland Basin. *Petroleum Geoscience*, **19**, 273-288.

Schofield, N., Holford, S., Millet, J., Brown, D., Jolley, D., Passey, S. R., Muirhead, D., Grove, C., Magee, C., Murray, J., Hole, M., Jackson, C. A.-L. & Stevenson, C. 2015. Regional magma plumbing and emplacement mechanisms of the Faroe-Shetland Sill Complex: implications for magma transport and petroleum systems within sedimentary basins. *Basin Research*, first published online November **19**, 2015, http://doi.org/10.1111/ bre.12164.

Shaw champion, M., White, N., Jones, S. & Lovell, J. 2008. Quantifying transient mantle convective uplift: an example from the Faroe–Shetland basin. *Tectonics*, **27**, TC1002.

Smallwood, J. R. & Maresh, J. 2002. The properties, morphology and distribution of igneous sills: modelling, borehole data and 3D seismic from the Faroe-Shetland area. *In*: Jolley, D. W. & Bell, B. R. (eds) *The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes*. Geological Society of London Special Publication, **197**, 271-306.

Sørensen, A. B. 2003. Cenozoic basin development and stratigraphy of the Faroes area. *Petroleum Geoscience*, **9**, 189-207.

Varming, T. 2009. Results from the drilling of the 1st licence round wells in the Faroese part of the Judd Basin. *In*: Varming, T. & Ziska, H (eds) *Faroe Island Exploration Conference: Proceedings of the 2nd Conference*. Annals Societatus Scientiarum Fàeroensis, Supplememtum **50**, 346-363.

Stoker, M & Varming, T. 2011. Cenozoic (sedimentary). *In*: Ritchie, J., Ziska, H., Johnson, H. & Evans, D. (eds) Geology of the Faroe-Shetland Basin and adjacent areas. British Geological Survey. Hawthornes, Nottingham.

Winchester, J. A. & Floyd, P. A. 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chemical Geology*, **20**, 325-434

White, R. & McKenzie, D. 1989. Magmatism at Rift Zones: The Generation of Volcanic Continental Margins and Flood Basalts. *Journal of Geophysical Research*, **94**, 7685-7729.

Figure Captions

Fig. 1. (a) Main structural elements of the Faroe-Shetland Basin, adapted from Ellis *et al.* (2009) and Mudge (2014). **(b)** Outline of the seismic coverage, including the wells used, and location of the four seismic lines shown in this paper (red lines: A-A', B-B', C-C' & D-D').

Fig. 2. Early Palaeogene stratigraphy of the FSB (modified from Schofield *et al.* 2015), using the lithostratigraphy of Ritchie *et al.* (2011), North Sea lithostratigraphy comparison of Shaw Champion *et al.* (2008), T-sequences of Ebdon *et al.* (1995) and North Sea pyroclastic phases of Knox & Morton (1988).

Fig. 3. Tuffaceous material in core appears either as (type 1) thin discrete tuffs (green-blue bands) interbedded with silts and claystones (light to dark grey bands), example from the Balder Fm. in the Central Graben, North Sea Basin (29/05a-3); or (type 2) massive units containing tuffaceous material, example from a sandstone (Kettla Mbr., Lamba Fm.) in the Flett Sub-basin, FSB (205/09-1). Gamma ray log values at the side of the core. Individual tuffs are below the vertical resolution of the tool. Images are from the BGS offshore database (2016a).

Fig. 4. Using real examples from multiple wells throughout the FSB, this figure shows how low gamma/high sonic velocity lithologies can be distinguished from each other. Tuffaceous units (**a**) are typically characterised by low gamma, high resistivity and high sonic velocity, which can be similar to sandstones, limestones and basalt (**b**). Tuffs however, have a distinct low to moderate density/high neutron response (**c**), similar to a claystone, which makes their identification simple. Confidence in identifying tuffaceous intervals in therefore reduced in the absence of density/neutron logs. The main difference between the two types of tuffaceous material is reflected in the gamma log, where 1) discrete interbedded tuffs (type 1) tend to have a serrated profile (**d**), and 2) massive clastic units containing tuffaceous material (type 2) exhibiting a blockier motif (**e**), and a marginally higher sonic velocity (**f**).

Fig. 5. Seismic line from FSB MegaSurvey Plus (Phase 2) perpendicular to the Flett Sub-basin. Thick tuffaceous intervals, such as the "Balder Tuff" and "Kettla Tuff" form prominent, laterally continuous hard kicks, making them ideal stratigraphic markers. Depending on the thickness and acoustic impedance contrast, these tuffaceous intervals can be fully seismically resolvable (as seen in the Balder Tuff example), or seismic identifiable (in the case of this Kettla Tuff example). Data courtesy of PGS, from the FSB MegaSurveyPlus.

Fig. 6. Figure showing the i) gravity, ii) magnetic and iii) seismic data covering the supposed Danian aged 'Volcanic Centres'. Both the Westray and Judd Centres were identified based on circular, positive gravity and magnetic anomalies (Naylor *et al.* 1999). Both have been drilled are now known as the Westray and Cambo highs. The gravity/magnetic anomalies are a result of underlying Caledonian plutonic bodies. Gravity and magnetic data from BGS Offshore Geoindex (2016a). Seismic data courtesy of PGS, from the FSB2011/12 MultiClient GeoStreamer® survey.

Fig. 7. Palaeogeography maps of the Faroe-Shetland Basin, showing the location of wells and distribution of tuffs referred to in this paper. The **a)** Vaila, **b)** Lamba and **c)** Flett palaeogeoographies are adapted from Mudge (2014), while the **d)** Balder map is the author's own. The regional Balder inset is adapted from Morton & Knox (1988). The southern depocentre shown in the Lamba map is modified from Eidesgaard & Ziska (2015), though the central depocentre extent is the author's own (based on well penetrations and seismic horizon mapping).

Fig. 8. Petrophysical character of the Sequence T35 tuff located in the Foinaven Sub-basin (well 204/17-1), exhibiting low gamma, high resistivity, high sonic velocity, and a density/neutron response typical of claystone.

Fig. 9. (a) Geochemical character of the Kettla and Balder tuffs. Cr and Ti are normalised to Th as it is analogous to detrital, nonvolcanic material. **(b)** Winchester & Floyd type (1977) discrimination chart, plotting the Kettla in the andesite field, and Balder tuffs mainly in the alkali basalt field. Adapted from Finlay *et al*. (2016).

Fig. 10. Well log correlation and seismic line through the Flett Sub-basin showing the character of the Sequence T36 Kettla Tuff Member. Data courtesy of PGS, from the FSB MegaSurveyPlus.

Fig. 11. Lamba volcaniclastic unit in seismic. The unit pinches out before 204/22-2, and is likely sequence T38 in age as it overlies the T36 Kettla Tuff Mbr. but is younger than the T38 regional uniformity surface. Data courtesy of PGS, from the FSB MegaSurveyPlus.

Fig. 12. Petrophysical character of T40 Flett tuffs, in well 219/28-2z. The Flett tuffs have a similar log profile to the overlying Balder tuffs, and sidewall cores examined by Fitch *et al.* (1988) confirm the presence of glassy basaltic material.

Fig. 13. **(i)** The majority of intra-basaltic volcaniclastic units appear as moderate to high density (2.4-2.6 g/cm^3) reworked basaltic siltstone/sandstones, for example in well 213/26-1, distinct from lower density tuffaceous units (2.15-2.35 g/cm^3). **(ii-v)** However, angular glassy fragments are visible in coeval sediments exposed onshore Faroe Islands (Sneis Formation), suggesting there may be a minor fallout component to these volcaniclastic interbeds in the FSB.

Fig. 14. The lower Balder Tuff Mbr. has an abundance of tuffaceous horizons, whereas the upper Balder Claystone Mbr. has fewer tuffaceous horizons, which conforms to observations from exposed sequence T50 sediments in the south east of England, near Thanet.

