The Rattray Volcanics: Middle Jurassic fissure volcanism in the UK Central North Sea

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Abstract

The Middle Jurassic Rattray Volcanic Province is located at the triple junction of the North Sea continental rift system. It has previously been thought to be sourced from three large central volcanoes: the Glenn, Fisher Bank and Ivanhoe Volcanic Centres. Re-interpretation using 3D seismic and well data shows that no volcanic centres are present and the Rattray Volcanics were instead sourced in fissure eruptions from linear vents including the Buchan-Glenn Fissure System, a ~25km-long zone of WSW-ENE striking linear fissure vents and associated small volcanic edifices across the Buchan-Glenn Horst. The orientation of the fissures is broadly parallel to the Highland Boundary Fault which intersects the Rattray Volcanics at the Buchan-Glenn Fissure System, implying that Middle Jurassic magmatism exploited pre-existing crustal structural anisotropies established during the Caledonian Orogeny. The lack of large intrusive complexes beneath the Rattray Volcanics indicates pre-Middle Jurassic sedimentary sequences (e.g. Devonian-Carboniferous Old Red Sandstone

Group, Permian Rotliegend and Zechstein Groups and Triassic Skagerrak Formation) extend further than previously supposed, and therefore the presence of possible sub-volcanic reservoir and source rock units may have been overlooked within the triple junction of the Central North Sea.

Introduction

The Middle Jurassic Rattray Volcanic Province (RVP) lies at the triple junction of the North Sea rift system at the intersection of the Viking Graben, Central Graben and Outer Moray Firth (Fig. 1). These volcanic rocks – variously referred to in literature as the Forties Volcanics (Woodhall & Knox 1979), the Forties-Piper basalt field (Dixon *et al.* 1981), the Forties Igneous Province (Ritchie *et al.* 1988) and the Rattray Formation (Deegan & Scull 1977) – were discovered by the Forties Field discovery well (21/10-1) in 1970 which unexpectedly drilled through >700 m of volcanic rocks beneath the Upper Cretaceous Chalk Group. The volcanic sequence has since been penetrated by >200 hydrocarbon exploration and appraisal wells and is comprised of basaltic lavas and volcaniclastic sedimentary units. The RVP covers an area of ~7,400 km^2, with the thickest drilled volcanic sequence reaching ~1.5 km thick on the Buchan-Glenn Horst.

Despite its position at the centre of the prospective rift system, little research has focussed on the volcanism in the last 25 years, due to low perceived hydrocarbon potential of the interval. The majority of research on the Rattray Volcanics was conducted in the late 1970s to early 1990s, focussing on analysis of core data such as lithological descriptions (Howitt *et al.* 1975; Woodhall & Knox 1979), geochemical analysis (Gibb & Kanaris-Sotiriou 1976; Dixon *et al.* 1981; Fall *et al.* 1982; Latin *et al.* 1990a; Latin & Waters 1992), and radiometric dating (Ritchie *et al.* 1988). The broader significance of the relationship of the Rattray Volcanics at the rift triple junction to the tectonic evolution of the North Sea has also been the subject of much discussion (Dixon *et al.* 1981) with some authors favouring a passive rift model of melt in areas of greatest stretching (Latin *et al.* 1990a and 1990b; Latin & Waters 1991 and 1992) and others favouring an active rift model of thermal anomaly-induced rifting (Underhill & Partington 1993). While the volcanics have been studied extensively at both core-scale and regional-scale, relatively few studies have used seismic reflection data to interrogate their nature and origin (e.g. Smith & Ritchie 1993; Stewart 1999). 3D seismic reflection data can be used to map magma plumbing pathways, extrusion points and lava flows in subsurface volcanic fields, allowing eruption histories and styles of volcanic provinces to be investigated (Planke *et al.* 2005; Magee *et al.* 2014; McLean *et al.* 2017; Schofield *et al.* 2017a; Reynolds *et al.* 2018; Hardman *et al.* 2018).

Here we use regional 3D seismic datasets to re-evaluate the architecture of the RVP and provide new insights into the nature of the volcanic eruptions at the centre of the North Sea trilete rift. The currently widely-accepted model (Husmo *et al.* 2002; Johnson *et al.* 2005) for the RVP invokes eruption from three potential central volcanoes (Smith & Ritchie 1993), termed the Glenn, Ivanhoe and Fisher Bank Volcanic Centres. We present evidence indicating that the lavas were extruded in a series of fissure eruptions from linear vents and small associated volcanic edifices rather than central point sources, and identify a major fissure system in the RVP. We observe no evidence in seismic and well data to support the premise of three central volcanoes sourcing Rattray volcanism. We suggest the lack of large central volcanoes and associated shallow magma chambers beneath the Rattray Volcanics indicates unexplored pre-volcanic petroleum systems may be present in the North Sea triple junction area.

Stratigraphy

The Rattray Volcanics Member comprises part of the Middle Jurassic Pentland Formation (Fig. 2) and is coeval with the Ron Volcanics Member ~150 km to the south in the West Central Graben (Richards *et al.* 1993). The origin of the Ron Volcanics Member is not studied in detail in this paper. Lavas and volcaniclastic sedimentary rocks of the Rattray Volcanics Member are interbedded with siliciclastic fluvio-deltaic sedimentary rocks (Richards *et al.* 1993) around the fringes of the lava field. The Pentland Formation is dated as Bajocian-Bathonian from sparse biostratigraphy data including long ranging miospores (Howitt *et al.* 1975), giving an age range of 170.3±1.4 Ma – 166.1±1.2 Ma for the intercalated fluvio-deltaic sedimentary rocks on the current chronostratigraphic timescale (Gradstein *et al.* 2012; Cohen *et al.* 2013). Radiometric dating of the Rattray Volcanics Member using ^{40}Ar-^{39}Ar dating indicated a likely magmatic age of 153±4 Ma - 148±2 Ma (Ritchie *et al.* 1988), during the Kimmeridgian-Tithonian (Gradstein *et al.* 2012; Cohen *et al.* 2013), contradicting the biostratigraphic ages from the interbedded sedimentary rocks. Although the absolute age of eruption of the Rattray Volcanics Member is inconclusive, the volcanics are generally presumed to have been erupted in the Bajocian-Bathonian to Callovian (~170 Ma - 163.5±1.0 Ma; Howitt *et al.* 1975; Underhill 1998; Husmo *et al.* 2002).

While Pentland Formation siliciclastics are present beneath the volcanics in some wells (e.g. 15/13-1 (Howitt *et al.* 1975)), the Rattray Volcanics Member usually sits unconformably over a varied subcrop of Triassic and older rocks, with Lower Jurassic strata absent across most of the triple junction area. This stratigraphic gap is known as the 'Mid-Cimmerian' or 'Intra-Aalenian' unconformity and is presumed to be the result of regional doming in the late Toarcian-Aalenian (~182-170 Ma), which caused widespread subaerial erosion of Lower Jurassic and uppermost Triassic strata across the Central North Sea (Underhill & Partington 1993). The presence of Late Jurassic marine sedimentary rocks overlying the Rattray Volcanics Member indicates post-volcanic transgression occurred, likely associated with the deflation and collapse of the dome (Underhill & Partington 1993). Transgression established shoreface and marine shelf conditions over the fringes of the RVP in the Oxfordian and deposited some of the major reservoirs in the Central North Sea, e.g. the Piper Formation sandstones in the Outer Moray Firth. The stratigraphic position of the RVP indicates the eruption occurred after the regional uplift in the latest Lower Jurassic–earliest Middle Jurassic (Underhill & Partington 1993) and before the main phase of extension which formed the deep grabens of the North Sea rift system in the Kimmeridgian-Tithonian of the Late Jurassic (Fraser *et al.* 2002).

Previous Work: current understanding of the Rattray Volcanics Member

Rattray lithologies

Detailed lithological descriptions and geochemical analyses of the Rattray volcanic rocks can be found in Howitt *et al.* (1975), Gibb & Kanaris-Sotiriou (1976), Woodhall & Knox (1979), Fall *et al.* (1982), Latin *et al.* (1990a) and Latin & Waters (1992). The Rattray Volcanics Member is dominated by silica undersaturated alkali olivine basaltic lava flows (Howitt *et al.* 1975; Woodhall & Knox; 1979; Fall *et al.* 1982). The lavas are extensively weathered indicating subaerial eruption and erosion (Gibb & Kanaris-Sotiriou 1976; Woodhall & Knox 1979). Examples of subaqueous eruption have not previously been reported, though, if present, likely occurred in fluvial and lacustrine settings in a broadly terrestrial environment (Latin *et al.* 1990a). The proportion of volcaniclastic sedimentary rocks increases towards the fringes of the volcanic province (Howitt *et al.* 1975; Woodhall & Knox 1979). The volcaniclastics are generally reworked and often incorporated into the interfingering Pentland Formation fluvio-deltaic sedimentary rocks (Latin *et al.* 1990a). Small localised intrusions are present within and beneath the lava pile (Howitt *et al.* 1975; Gibb & Kanaris-Sotiriou 1976; Fall *et al.* 1982; Ritchie *et al.* 1988).