Fig. 15. Stratigraphic summary of tuffs in the FSB, described in this paper. The relative tuff abundance is an approximation for the thickness and lateral continuity, and is based on Knox & Morton's (1988) tuffs of the North Sea. The majority of tuffaceous intervals are preserved in claystone dominated successions in the FSB.

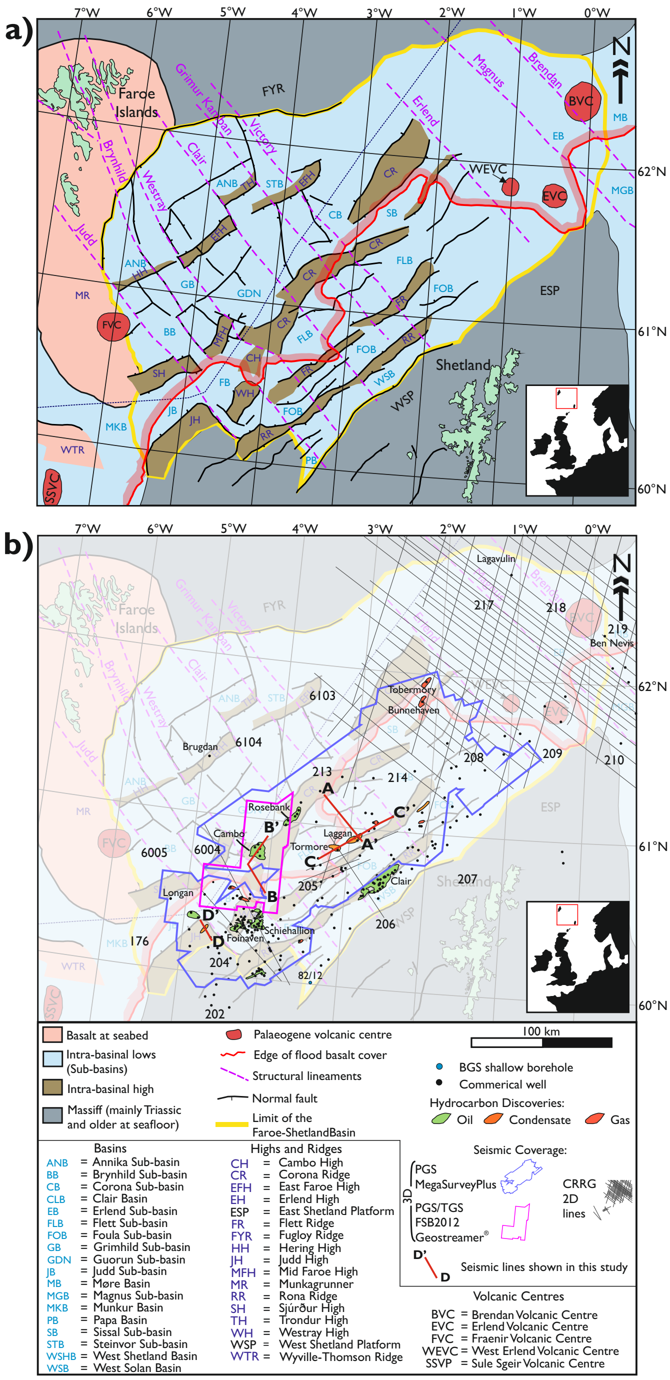
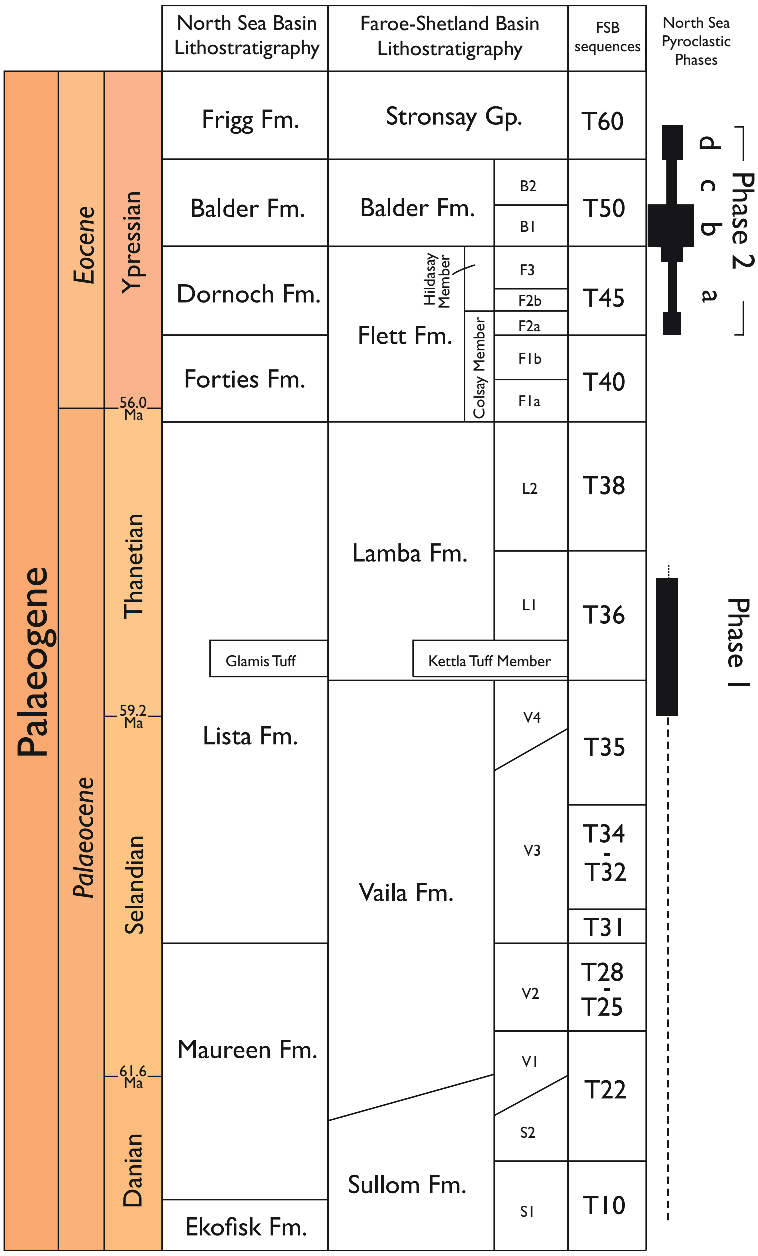

a)
b)
7°W 6°W 5°W 4°W 3°W 2°W 1°W 0°W
62°N 61°N 60°N
N
Faroe Islands
Shetland
FYR
ESP
MR
WTR
BVC EVC WEVC FVC SSVC
Grimur Kamban
Victory
Clair
Westray
Brynhild
Judd
Erlend
Magnus
Brendan
Lagavulin
Ben Nevis
Tobermory
Bunnehaven
Brugdan
Rosebank
Cambo
Laggan
Tormore
Clair
Longan
Foinaven
Schiehallion
6103 6104 6005 6004 213 214 208 209 210 217 218 219 205 206 207 176 204 202 82/12
A A' B B' C C' D D'
Basalt at seabed
Intra-basinal lows (Sub-basins)
Intra-basinal high
Massiff (mainly Triassic and older at seafloor)
Palaeogene volcanic centre
Edge of flood basalt cover
Structural lineaments
Normal fault
Limit of the Faroe-ShetlandBasin
100 km
BGS shallow borehole
Commerical well
Hydrocarbon Discoveries:
Oil
Condensate
Gas
Basins
ANB = Annika Sub-basin
BB = Brynhild Sub-basin
CB = Corona Sub-basin
CLB = Clair Basin
EB = Erlend Sub-basin
FLB = Flett Sub-basin
FOB = Foula Sub-basin
GB = Grimhild Sub-basin
GDN = Guorun Sub-basin
JB = Judd Sub-basin
MB = Møre Basin
MGB = Magnus Sub-basin
MKB = Munkur Basin
PB = Papa Basin
SB = Sissal Sub-basin
STB = Steinvor Sub-basin
WSHB = West Shetland Basin
WSB = West Solan Basin
Highs and Ridges
CH = Cambo High
CR = Corona Ridge
EFH = East Faroe High
EH = Erlend High
ESP = East Shetland Platform
FR = Flett Ridge
FYR = Fugloy Ridge
HH = Hering High
JH = Judd High
MFH = Mid Faroe High
MR = Munkagrunner
RR = Rona Ridge
SH = Sjúrður High
TH = Trondur High
WH = Westray High
WSP = West Shetland Platform
WTR = Wyville-Thomson Ridge
Seismic Coverage:
3D
PGS MegaSurveyPlus
PGS/TGS FSB2012 Geostreamer®
CRRG 2D lines
Seismic lines shown in this study
Volcanic Centres
BVC = Brendan Volcanic Centre
EVC = Erlend Volcanic Centre
FVC = Fraenir Volcanic Centre
WEVC = West Erlend Volcanic Centre
SSVP = Sule Sgeir Volcanic Centre

Figure 2 revised



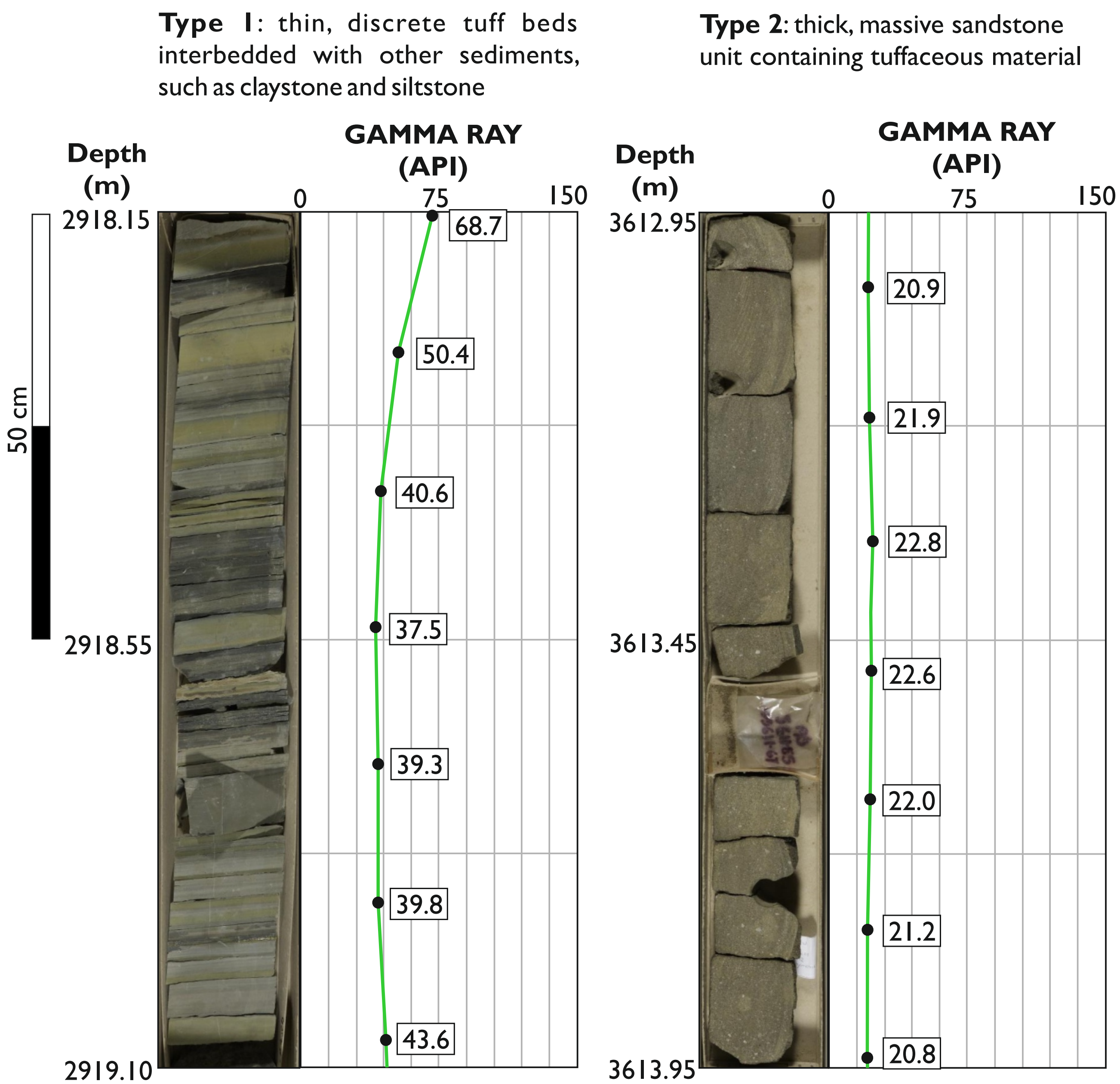

Type 1: thin, discrete tuff beds interbedded with other sediments, such as claystone and siltstone
Type 2: thick, massive sandstone unit containing tuffaceous material
Depth (m)
GAMMA RAY (API)
0
75
150
50 cm
2918.15
2918.55
2919.10
68.7
50.4
40.6
37.5
39.3
39.8
43.6
3612.95
3613.45
3613.95
20.9
21.9
22.8
22.6
22.0
21.2
20.8