Proposed eruption mechanisms for the Rattray Volcanics

Multiple different eruption styles and source areas have been proposed for the RVP including extrusive vents (Howitt *et al.* 1975), fissure volcanism (Woodhall & Knox 1979), central volcanoes (Smith & Ritchie 1993) and maar-diatremes (Stewart 1999).

Extrusive vents

Howitt *et al.* (1975) suggested three possible central extrusive vents trending from east to west across the centre of the RVP in areas of increased drilled volcanic thicknesses and positive aeromagnetic anomalies. The proposed vents are approximately aligned with the Witch Ground Graben. Howitt *et al.* (1975) found no evidence of large scale intrusive bodies associated with the magmatism and suggested that upwelling of the basaltic magma likely occurred during the rifting of the Witch Ground Graben, exploiting pre-existing weaknesses in the crust.

Fissure volcanism

Fissure volcanism involves the repeated effusion of low viscosity basaltic magma from a series of linear fissure vents without a large-scale centralised volcanic vent system (Walker 1995). Fissure vents are the surface expression of deep, narrow feeder dykes which feed the surface volcanism from lower crustal magma reservoirs (Gudmundsson 1987), >20km depth (Thordarson & Larsen 2007). Woodhall & Knox (1979) suggested the Rattray basalts were erupted during repeated periods of fissure volcanism, citing a lack of evidence for suites of intrusions and associated vent structures.

Central volcanoes

Central volcanoes have a sub-circular vent structure, commonly erupting both silicic and mafic magmas (Walker 1971), and have a large plutonic intrusive complex beneath the core of the structure (Walker 1995) forming the magma chamber for the volcano. Eroded roots of central volcanoes are often observed onshore as large granitic and gabbroic plutons, e.g. the Skye and Mull Central Complexes (Emeleus & Bell 2005), representing solidified magma chambers (Walker 2000). Central volcanoes are usually associated with large sub-circular magnetic and gravity anomalies as seen in the West of Scotland igneous complexes (Emeleus & Bell 2005), offshore West of Britain in the Rockall Basin (Archer *et al.* 2005; Schofield *et al.* 2017b) and Faroe-Shetland Basin (Chalmers & Western 1979; Jolley & Bell 2002). Smith & Ritchie (1993) used seismic data, volcanic well thicknesses and magnetic anomaly data to suggest the Rattray Volcanics were erupted from three central volcanoes: the Glenn Volcanic Centre on the Buchan-Glenn Horst, the Fisher Bank Volcanic Centre in the Fisher Bank Basin, and the postulated Ivanhoe Volcanic Centre in the Outer Moray Firth (Fig.1). This model is currently the widely accepted eruption mechanism for the RVP (Husmo *et al.* 2002; Johnson *et al.* 2005).

Maar-Diatremes

Maars are volcanic craters, fed by pipes called diatremes, associated with the explosive interaction of magma with shallow groundwater (Lorenz 1986; Stewart 1999). Stewart (1999) interpreted four circular down-thrown fault blocks in the RVP on the southern slope of the Renee Ridge affecting the Triassic and older stratigraphy as maar craters. These potential maars are outwith the 3D seismic surveys used in this current study (Fig.3).

Data & Methodology

Seismic and Geophysical Data

This study uses two 3D seismic reflection surveys from the Central North Sea – the PGS 3D Central North Sea MegaSurveyPlus (MSP) and the PGS 3D North Sea MegaSurvey (MS) which extend to ~6-7 seconds two-way-time (s TWT). The surveys cover an extensive area across the North Sea; this study utilises the northern ~10,000 km^2 of the MSP and ~8,600 km^2 of the MS covering areas of the RVP outwith the MSP (Fig.3a). The data are displayed in the time domain where a downwards increase in acoustic impedance ('hard kick') corresponds to a negative amplitude reflection (displayed in blue) (Fig.3b), and a downwards decrease in acoustic impedance ('soft kick') corresponds to a positive amplitude reflection (displayed in red). The vertical resolution ($\lambda/4$ (Kallweit & Wood 1982)) of the seismic data within the subaerial Rattray lava package is calculated using an internal velocity of ~5504 m.s^{-1} (calculated from well 15/24b-3 depth ~3313m) with a dominant frequency in MSP seismic data of 24 Hz; a lava thickness of ~57 m is required for an individual flow to be fully resolvable. Nexen's AM852D1009 2D survey is used to aid interpretation in a gap between the MS and MSP 3D data in the south of Block 15/23 (Fig.3). The vertical resolution of the 2D survey for subaerial lavas, using an internal velocity of ~5504m.s^{-1} with a dominant frequency of 18 Hz, is ~76 m.

Digital Magnetic Anomaly data at 1:50,000 for Central North Sea Quads 6 through to 39 is provided by the British Geological Survey (BGS). Magnetic anomaly data outside of this area, as well as offshore gravity anomaly data, is accessed on the BGS Offshore Index. Formation depths from well data were used to guide seismic interpretation with wells (Fig.3) accessed on the UK Oil and Gas Database.

Wireline facies interpretation

Detailed volcanic wireline facies analysis was undertaken in several wells across the RVP. Digital log curves used for facies interpretation include gamma ray, deep resistivity, density, neutron, and acoustic travel time curves. Volcanic facies analysis in this study has been guided by the wireline facies interpretation and methodologies of Planke (1994), Nelson *et al.* (2009), Watton *et al.* (2014), Millett *et al.* (2016a) and Watson *et al.* (2017) and was checked against Rattray core facies where available. Typical examples of the petrophysical characteristics of the main basaltic volcanic facies in the Rattray Volcanics Member are shown in Figure 4. All basaltic facies produce low gamma values, typically between 15-60 API, due to the low proportion of potassic minerals. Tabular basaltic lava flows – formed by thick, individual flow units – produce blocky log motifs of high resistivity (>50-200 ohm.m), high density (~2.7-2.9 g.cm^{-3}) and fast internal velocity (~40-60 μs.ft^{-1} or ~5.1-7.6 km.s^{-1}). Compound basaltic lava flows – formed by multiple stacked thin flow units – exhibit more serrated log motifs than tabular lavas and typically have slightly lower densities and acoustic velocities (Nelson *et al.* 2009) due to the high proportion of vesicular crust in compound flows.

Hyaloclastite is formed by the quenching and fragmentation of lava during interaction with water (Watton *et al.* 2014) and is identified in the RVP in this study. Subaqueous basalt typically has lower resistivity, density and acoustic velocity than subaerial basalt due to increased fracturing and higher porosity (Bartetzko *et al.* 2005). Hyaloclastite log profiles can be highly variable dependent on its physical properties and composition (Nelson *et al.* 2009; Watton *et al.* 2014; Millett *et al.* 2016a). Hyaloclastite has high neutron porosity values (40-60 pu in the Rattray Volcanics) due to high vesicularity and clay-bound water (Planke 1994; Bartetzko *et al.* 2005; Watton *et al.* 2014). Basaltic volcaniclastic sedimentary rocks exhibit low gamma, medium-high resistivity (~10-20 ohm.m), are acoustically fast but slower than subaerial lavas (~60-80 μs.ft^{-1}) and are less dense than subaerial lavas (~2.3-2.5 g.cm^{-3}). Basaltic volcaniclastics exhibit high neutron values due to clay-bound water, and produce a characteristic density-neutron response similar to shales, with the neutron on the left of the density curve (Watson *et al.* 2017).

Subsurface mapping of the Rattray Volcanics

The depth to the top of the Pentland Formation is highly variable across the triple junction area (Fig. 5) due to faulting during the major Late Jurassic rifting event. The Rattray Volcanics Member is at its shallowest depth on the footwalls of Late Jurassic fault blocks (e.g. Piper Shelf, Renee Ridge) at 2-2.4 s TWT (approximately 2.3-2.8 km vertical depth below the sea surface). The deepest burial of the volcanics is in the downthrown structures of the Witch Ground Graben and Fisher Bank Basin, where the top of the Pentland Formation is at depths of 4.4-4.9 s TWT (~5.6-6.2 km).

Figure 1b shows the thickness of the Pentland Formation around the triple junction area. Most wells stopped drilling within the volcanics without reaching the base of the Rattray sequence. The thickness map is constructed from well thicknesses and seismic mapping of the near top and base Pentland Formation surface. The Rattray Volcanics Member is thickest in the Witch Ground Graben and Buchan-Glenn Horst, where it reaches thicknesses of ~1.3-1.5 km (Fig.1b). The thickest drilled Rattray sequence is on the Buchan-Glenn Horst, with ~1469m of volcanics penetrated in well 21/03b-3.

Investigating source areas of Rattray volcanism

Here we re-evaluate the architecture of the RVP using 3D seismic data to determine the type of eruptions that sourced the Rattray volcanism.

Buchan-Glenn Horst

The Buchan-Glenn Horst is the site of an elongate positive magnetic anomaly (200-250 nT), ~25 km long and ~9 km wide, oriented WSW-ENE (Fig. 6a). The elongate shape of the magnetic anomaly aligns with the shape of the uplifted horst block and is likely a response of the dense basement and thick (~1.5 km) ridge of Rattray volcanic rock on the Buchan-Glenn Horst.