Figure 4 revised

Click here to download Figure Figure 4 revised.pdf

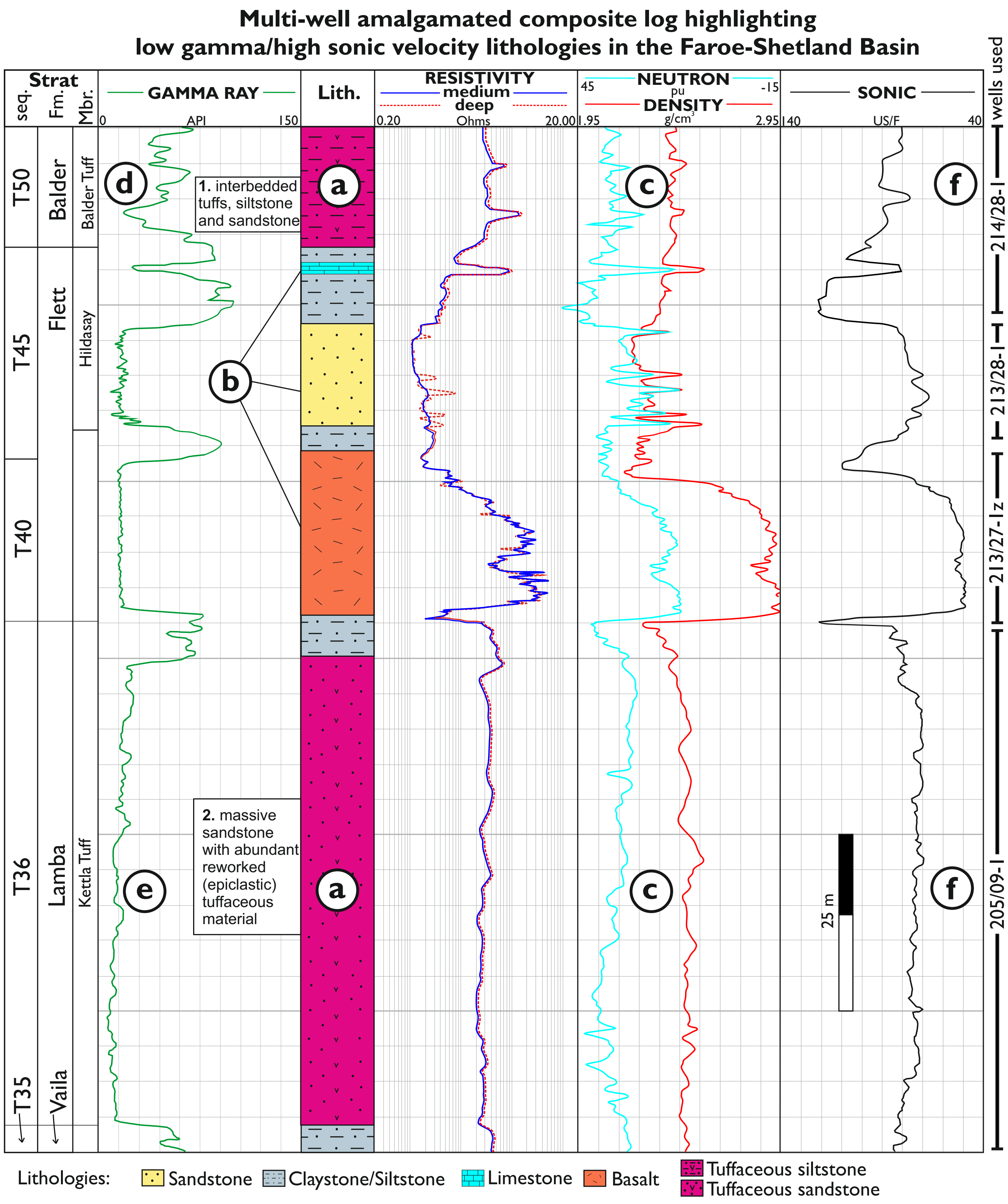
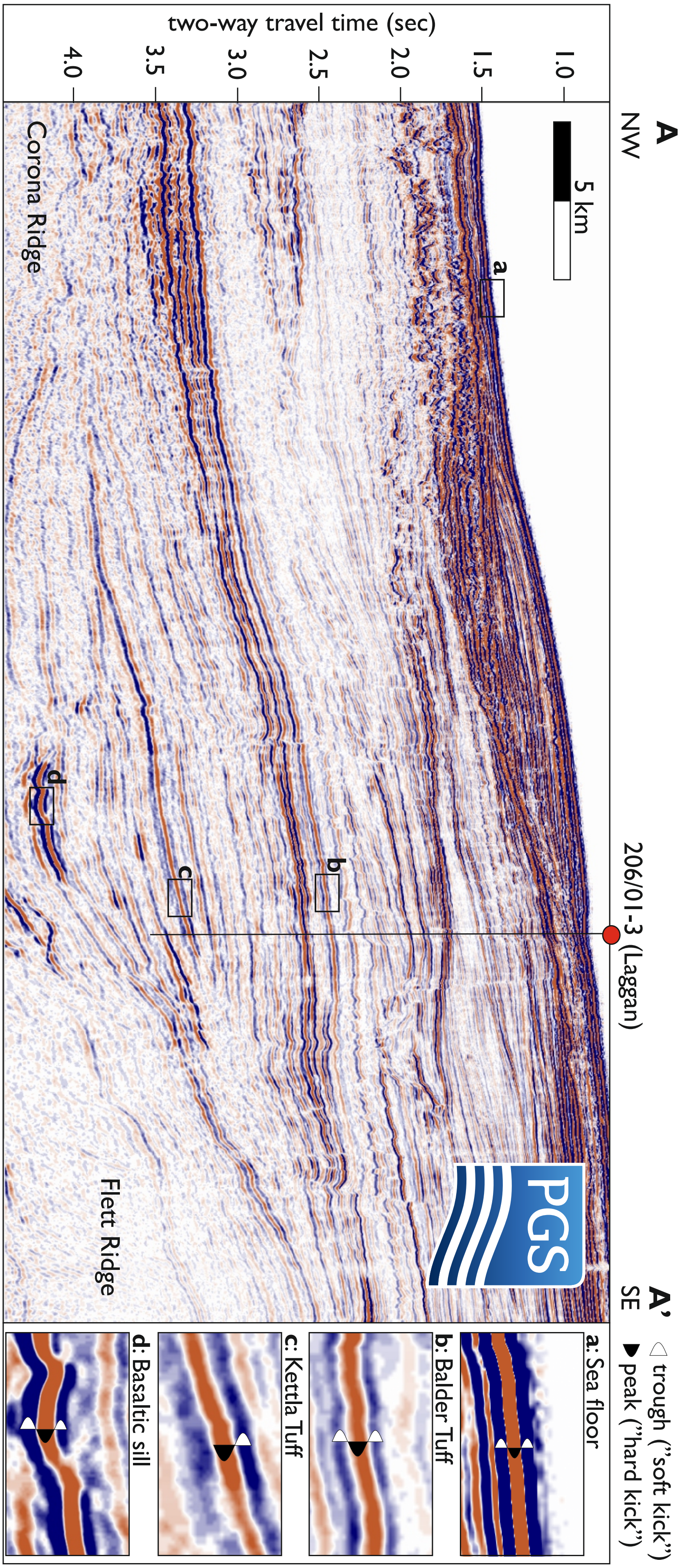


Figure 5



A
A'
NW
SE
5 km
two-way travel time (sec)
1.0
1.5
2.0
2.5
3.0
3.5
4.0
206/01-3 (Laggan)
a
b
c
d
Corona Ridge
Flett Ridge
PGS
trough ("soft kick")
peak ("hard kick")
a: Sea floor
b: Balder Tuff
c: Kettla Tuff
d: Basaltic sill

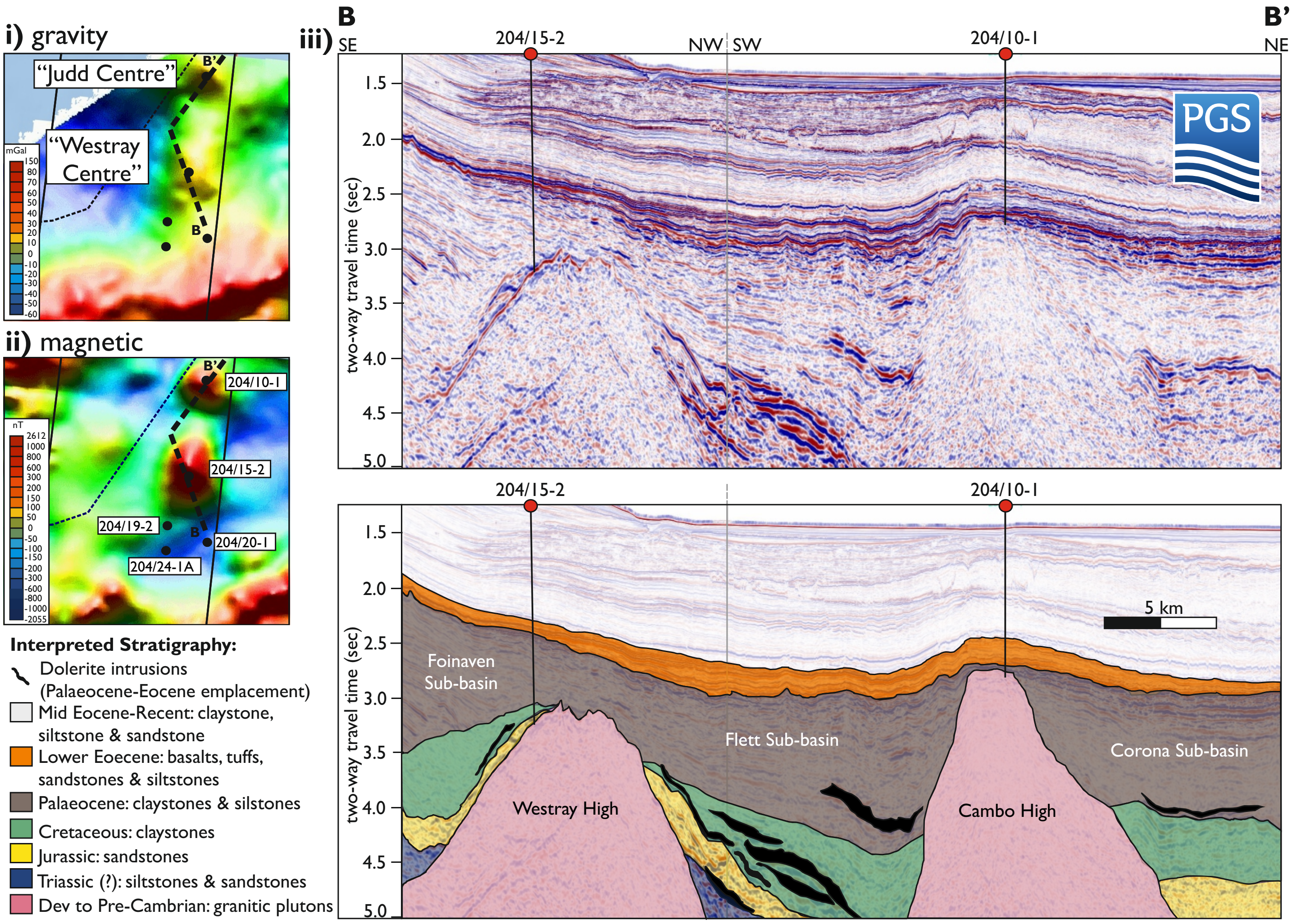

i) gravity
"Judd Centre"
"Westray Centre"
mGal
B'
B
ii) magnetic
nT
204/10-1
204/15-2
204/19-2
204/20-1
204/24-1A
iii)
B
B'
SE
NW
SW
NE
204/15-2
204/10-1
two-way travel time (sec)
PGS
Foinaven Sub-basin
Flett Sub-basin
Corona Sub-basin
Westray High
Cambo High
5 km
Interpreted Stratigraphy:
Dolerite intrusions (Palaeocene-Eocene emplacement)
Mid Eocene-Recent: claystone, siltstone & sandstone
Lower Eoecene: basalts, tuffs, sandstones & siltstones
Palaeocene: claystones & silstones
Cretaceous: claystones
Jurassic: sandstones
Triassic (?): siltstones & sandstones
Dev to Pre-Cambrian: granitic plutons