Seismic Line A-A': Buchan-Glenn Horst

Figure 6b/c shows a seismic line running W-E across the Buchan-Glenn Horst. The Rattray Volcanics Member forms a ridge of material ~0.45 s TWT (~1.2 km) thick across the Buchan-Glenn Horst structure, above a thick (0.86 s TWT; ~2.1 km) siliciclastic sedimentary package, likely comprising Devonian-Carboniferous Old Red Sandstone (ORS), with a thin (~24 m) Permian carbonate package between the ORS and volcanics (21/03b-3 end-of-well report). The ORS seismic reflections beneath the volcanic sequence are laterally continuous and can be traced beneath the Rattray on the Buchan-Glenn Horst and into the adjacent basin (Fig. 6c(1)). A bright, discontinuous, discordant reflection is highlighted within the Rattray sequence to the west of the Glenn anomaly peak (Fig. 6c(2)). Bright, discontinuous stratigraphically concordant reflections are present within the ORS package (Fig. 6c(3)).

A thick (~0.45 s TWT/1.2 km) package of inclined seismic reflections (Fig. 6c(4)) is observed within the volcanic sequence and appears to downlap the sub-Rattray sedimentary sequence, dipping in a south-westerly direction. The inclined reflections appear to be truncated at the Top Rattray surface (Fig. 6c(5)), possibly recording post-volcanic erosion in this area. Similar packages of inclined seismic reflections are observed within the Rattray Volcanics Member across the Buchan-Glenn Horst, Renee Ridge and extend into the Witch Ground Graben to the north and Forties-Montrose High to the south.

Seismic Line A-A' Interpretation

We observe no evidence of large-scale volcanic vent structures in seismic data indicative of a central volcano in the Buchan-Glenn Horst area. The bright, discontinuous reflections within the volcanic and ORS packages likely represent igneous intrusions. A sill cross-cuts the Rattray lava seismic reflections and is not observed to be feeding a volcanic vent or edifice (Fig. 6c(2)), indicating that the intrusion occurred after the eruption of the majority of the lavas. While sills are present on the Buchan-Glenn Horst structure (Ritchie *et al.* 1988), they are spatially restricted and not mappable on seismic across a large area; there is no evidence on seismic data for a kilometre-scale intrusive sill complex expected with central complex volcanism.

The inclined seismic reflections on the Buchan-Glenn Horst have previously been interpreted as the depositional dips of lavas on the flanks of a central volcano (Smith & Ritchie 1993) or tectonically-induced dips (Stewart 1999). Inclined seismic reflections in volcanic sequences can represent the presence of lava deltas, which form at the transition from subaerial to subaqueous lava emplacement (Jones & Nelson 1970; Wright *et al.* 2012) when lava builds out into a standing water body. Our re-evaluation of wireline volcanic facies in nearby wells (e.g. 15/21-3 and 15/24b-3) indicates that thick (~70 m) hyaloclastite packages are present in the Rattray Volcanics Member. We therefore suggest that the inclined seismic reflections in Fig. 6c(4), while likely also affected by later tectonic rotation during Late Jurassic extension, actually represent foresets of lava that built out in a standing water body forming a hyaloclastite delta.

Seismic Line B-B': Sub-vertical seismic discontinuities

Seismic line B-B' from north to south across the Buchan-Glenn Horst shows a series of sub-vertical discontinuities through the Rattray and older strata (Fig. 7). Each discontinuity is represented by red-blue-red triplets of sub-vertical seismic reflections (Fig. 7a(1)). The reflection triplets are ~0.4-1 km apart. These reflection triplets extend to depths of around 4 s TWT; below this discontinuities in the seismic continue in the same orientation and extend towards the base of the seismic line, but do not extend above the Rattray sequence. The discontinuities dip ~65° north-westwards, trend in a broadly WSW-ENE direction, and can be mapped across numerous seismic lines across the central Rattray area on the Buchan-Glenn Horst, reaching ~25 km in length.

Seismic Line B-B' Interpretation

We interpret the NW-dipping linear features as reflections caused by igneous dykes. Dykes are rarely clearly imaged on seismic data due to their narrow width and near-vertical structure. However, sub-vertical zones of seismic disturbance have been interpreted as representative of igneous dykes in the Southern North Sea (Underhill 2009; Wall *et al.* 2010) and offshore South Australia (Holford *et al.* 2017), and reflections from dykes have been imaged offshore southern Norway (Phillips *et al.* 2017). The Rattray dykes would have been near vertical at the time of emplacement; their current orientation of dipping ~65° to the NW is presumably related to later tectonic movements, possibly regional tilting that occurred across the triple junction area following Late Jurassic rifting (Stewart 1999). Rotation of the dykes to approximately vertical re-instates the lavas across the area to sub-horizontal.

Spectral Decomposition of Seismic Data

A frequency decomposition flattened on the Top Rattray surface in the Buchan-Glenn Horst area highlights a linear seismic discontinuity coincident with the position of the interpreted dykes (Fig. 8a). The WSW-ENE linear feature is ~25 km long and <800 m wide and has bright areas extending NW and SE on either side. Five small circular features ~1 km in diameter are aligned along the discontinuity. Four shorter (~2.5-8.5 km long) discontinuities are found ~1-7 km to the north and south of the main linear feature. These discontinuities variably trend WSW-ENE and SW-NE and are less pronounced than the main feature.

Spectral Decomposition Interpretation

The dyke highlighted in Fig. 7b(1) is interpreted as having fed a ~25 km long linear volcanic fissure system running WSW-ENE through the Buchan-Glenn Horst (Fig. 8b(1)), coincident with the location and orientation of the positive magnetic anomaly. The linear nature of the interpreted fissure system differs markedly from the curvilinear shape of the major post-volcanic Late Jurassic fault planes (Fig. 8b(2)), an aspect also noted in seismically imaged dykes offshore southern Australia (Holford *et al.* 2017). The other discontinuities (e.g. Fig. 8b(3)) likely represent other dykes in close proximity to the fissure – the dyke in Fig. 7b(2) is coincident with the discontinuity in Fig. 8b(3). It is unclear whether these dykes fed surface lavas, but if so they may represent minor fissure vents. Bright areas in the Top Rattray surface are highlighted appearing to extend away from the fissure zone (Fig. 8b(4)). These bright zones are interpreted as lava flows, similar to those mapped within the Palaeogene lava sequences of the Faroe-Shetland Basin (Schofield & Jolley 2013; Hardman *et al.* 2018), extruded from the fissure system. The five circular structures (Fig. 8b(5)) are positioned centrally along the interpreted fissure system and appear to source some of the lava flows in the area. A flow extending south-eastwards from the eastern end of the fissure system has a different internal morphology to lava flows (Fig. 8b(6)). Whereas the lava flows are relatively smooth surfaces, this area has thin internal striations across the surface, and is dimmer than the nearby lava flows. This may represent an alluvial system made up of eroded volcanic debris generated by flow through the channelised fissure system after eruption had ceased.

Seismic Lines C-C' and D-D'

Seismic cross-sections through two of the circular structures located on the fissure are shown in Figure 9. Each structure has positive relief relative to the surrounding Top Rattray surface with a central depression and directly overlies a narrow zone of chaotic seismic reflections within the Rattray sequence.

Seismic Lines C-C' & D-D' Interpretation

The circular structures in Fig. 8/9 are interpreted as small volcanic vents on the fissure system. Vent C-C' is steep and narrow with a high vent rim and narrow crater. It is ~200 m high and ~800 m in diameter, with an aspect ratio of ~1:4, close to the typical aspect ratio of a cinder cone (1:5, Heiken 1971). Vent D-D' is ~150 m high and ~1320 m across, giving an aspect ratio of ~1:9, which is typical of a tuff cone (Heiken 1971). The deep, narrow zone of seismic disturbance beneath vent D-D' is also similar to the described morphology of a maar-diatreme structure (Stewart 1999). Small volcanic cones can build up along fissure vents due to fire-fountaining of basaltic magma as it degasses during effusion from the fissure (Kereszturi & Németh 2012; Reynolds *et al.* 2016 and references therein).

Buchan-Glenn Horst Summary

Multiple sub-vertical discontinuities through the volcanic sequence and underlying stratigraphy, and terminating at the top Rattray surface, are visible across the Buchan-Glenn Horst. These discontinuities are interpreted as feeder dykes sourcing the Rattray Volcanics in a series of fissure eruptions. A modern-day analogue for the Buchan-Glenn Horst fissure and associated volcanic edifices is the ~27 km-long Laki fissure system, known as Lakagígar, in southern Iceland (Thordarson & Self 1993) (Fig.8c). The Laki fissure system comprises ten individual fissures, ~1.6-5.1 km in length, aligned en-echelon in close proximity (Thordarsen & Self 1993). The identification of a closely-spaced suite of multiple feeder dykes on the Buchan-Glenn horst is interpreted as forming a similar structure of individual fissure vents forming one large fissure system.