Figure 7 revised

Click here to download Figure Figure 7 revised.pdf

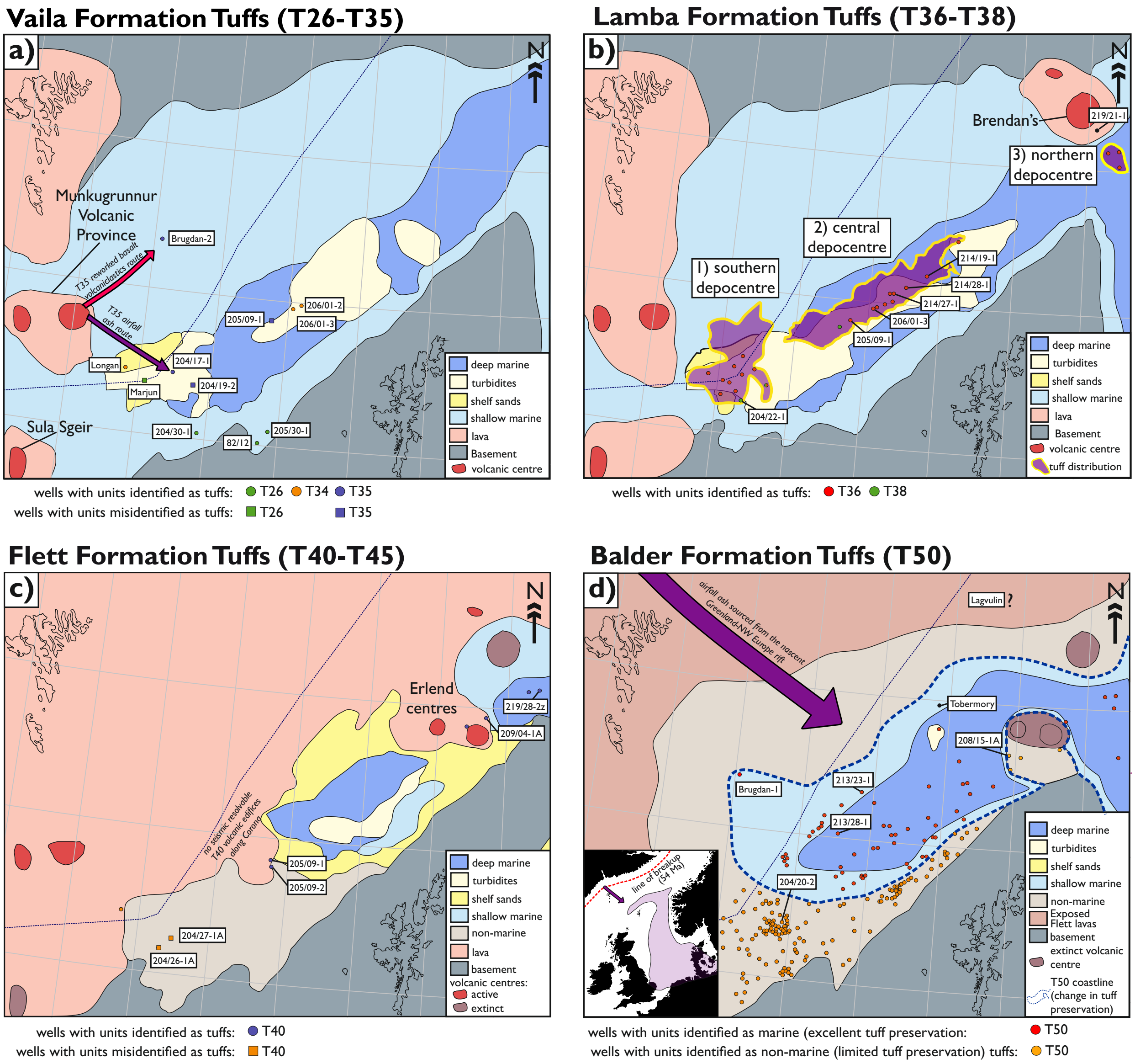


Figure 8

Click here to download Figure Figure 8.pdf

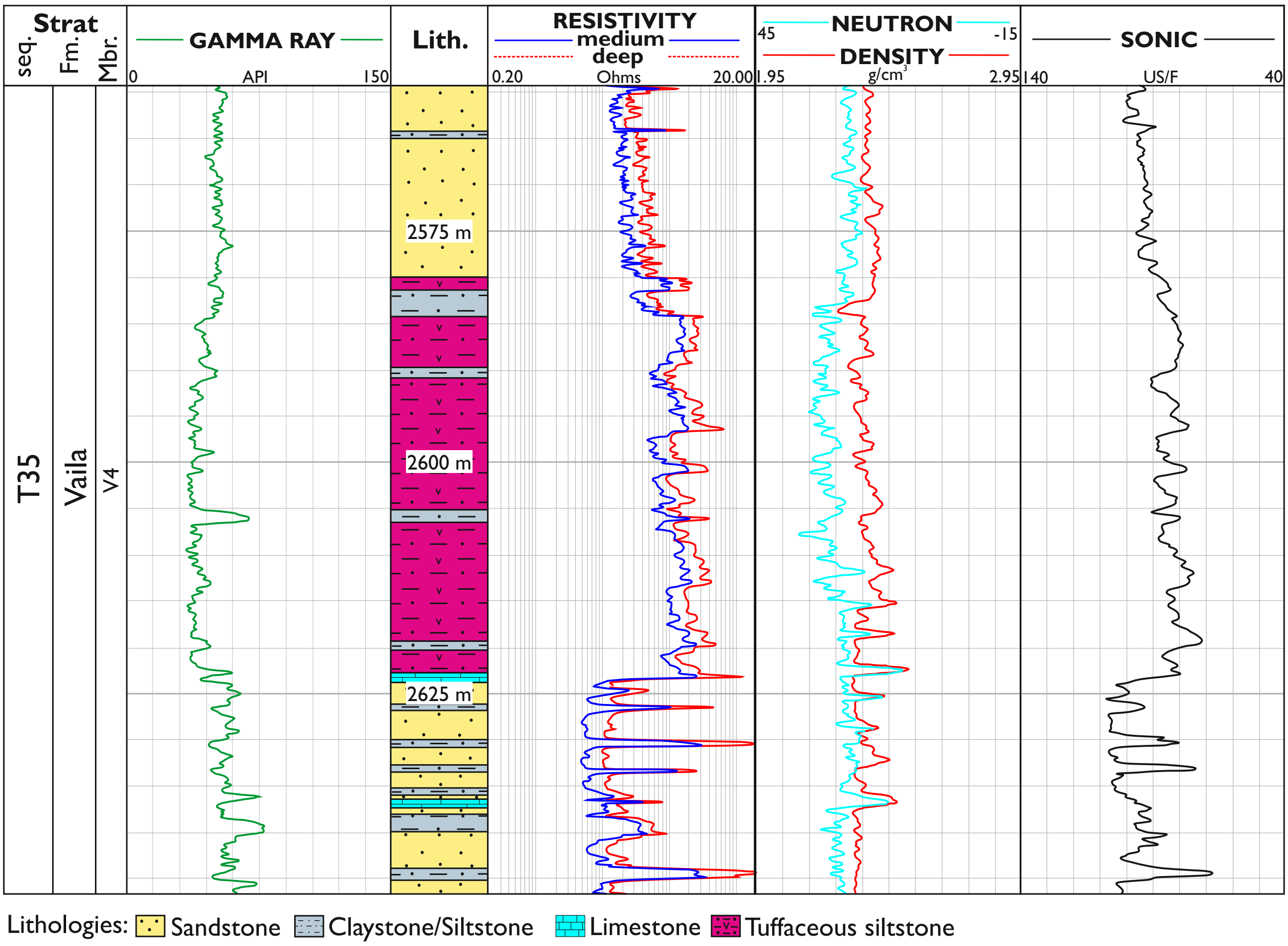


Figure 9

Click here to download Figure Figure 9.pdf

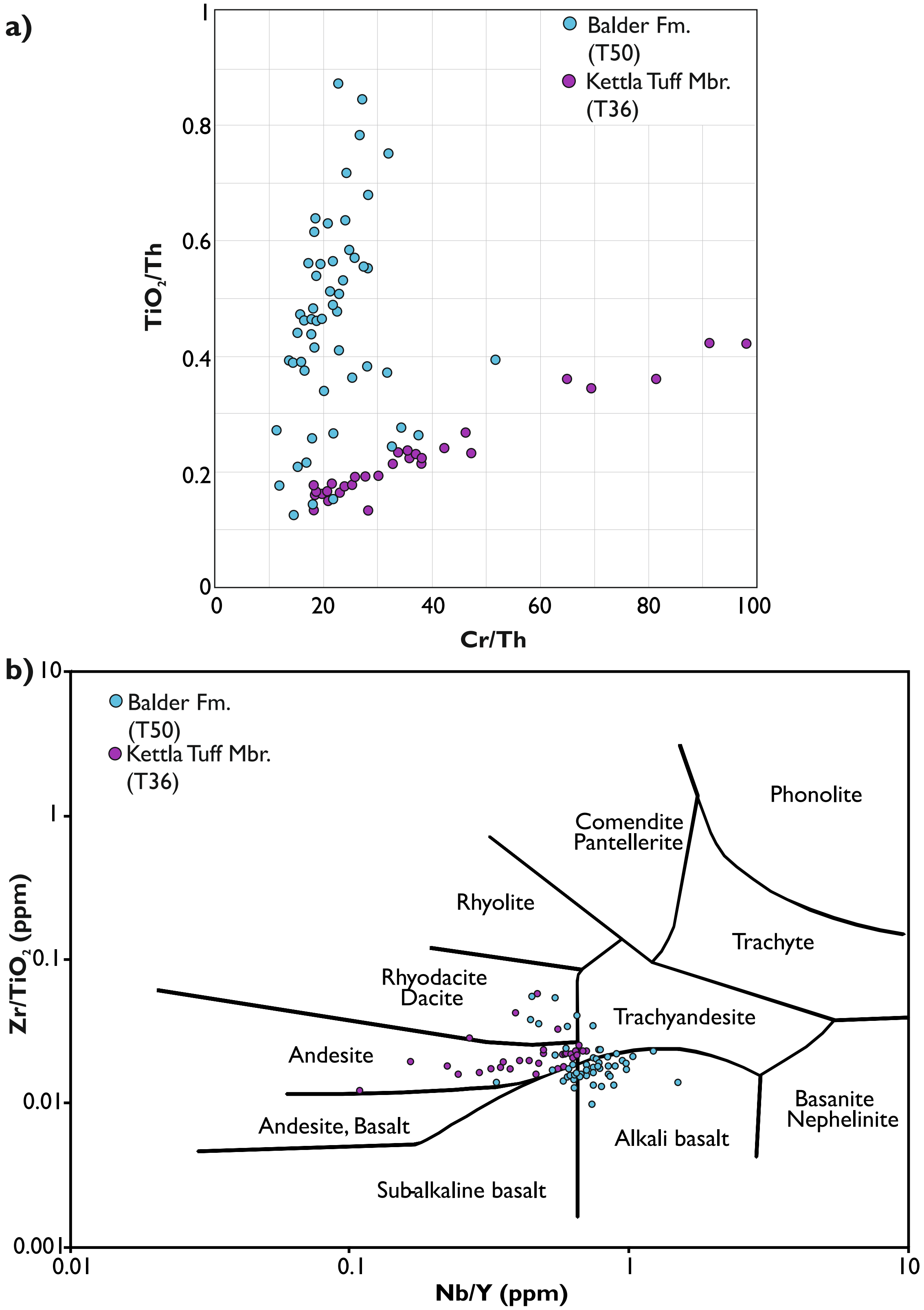


Figure 10

Click here to download Figure Figure 10.pdf

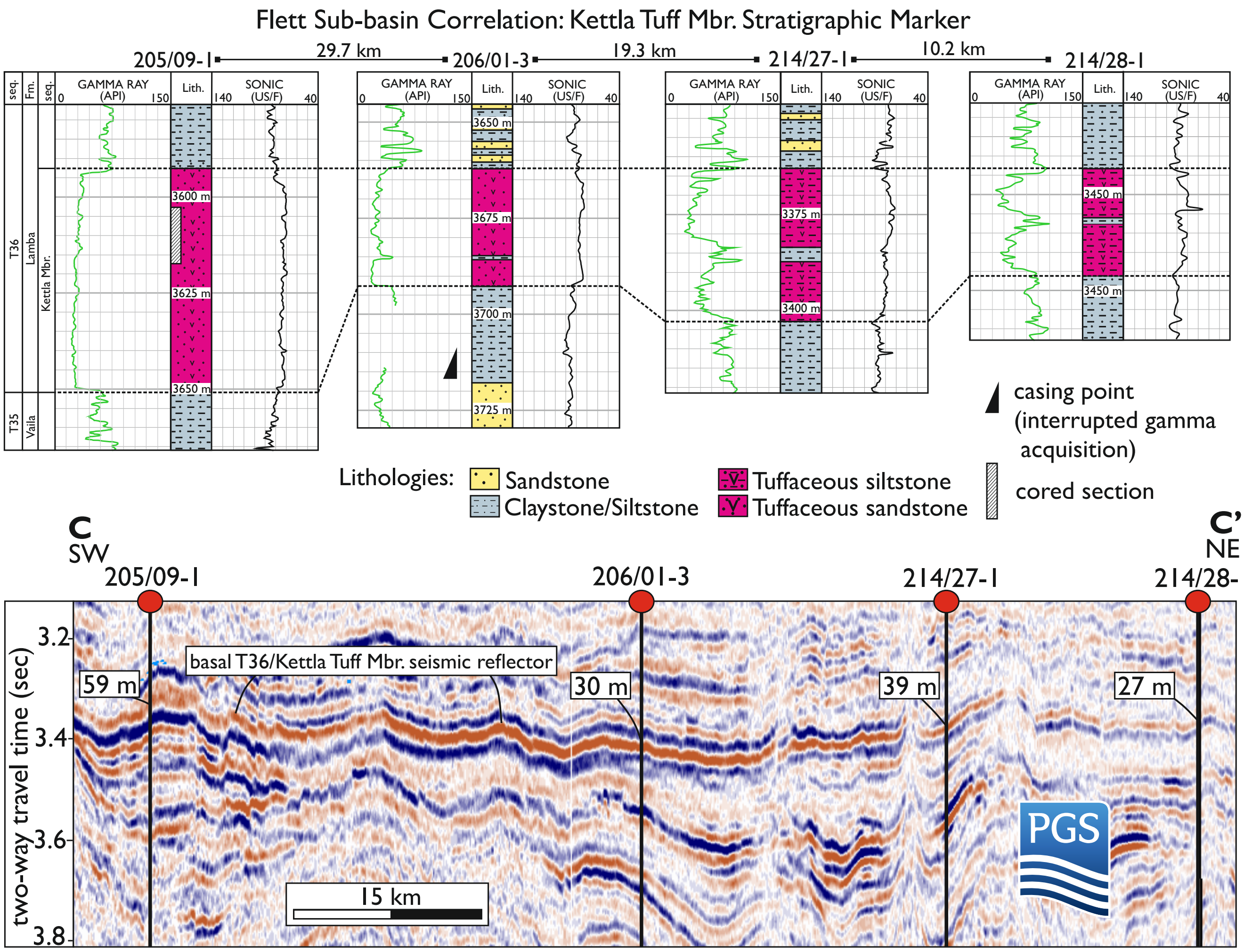


Figure 11 Click here to download Figure Figure 11.pdf

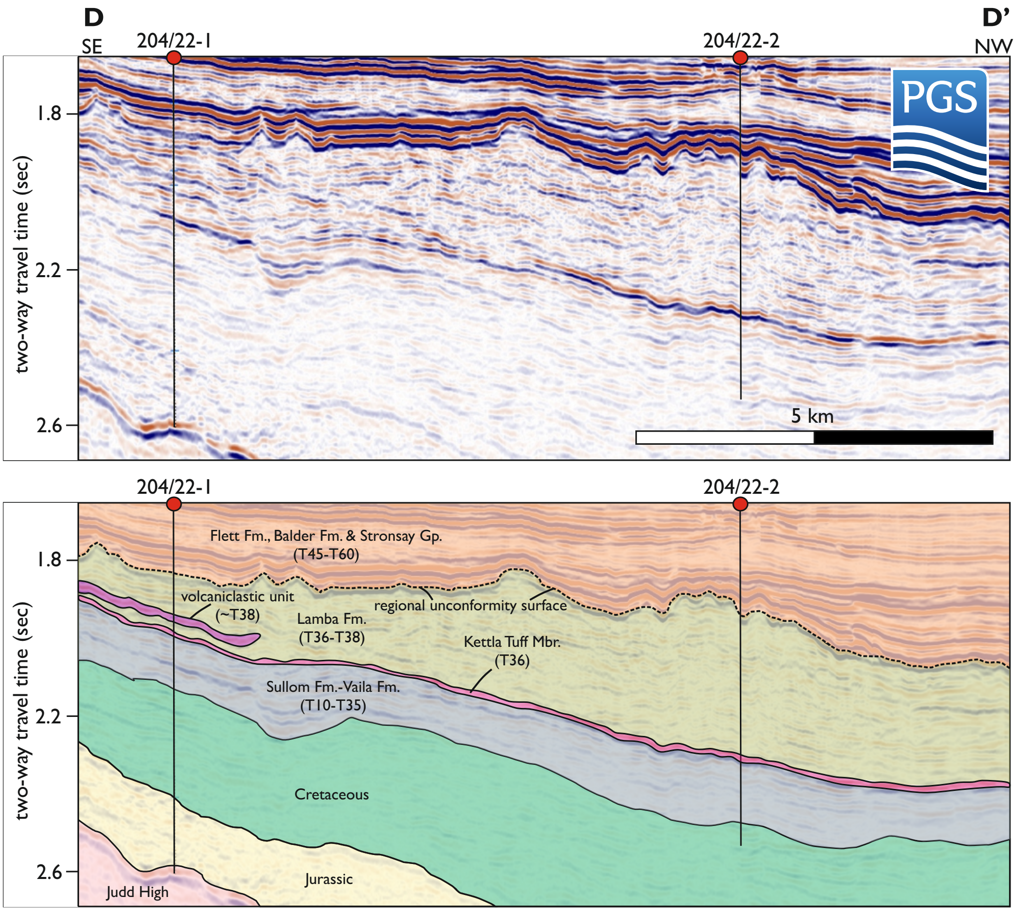


Figure 12 revised

Click here to download Figure Figure 12 revised.pdf