The Buchan-Glenn Horst is close to the source of the Rattray volcanism, as previously noted (Smith & Ritchie 1993). However, despite the thick volcanic succession present, there is no obvious large-scale central volcano in the Rattray succession nor identifiable sill or plutonic complex observed in the Rattray subsurface in the Buchan-Glenn Horst area. We suggest the evidence is indicative of a feeder dyke swarm across the Buchan-Glenn Horst sourcing the Rattray Volcanics in a series of fissure eruptions, and propose the name the Buchan-Glenn Fissure System.

Northern Witch Ground Graben

A positive magnetic anomaly of magnitude ~320 nT is present across Blocks 15/22, 15/23 and 15/24, ~35 km east of the Halibut Horst (Fig. 10a). It stretches ~40 km NW-SE and ~20km NE-SW and covers an area of ~700 km^2. It reaches a magnitude of ~320 nT close to well 15/23b-14 (Fig. 10a). Smith & Ritchie (1993) postulated that this magnetic anomaly may represent an eruptive centre in the RVP, the Ivanhoe Volcanic Centre, but did not identify the nature of the magnetic anomaly using seismic data.

Seismic Line E-E'

The peak of the magnetic anomaly is situated in a gap between the MSP and MS 3D seismic surveys, but is imaged in Nexen's AM852D1009 2D survey (Fig. 10). Around the peak of the magnetic anomaly near well 15/23b-14 the Rattray Volcanics seismic package is composed of relatively laterally continuous seismic reflections which can be traced northwards across the Witch Ground Graben. The Top Rattray surface does not contain any prominent structures with positive relief indicative of a volcanic vent or edifice, although post-volcanic erosion could have removed such features.

The Rattray Volcanics Member is downthrown to the north by a normal fault. A Late Jurassic syn-rift seismic package of laterally continuous reflections lies above the Rattray on the downthrown side, reaching ~570 m in thickness. The Rattray Volcanics Member thins to the north from ~800 m (~0.36s TWT) against the fault to ~419 m in well 15/23-1Z. The seismic reflections beneath the Rattray sequence are unclear, but a Permian sequence can be extrapolated from the well penetration 15/23-1Z.

Seismic Line E-E' Interpretation

We do not observe any large-scale vent indicative of a central volcano, nor any discordant seismic reflections in the volcanic subsurface which could indicate an igneous plumbing complex beneath the Rattray Volcanics Member. There is no positive evidence on available seismic data supporting the interpretation of a central volcano associated with the Ivanhoe magnetic anomaly.

Volcanic Wireline Facies in the Northern Witch Ground Graben

Wells in the northern Witch Ground Graben contain thick (up to 70 m) sequences of basaltic hyaloclastite and tabular lava flows (individual flows reaching over 30 m thick) with volcaniclastic and siliciclastic sedimentary interbeds (Fig. 11). The full volcanic succession, encountered in well 15/21-3, contains two repeated sequences of hyaloclastite to tabular lava flows.

Volcanic Facies Interpretation

The presence of hyaloclastite indicates the area was at times subaqueous, with lava building out into a standing water body. Thick tabular lava flows indicate large volumes of magma with a fast effusion rate (Walker 1971), likely being erupted into an area of increased accommodation space allowing inflation of individual flows. The volcanic wireline facies interpreted in the northern Witch Ground Graben are typical of flood basalt eruptions (Jerram *et al.* 2009; Nelson *et al.* 2009; Millet *et al.* 2016a). The repetition of subaqueous hyaloclastite overlain by subaerial tabular lava flows in well 15/21-3 (Fig. 11) indicates that relative water level rose during continued volcanic eruption, either by eustatic sea level rise or active subsidence in the area.

Northern Witch Ground Graben Summary

No volcanic edifice nor associated magmatic plumbing system is visible on the available seismic data in the northern Witch Ground Graben. We see no positive evidence on seismic to support the interpretation of a large-scale central volcano in the Ivanhoe area (Block 15/23). The volcanic sequence thins northwards from ~1.5 km thick in the centre of the RVP to ~0.4 km thick in the northern Witch Ground Graben (Fig. 1). The northwards thinning of the volcanic sequence leads us to speculate that the extrusives of the Rattray Volcanics Member in the northern Witch Ground Graben area were sourced from the Buchan-Glenn Fissure System, ~37 km to the southeast in Blocks 21/04 and 21/05 (Fig. 8 inset map).

Fisher Bank Basin

A large sub-circular positive magnetic anomaly of magnitude ~350 nT and diameter ~30 km is present in the Fisher Bank Basin (Fig. 12a). This sub-circular shape is typical of igneous centres elsewhere on the UKCS (Archer *et al.* 2005; Emeleus & Bell 2005; Schofield *et al.* 2017b). Smith & Ritchie (1993) interpreted the Fisher Bank Volcanic Centre to be almost coincident with the peak of the magnetic anomaly. The volcanic centre was identified on seismic data from the interpreted thickening of the volcanic sequence into the Fisher Bank Basin, and a ‘structural culmination’ at the base of the Upper Jurassic (Smith & Ritchie 1993).

No wells penetrate to Jurassic level in the centre of the Fisher Bank Basin, though several wells penetrate the Middle Jurassic towards the flanks of the basin (Fig. 12b). The Fisher Bank Basin formed during Late Jurassic rifting, after the volcanism (Clark *et al.* 1993) and therefore wells on the basin flanks should contain a similar Rattray sequence to the undrilled Rattray in the depths of the basin.

Volcanic Thickness and Facies around the Fisher Bank Basin

The Rattray Volcanics Member is >800 m thick on the northern flanks of the Fisher Bank Basin (16/29a-8) and thins southwards (624 m in 22/05b-4). The Middle Jurassic sequence thickness is shown on seismic line F-F' (Fig. 12d/e), with seismic mapping indicating that it thins southwards into the Fisher Bank Basin, contrary to the thickness map of Husmo *et al.* (2002) (Fig. 12c). Investigation of the Rattray volcanic wireline facies on the flanks of the Fisher Bank Basin indicates the volcanic sequence is dominated by compound basaltic lava flows and volcaniclastic sedimentary rocks (e.g. 16/29a-8, 22/05b-4) (Fig. 12b), with the proportion of sedimentary material in the volcanic sequence increasing southwards (Fig. 12b). The Middle Jurassic succession in 22/05b-4 includes a thick (~100 m) Pentland Formation siliciclastic sequence of sandstone, claystone and coal above the Rattray Volcanics Member. A similar siliciclastic sequence is found overlying the volcanics in well 22/02-2 (~286 m), while well 22/07-1 on the Forties-Montrose High contains a 123 m thick Pentland Formation sandstone and coal package but does not contain the Rattray Volcanics Member.

Thickness and Facies Interpretation

The overall southwards-decrease in thickness of the volcanic pile and the change in facies to predominantly compound flows and sedimentary rocks indicates the Fisher Bank Basin was distal to the volcanic source. The presence of thick Middle Jurassic siliciclastic sedimentary rocks above the volcanics indicates the Fisher Bank area was a subsiding sedimentary depocentre after volcanism in the area ceased, before the onset of Late Jurassic rifting. It is therefore likely that the relatively thin Rattray succession in the south of the Fisher Bank Basin is due to cessation of volcanism reaching the basin, rather than emplacement and subsequent erosion.

Seismic Line G-G': NW-SE across the Fisher Bank Basin

The Middle Jurassic seismic package undulates and thins southwards across the Fisher Bank Basin from ~630m (0.295 s) to ~270m (0.129 s) against the bounding fault to the Jaeren High (Fig. 13(1)). Middle Jurassic strata appear to be domed upwards in the centre of the basin (Fig. 13(2)) and are onlapped by continuous seismic reflections of Late Jurassic age. A package with limited internal reflectivity is present in the sub-Rattray sequence beneath this central structure, but towards the basin margins a thick (~1.1 km, ~0.5 s TWT) package with faint continuous reflections is present (Fig. 13(3)).

Seismic Line G-G' Interpretation

No large-scale vent structure is observed in the Fisher Bank Basin. The area of limited internal reflectivity beneath the Middle Jurassic is interpreted as a diapir of Permian Zechstein Group halite, surrounded by pods of Triassic sedimentary rocks (Fig. 13(3)). Above the interpreted salt diapir an antiform structure is visible in the top Upper Jurassic reflection (Fig. 13(4)), similar to the top Upper Jurassic structure above a drilled halite diapir at the north-western edge of the Fisher Bank Basin (wells 16/27-1A and 16/28-1 (Fig. 13(5)); see inset map Fig. 12a). Beneath the interpreted halite diapir seismic imaging becomes less clear. However no obvious discordant seismic reflections indicative of plumbing system of a central volcano are visible on the available seismic data (Fig. 13).