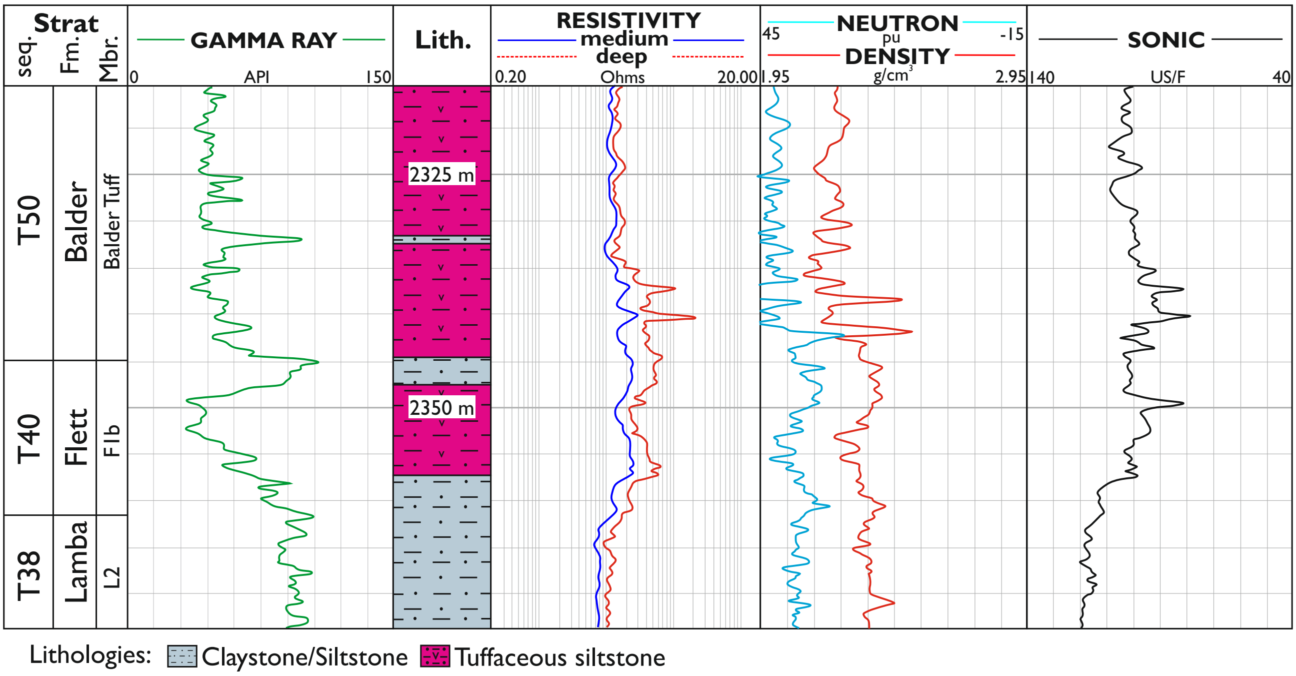


Figure 13 revised

Click here to download Figure Figure 13 revised.pdf

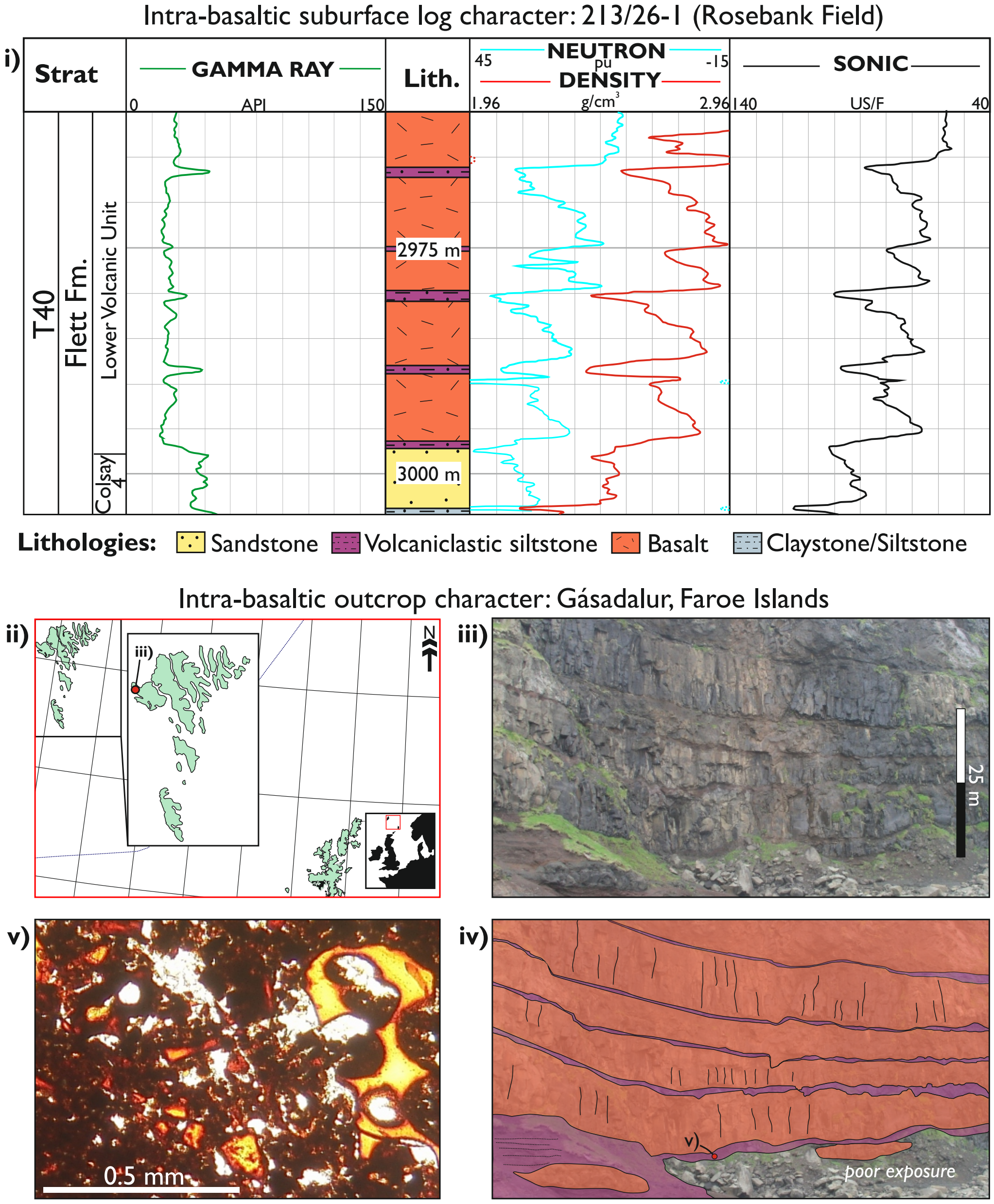


Figure 14 revised

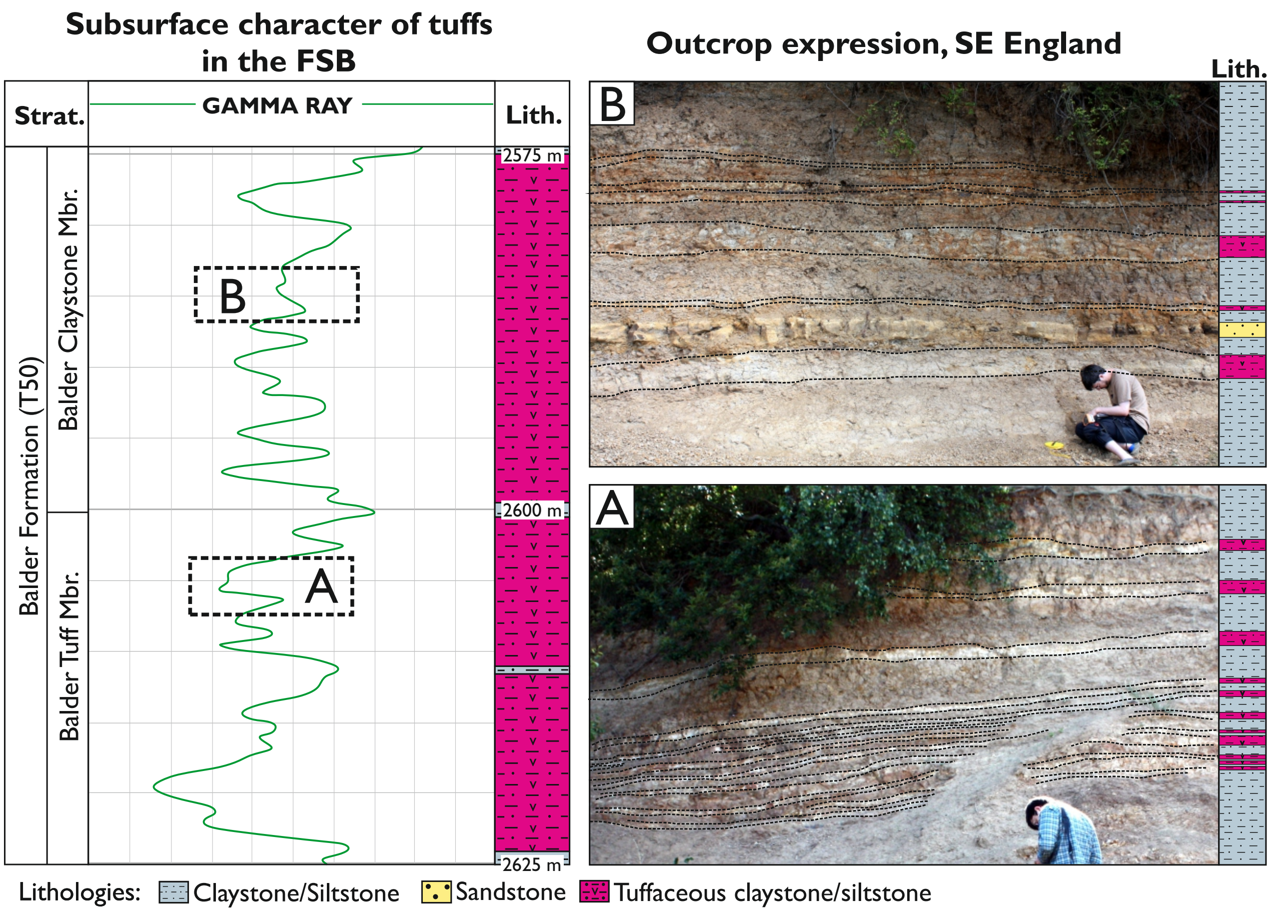


Figure 15 revised

Click here to download Figure Figure 15 revised.pdf