Fisher Bank Basin Summary

We find no positive evidence of a volcanic source area in the Fisher Bank Basin. We interpret the base Upper Jurassic structure as the top of a salt diapir, caused by upwelling of Zechstein Group evaporites (Fig. 13). The Fisher Bank Basin is at the northern extent of the Zechstein Group evaporite sequence (Glennie *et al.* 2003). Thick evaporite packages, including halite and anhydrite, are drilled on the surrounding Forties-Montrose and Jaeren Highs with Triassic sediments deposited in pods in areas of salt withdrawal (Smith *et al.* 1993). The undulation observed in the Rattray seismic sequence across the basin is likely due to movement of Zechstein Group halite, which influences Jurassic sedimentation in the area (Clark *et al.* 1993).

The southwards-thinning Pentland Formation sequence and increasing proportion of sedimentary material in the Fisher Bank Basin indicates the area was distal to the site of volcanic eruption. The underlying cause of the positive magnetic anomaly in the Fisher Bank Basin is therefore unclear and is discussed below. We suggest the extrusives of the Rattray Volcanics Member in the Fisher Bank Basin and surrounding areas were likely sourced from the Buchan-Glenn Fissure System, ~45 km to the northwest (Fig. 8 inset map).

Discussion

Eruption style of the Rattray Volcanic Province

The identification of feeder dykes and small associated volcanic edifices in the centre of the RVP indicates the volcanics were effused in a series of low-viscosity flood basalt eruptions from at least one fissure system. The Buchan-Glenn Fissure System trends WSW-ENE across the Buchan-Glenn Horst and, given its position in the centre of the RVP where the lava pile is thickest, was likely the primary source area for the lavas. Magma conduits can be re-exploited during later eruptions (Needham *et al.* 2011); it is possible that the area of the

Buchan-Glenn Fissure System was the site of several pulses of magmatism during the eruption of the Rattray Volcanics Member.

In addition to the Buchan-Glenn Fissure System, there are likely many more fissure vents associated with the RVP that remain as yet unidentified. Overprinting of earlier fissures by other later lava flows may obscure fissure vents in seismic data. The identification of a series of maar craters on the Renee Ridge by Stewart (1999) indicates that this area may also have been the location of a volcanic fissure. However, as this area is outside the extent of our available 3D seismic data we cannot investigate further. We suggest it is likely that other volcanic fissures may be present across the Forties-Montrose High area, given the thickness of the volcanic pile across that region (0.8-1.0 km). However, the presence of thick Zechstein Group evaporites across the Forties-Montrose High creates uncertainty in interpreting possible sub-vertical reflections associated with potential feeder dykes.

We do not see any large-scale volcanic vent structures in the available seismic data, nor kilometre-scale suites of intrusive sill complexes or plutonic magma chambers in the Rattray subsurface indicative of central complex plumbing systems. We find no evidence in seismic data to support the interpretation of a series of large central volcanoes sourcing the Rattray volcanism.

Influence of structural lineaments on volcanism

While the main phase of rifting forming the trilete rift system in the Central North Sea occurred during the Late Jurassic (Fraser *et al.* 2002), initiation of Jurassic rifting in the triple junction area is thought to have begun during the Bathonian-Callovian in the Middle Jurassic (Boldy & Brealey 1990; Davies *et al.* 1999; Stewart 1999; Husmo *et al.* 2002) and has previously been suggested to exert a control on the distribution of the Rattray Volcanics (Howitt *et al.* 1975; Woodhall & Knox 1979). The initial phase of Jurassic rifting in the Bathonian-Callovian was focussed along N-S Viking Graben trending faults and NE-SW Caledonian-trending faults (Boldy & Brealey 1990; Erratt *et al.* 1999). The Caledonian-trending faults include the offshore extension of the Highland Boundary Fault, which can be traced across the Central North Sea from onshore Scotland to Norway (Doré & Gage 1987; Zanella *et al.* 2003). It strikes WSW-ENE through the triple junction area and is approximately coincident with the Buchan-Glenn Fissure System (Fig. 14), which trends in a similar orientation. The coincident positions of the Buchan-Glenn Fissure System and the Highland Boundary Fault, and their shared WSW-ENE orientation, suggests Caledonian structural lineaments may have influenced the opening of Middle Jurassic volcanic fissure systems.

The pre-rift geometry of the Rattray Volcanics Member (Fig. 10) indicates the eruption of the Rattray Volcanics Member occurred prior to the main phase of Late Jurassic rifting, as suggested by Underhill & Partington (1993). However, it is possible that the initiation of extension during the Middle Jurassic reactivated pre-existing Caledonide structural weaknesses which were then exploited during volcanism. This link remains speculative; quantitative analyses of the trends of the fissures and the Caledonian lineaments is needed to investigate any relationship further.

Relationship of Rattray Volcanics Member to magnetic anomalies

The Buchan-Glenn Fissure System is coincident with the WSW-ENE oriented elongate magnetic anomaly of the Buchan-Glenn Horst, with the deep-rooted feeder dykes likely associated with the positive magnetic response. The Fisher Bank magnetic anomaly (Fig. 14a) displays a sub-circular shape analogous to the igneous centres seen along the west of Scotland and offshore along the Northeast Atlantic Margin, but is not associated with a Middle Jurassic volcano. The magnetic anomaly may alternatively represent a Jurassic intrusion associated with Rattray magmatism without resulting in surface volcanism in the Fisher Bank Basin.

Woodhall & Knox (1979) suggest a large mafic intrusion is buried at depths of around 8 km in the Fisher Bank Basin, although note its link to the Rattray volcanism is unknown. We observe no evidence in seismic data linking the Fisher Bank magnetic anomaly to the RVP, and explore an alternative explanation.

The Fisher Bank magnetic anomaly is of similar size and shape to other magnetic anomalies on the UKCS (Fig. 14). Two similar sub-circular magnetic anomaly highs in the Faroe-Shetland Basin (Fig. 14b) were originally interpreted as Palaeogene volcanic centres associated with the formation of the North Atlantic Igneous Province, named the Westray and Judd Central Complexes (Naylor *et al.* 1999). Later hydrocarbon drilling showed that this interpretation was incorrect. The magnetic anomaly highs are caused by older (Westray dated as late Precambrian, 204/15-2 end of well report) granite and granodiorite plutonic intrusions unrelated to Palaeogene volcanism, now called the Westray and Cambo Highs (Watson *et al.* 2017). We suggest the Fisher Bank magnetic anomaly may represent a similar older intrusive body with no relation to Rattray volcanism.

The subduction of Avalonia under Laurentia in the Caledonian Orogeny emplaced a series of mafic and granitic plutons forming the Grampian Caledonides across NE Scotland and Scandinavia on the Grampian terrane north of the Highland Boundary Fault (Stephenson *et al.* 2000). The onshore magnetic anomaly map of Scotland displays circular magnetic anomaly highs (e.g. the Cairngorm granite, Fig. 14c), of similar size (~30 km in diameter) to the anomaly in the Fisher Bank Basin. Positive sub-circular magnetic anomalies offshore northeast Scotland (Fig. 14d) are presumed to represent the continuation of the Grampian Caledonide plutonic intrusions (Gatliff *et al.* 1994). Caledonian plutons are drilled in the Moray Firth (Fig. 14e) and to the NE of the RVP in the Norwegian sector (Fig. 14f), with emplacement ages dated as Middle Ordovician (463Ma in well Nor. 16/5-1) to Late Silurian (421Ma in Nor. 16/1-4) (Slagstad *et al.* 2011).

The Fisher Bank magnetic anomaly is south of the HBF on the Midland Valley Terrane. Similar sized and shaped magnetic anomalies on the Midland Valley terrane to that of the Fisher Bank Basin are also found across the West Central Shelf (Fig. 14g/h), between mainland Scotland and the Central Graben (Fig. 1(a)). The basement rocks causing these magnetic anomalies have not been drilled but are assumed to be deeply buried older igneous plutons rather than associated with Middle Jurassic volcanism, due to their location away from the RVP. We therefore suggest that given the presence of Caledonian plutons surrounding the triple junction, and the lack of volcanic structures in the Fisher Bank Basin, the Fisher Bank magnetic anomaly may be a similar Caledonian-aged intrusion, unrelated to the later Middle Jurassic RVP.

Rattray Magma Reservoir

The position and depth of Rattray magma reservoir is unknown, as is its effect on geophysical anomalies in the area. We have interpreted the Rattray Volcanics Member to be sourced from a series of fissure eruptions from deep-rooted feeder dykes connected to a lower crustal magma reservoir. We suggest the positive magnetic anomalies in the western area of the RVP (e.g. Ivanhoe magnetic anomaly) do not represent upper crustal magma chambers associated with central volcanoes, but may be associated with the deeply buried magma reservoir sourcing the fissure eruptions. Magnetic and gravity modelling has been conducted on geophysical anomalies across the UKCS (Donato & Tully 1981, 1982; Donato *et al.* 1983; Archer *et al.* 2005); modelling of the anomalies at the triple junction may help elucidate the depth, shape and composition of the Rattray magma reservoir.

Implications for Sub-Volcanic Hydrocarbon Prospectivity

The lack of large-scale suites of igneous intrusions beneath the Rattray Volcanics Member in the Witch Ground Graben, Buchan-Glenn Horst and Fisher Bank Basin areas has implications for the extent of potential pre-Middle Jurassic hydrocarbon reservoirs and source rocks, with the gross sedimentary rock volume beneath the extrusive volcanic cover likely greater than previously supposed. Hydrocarbon accumulations in pre-Middle Jurassic reservoirs are found across the triple junction area, e.g. Devonian sandstones (Edwards 1991; Gambaro & Currie 2003), Carboniferous sandstones and Permian Zechstein Group carbonates (Harker *et al.* 1991) and Triassic Skagerrak Formation sandstones (Samuel *et al.* 2005). The presence of pre-Middle Jurassic hydrocarbon reservoirs around the triple junction indicates the possibility of similar unexplored reservoir units beneath the RVP.

A schematic comparison of the likely sub-volcanic stratigraphy associated with the previous volcanic centre eruption model and that of the revised fissure eruption model is shown in Figure 15. The absence of a central volcano and associated plumbing system in the undrilled Fisher Bank Basin (Fig. 15(a)) suggests thick pre-Middle Jurassic sedimentary units, including potential Triassic sandstone reservoirs, may be present in the area. An extension of the Triassic play, or older Permian, Carboniferous or Devonian plays, in the Fisher Bank Basin may have been largely overlooked.

The Witch Ground Graben (Fig. 15(b)) and Buchan-Glenn Horst (Fig. 15(c)) contain much thicker volcanic sequences than the Fisher Bank Basin. They too lack large igneous intrusive complexes, suggesting that extensive sedimentary sequences are present beneath the Rattray Volcanics Member. However, drilling for any pre-Middle Jurassic plays in these areas would necessitate penetrating over a kilometre or more of volcanic material, which may present a variety of drilling issues (Archer *et al.* 2005; Millett *et al.* 2016b).

The Rattray Volcanics Member overlies a thin Zechstein Group carbonate sequence on top of the Devonian-Carboniferous Old Red Sandstone (ORS) Group on the Buchan-

Glenn Horst (Fig. 6). The ORS is the reservoir unit in the Buchan oilfield ~50 km west along the Buchan-Glenn Horst structure. Although the Buchan field ORS is shallower (~3 km depth), the possibility of oil-bearing ORS beneath the Rattray further east on the Buchan-Glenn Horst (blocks 21/03, 21/04 and 21/05) cannot be ruled out. However, the presence of igneous dykes in the Buchan-Glenn Horst area adds further complexity to the consideration of any pre-volcanic hydrocarbon plays; any pre-Middle Jurassic plays beneath the Rattray Volcanics on the Buchan-Glenn Horst may be compartmentalised by the feeder dyke swarm (Rateau *et al.* 2013).

Palaeozoic petroleum systems in the UKCS have recently become a subject of renewed interest in the 21st Century Exploration Road Map (21CXRM) Palaeozoic project (Monaghan *et al.* 2015, 2016). We suggest the identification of the potential for a large unexplored gross sedimentary rock volume immediately beneath the Rattray Volcanics Member indicates that the Palaeozoic (and potential Triassic) petroleum system in the triple junction area of the Central North Sea (Quads 15, 16, 21 and 22) warrants further study.

Conclusions

We have reviewed previous interpretations of mechanisms for the eruption of the Middle Jurassic Rattray Volcanics Member at the triple junction of the North Sea rift system. With the benefit of 3D seismic data we have shown there are likely no central volcanoes associated with Rattray volcanism. The Rattray Volcanics were instead extruded in a series of fissure eruptions from WSW-ENE trending fissure zones, including the Buchan-Glenn Fissure System.

The presence of thick sequences (up to ~70 m) of hyaloclastite as well as phreatomagmatic vents and craters in the RVP indicates the volcanism occurred in a wetter environment than previously thought.

The pre-existing NE-SW Caledonide trend has previously been shown to control the orientation of faulting during the initiation of the North Sea rift; we suggest it is likely the Caledonian trend controlled the emplacement of the Rattray Volcanics during the initial stages of extension in the triple junction area during the Middle Jurassic.

The Fisher Bank Basin magnetic anomaly previously interpreted as a Middle Jurassic volcanic centre may be linked to a deeply buried igneous pluton of Caledonian age.

The lack of large intrusive complexes beneath the Rattray Volcanics Member indicates that pre-Middle Jurassic sedimentary sequences are likely more extensive than previously thought. Pre-Middle Jurassic reservoir and source rock potential in the Rattray area may therefore have been underestimated. However, the feeder dykes may cause compartmentalisation of pre-volcanic reservoirs.

We have shown how the use of 3D seismic data and tools such as frequency decomposition can help elucidate the presence of previously unidentified igneous dykes, which has implications for basin development and possible effects on petroleum systems. This workflow could aid interpretation in other basins where intrusive igneous activity is thought to influence hydrocarbon migration pathways.

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Fig. 1. A: Map of the North Sea rift system with the position of the Rattray Volcanic Province at the triple junction of the Viking Graben, Central Graben and Outer Moray Firth Basin. Adapted from Fraser *et al.* 2002. **B:** Present-day thickness and structure map of the Rattray Volcanics Member constructed using well and seismic mapping. Structures adapted from Fraser *et al.* 2002. Volcanic centres of Smith & Ritchie (1993): I – Ivanhoe Volcanic Centre, G – Glenn Volcanic Centre, F – Fisher Bank Volcanic Centre.

Fig. 2. Stratigraphic column for the triple junction area of the Central North Sea. The Rattray Volcanics Member comprises part of the Middle Jurassic Pentland Formation in the Fladen Group, as does the Ron Volcanics Member in the West Central Graben. The Middle Jurassic

rocks sit unconformably on Triassic or older strata, with the majority of the Lower Jurassic and uppermost Triassic having been eroded in the regional doming event creating the Intra-Aalenian Unconformity. The Middle Jurassic strata are overlain by marine sedimentary rocks of the Upper Jurassic. *Chart based on:* Cohen *et al.* 2013. *Stratigraphy based on:* **Palaeozoic:** Bassett 2003; Marshall & Hewett 2003; Bruce & Stemmerik 2003; Glennie *et al.* 2003; Cameron 1993. **Mesozoic:** Cameron 1993; Richards *et al.* 1993; Johnson & Lott 1993; Goldsmith *et al.* 2003; Fraser *et al.* 2002; Copestake *et al.* 2003; Surlyk *et al.* 2003.

Fig. 3. A: Map of seismic surveys and well penetrations utilised in this study. Outline of Rattray Volcanic Province in red. Positions of seismic lines included in this paper in yellow. **B:** Polarity of 3D and 2D seismic data. A downwards increase in acoustic impedance is represented by a negative amplitude response (trough), here displayed in blue.

Fig. 4. Frankenstein well log showing typical petrophysical characteristics of the main basaltic volcanic facies in the Rattray Volcanic Province. The log is composed of examples from different wells drilled through the Rattray Volcanics Member (wells highlighted on right hand side). GR – Gamma ray log. Res – Deep resistivity log. Dens – Density log. Neut – Neutron porosity log. DT – Acoustic travel time log.

Fig. 5. Depth to present-day Top Pentland Fm (s TWT) across the MS and MSP. Well penetration depths to the Rattray Volcanics Mbr are highlighted. The Pentland Fm is shallowest on structural highs such as the Piper Shelf (PS), Renee Ridge (RR) and Buchan-Glenn Horst (BGH) (2.3-2.8 km depth) and deepest in Witch Ground Graben (WGG) and Fisher Bank Basin (FBB) (>5 km depth). HH: Halibut Horst; FGS: Fladen Ground Spur; SVG: South Viking Graben; NBG: North Buchan Graben; SBG: South Buchan Graben; FMH: Forties Montrose High; JH: Jaeren High.

Fig. 6. A: Magnetic anomaly map of the Rattray area with the magnetic anomaly coincident with the Buchan-Glenn Horst structure highlighted. Volcanic centres of Smith & Ritchie (1993) indicated. I – Ivanhoe Volcanic Centre; G – Glenn Volcanic Centre; F – Fisher Bank Volcanic Centre. Reproduced from the British Geological Survey Map data at the original scale of 1:50,000. Licence 2016/103 ED British Geological Survey. ©NERC. All rights reserved. Positions of seismic lines shown in Figures 6, 7 and 9 are highlighted in the inset map. **B and C (interpreted)**: Seismic line A-A' W-E across the Buchan-Glenn Horst over the peak of the magnetic anomaly. The Rattray Volcanics Member is ~1.2 km thick across this section of the Buchan-Glenn Horst. It lies above a thin Permian carbonate succession above the Devonian-Carboniferous Old Red Sandstone Group with laterally continuous seismic reflections. There is no obvious large-scale volcanic vent structure observed in the Rattray succession, nor kilometre-scale discordant seismic reflections in the sub-Rattray stratigraphy which would indicate an intrusive sill complex feeding a large central volcano. A sill cross-cuts the volcanic reflections in the Rattray package, indicative of later-stage intrusion which did not feed the majority of the Rattray volcanism. Inclined seismic reflections in the Rattray sequence downlap the substrate, likely a hyaloclastite delta.

Fig. 7. A and B (interpreted): Seismic line B-B' from N-S across Buchan-Glenn Horst showing sub-vertical discontinuities through the Rattray and older strata. The discontinuities in the centre of the horst do not show displacement of the volcanic seismic reflections and are interpreted as igneous dykes rather than fault planes. The dykes intrude through the sub-Rattray stratigraphy and the volcanics themselves, but are not found above the Rattray Volcanics Member. The dykes would have been almost vertical when emplaced – the tilting is due to rotation during later tectonic events.

Fig. 8. A: Spectral decomposition of flattened Top Rattray surface in the Buchan-Glenn Horst area. **B:** Interpreted. Linear discontinuity of dykes in Fig. 7 is interpreted as a volcanic fissure (1) sourcing lava flows. The linear fissure is a notably different morphology to the curvilinear fault planes (2) formed after cessation of volcanism during Late Jurassic rifting. Five small volcanic edifices are interpreted along the fissure (5), likely spatter or cinder cones formed during fissure eruptions. **C:** Satellite image of Laki Fissure in Iceland, showing cones aligned along fissure. **D:** Photograph of the Laki Fissure and cone-row courtesy of *Encyclopaedia Britannica Online*.

Fig. 9. Seismic lines C-C' and D-D' SW-NE across the main fissure zone on the Buchan-Glenn Horst and Renee Ridge intersection. Small volcanic edifices protrude from the Top Rattray surface overlying chaotic reflections of the fissure zone. The vents are of different morphologies: C-C' has the aspect ratio of a cinder cone (Heiken 1971) and D-D' of a tuff cone (Heiken 1971) although the deep funnel-like shape in D-D' is also reminiscent of a maar-diatreme, which have been previously identified in the RVP further west along Renee Ridge (Stewart 1999). The presence of tuff cones/maars and hyaloclastite indicates that the eruption of the Rattray Volcanics Member involved a high proportion of interaction with both surface water and groundwater.

Fig. 10. A: Large positive magnetic anomaly in the northern Witch Ground Graben. Inset map shows position of seismic line in Fig.10B and C. **B and C (interpreted):** Composite seismic line E-E' across peak of the magnetic anomaly. The Rattray Volcanics Member is downthrown to the north during Late Jurassic faulting. The volcanics package thins northwards from ~800 m beside the fault to ~419 m in well 15/23-1Z. It overlies a Permian sequence drilled in 15/23-1Z, the base of which is uncertain but is tentatively identified on a dim continuous 'soft' reflection. No volcanic vent structures are present in the Rattray succession, nor large scale discordant seismic reflections typical of an intrusive sill complex is visible in the Rattray subsurface in the Northern Witch Ground Graben. There does not appear to be any positive evidence on seismic to support the interpretation of a central volcano.

Fig. 11. Volcanic facies in wells in the northern Witch Ground Graben area (well positions in Fig. 10 inset map). Thick tabular lava flows (1) indicate a high rate of effusion and ponding in areas of increased accommodation space. Hyaloclastite packages (2) are indicative of eruption of lava into a standing water body. The repetition of hyaloclastite capped by subaerial tabular lava flows in well 15/21-3 is indicative of relative base level rise, either by eustatic sea level rise or relative rise due to active subsidence in the basin. These facies are typical of flood basalt eruptions from fissure systems.

Fig. 12. A: Fisher Bank Basin magnetic anomaly. Inset map shows positions of wells and seismic lines in Figures 12 and 13. **D and E (interpreted):** The Pentland Fm is interpreted on seismic data in this study to thin southwards into the Fisher Bank Basin, contrary to the thickness interpretation of Husmo *et al.* (2002) **(C). B:** Proportion of facies in Pentland Fm of wells surrounding Fisher Bank Basin on Middle Jurassic thickness map. The proportion of crystalline material (lavas and hyaloclastite) decreases towards the south of the Fisher Bank Basin while the proportion of volcaniclastic and siliciclastic sedimentary rocks increase. This facies change is likely to occur as the system becomes more distal to the source of the volcanic eruption.

Fig. 13. Seismic line G-G' from NW to SE through Fisher Bank Basin over the peak of the magnetic anomaly. A ~0.5 s (~1.1 km) thick Permo-Triassic succession makes up the majority

of the basin fill beneath the thin Middle Jurassic sequence. No obvious volcanic vent structure nor sub-volcanic intrusive complex is visible. The seismic culmination at base Upper Jurassic level is interpreted here as a diapir of Zechstein halite, drilled nearby in 16/28-1 and 16/27-1A.

Fig. 14. Magnetic anomaly map of UK Central North Sea, West of Shetland area and onshore Scotland courtesy of BGS. Positions of wells which have drilled Caledonian intrusions in the basement of CNS are shown **(e,f)**, surrounding the RVP. Fisher Bank magnetic anomaly is highlighted **(a)** along with similar shaped anomalies from across the UK and UKCS **(b,c,d,g,h).** The majority of these magnetic anomalies are granitic intrusions emplaced during or prior to the Caledonian Orogeny, e.g. the Westray and Cambo Highs in the Faroe-Shetland Basin **(b)** and the onshore Grampian Caledonides **(c)**. Also highlighted is the Highland Boundary Fault, which intersects with the Rattray Volcanics Member around the Buchan-Glenn Fissure System in the same orientation (WSW-ENE).

Fig. 15. Schematic cross sections across the RVP from the Piper Shelf in NW to the Jaeren High in SE (approximate position of cross-section on Fig. 1) showing possible sub-volcanic stratigraphy implied by the volcanic centres model (above) and fissure system model (below). Fissure-fed volcanism from the Buchan-Glenn Fissure System and a lack of central volcanoes in the Witch Ground Graben and Fisher Bank Basins indicates a large un-intruded sedimentary gross rock volume is present beneath the RVP. Approximate positions of the seismic lines shown in figures 7, 10 and 13 are highlighted.

Fig. 1

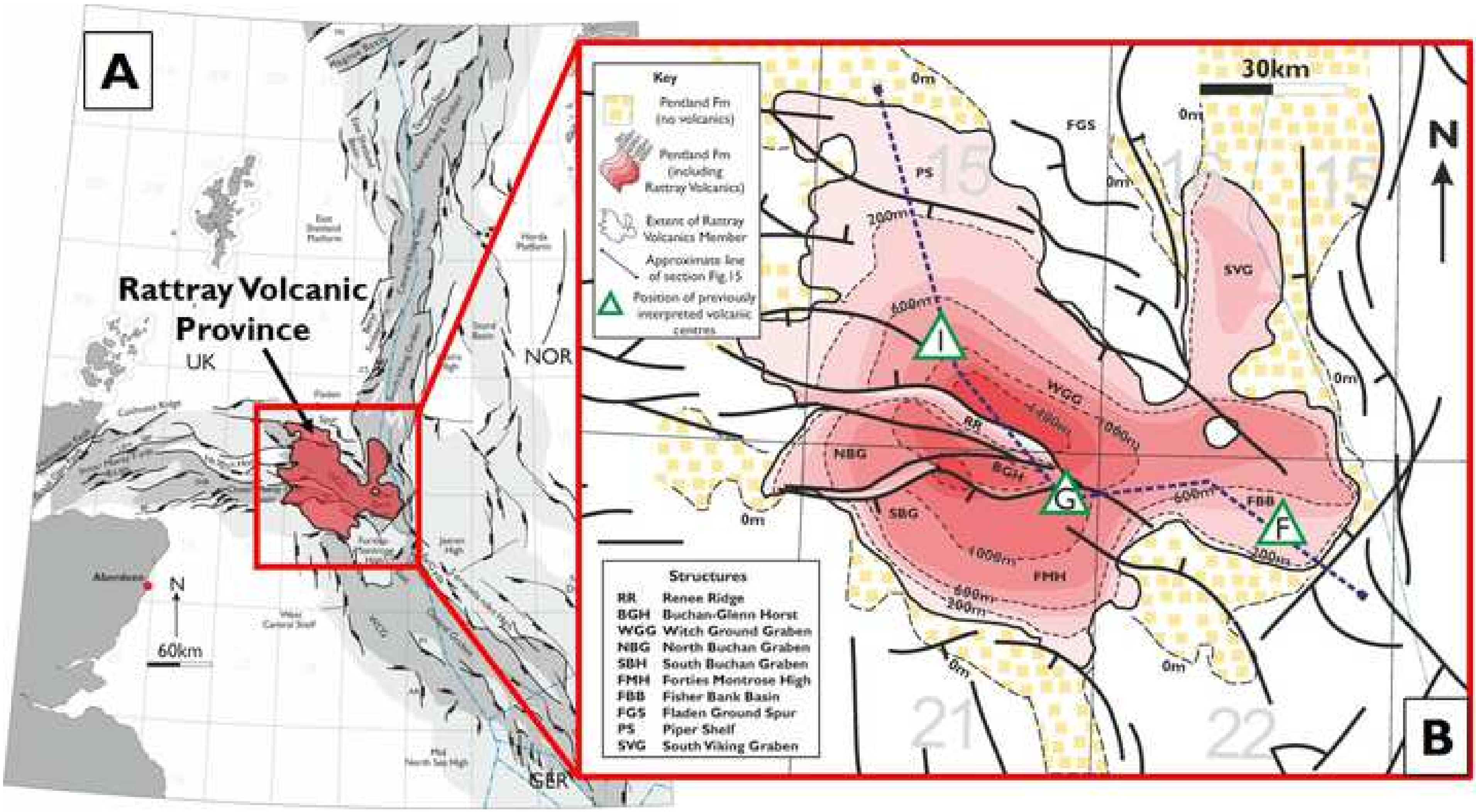
A
Rattray Volcanic Province
UK
NOR
GER
60km
N
B
30km
N
Key
Pentland Fm (no volcanics)
Pentland Fm (including Rattray Volcanics)
Extent of Rattray Volcanics Member
Approximate line of section Fig.15
Position of previously interpreted volcanic centres
Structures
RR Renee Ridge
BGH Buchan-Glenn Horst
WGG Witch Ground Graben
NBG North Buchan Graben
SBH South Buchan Graben
FMH Forties Montrose High
FBB Fisher Bank Basin
FGS Fladen Ground Spur
PS Piper Shelf
SVG South Viking Graben
I
G
F
21
22

Fig. 2

Click here to access/download;figure;Quirie Fig.2.jpg

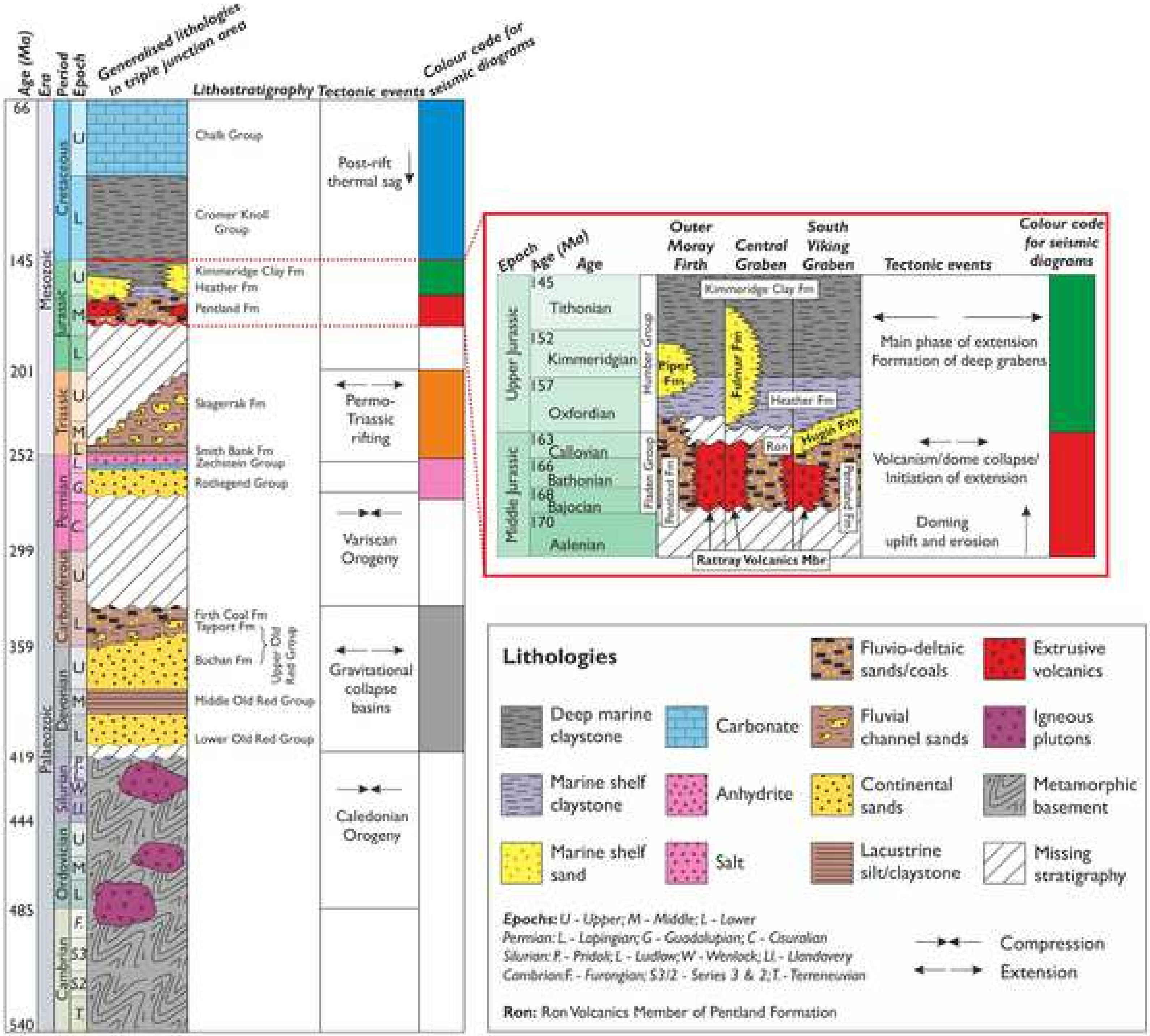

Fig. 3

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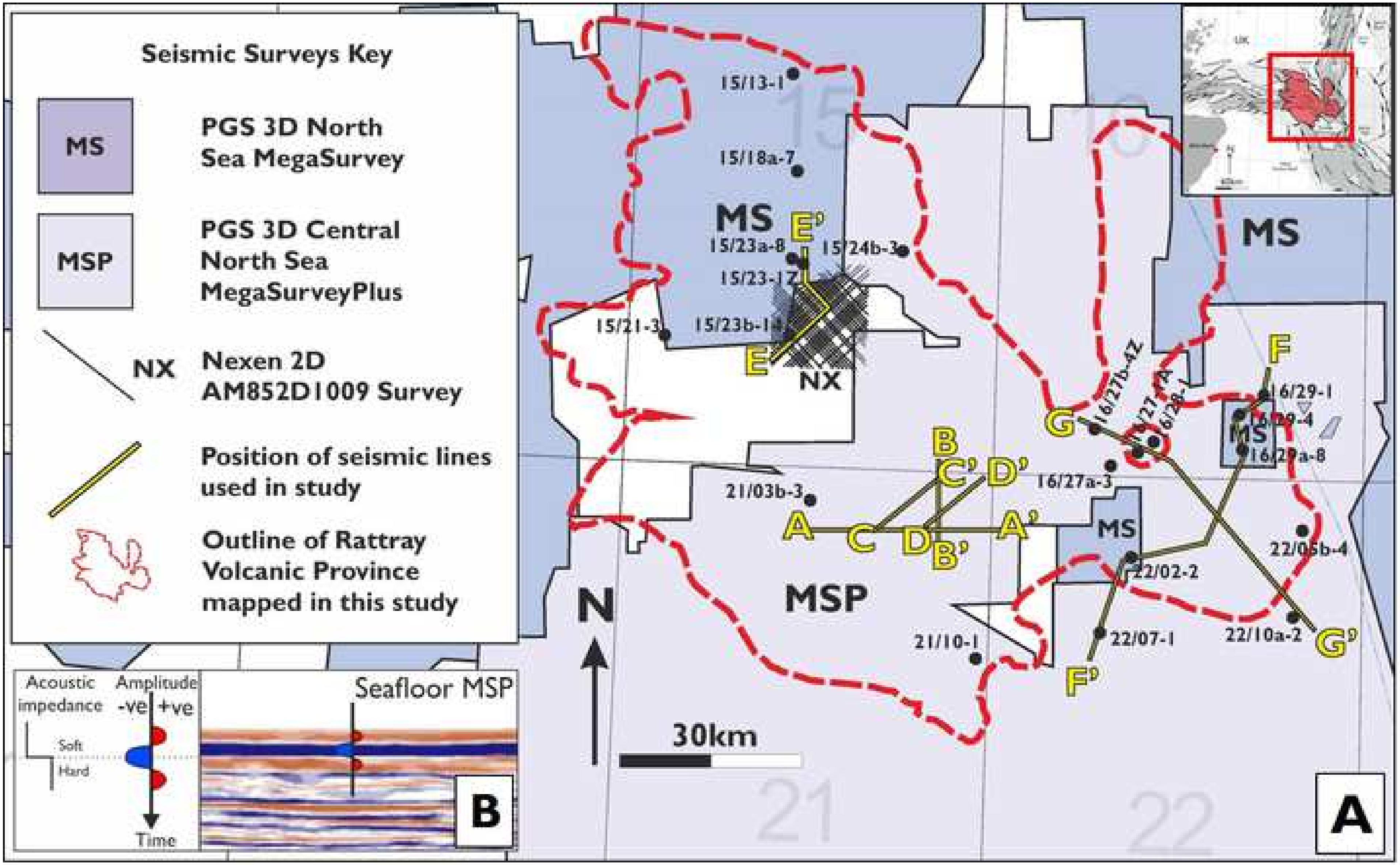

Fig. 4 Click here to access/download;figure;Quirie Fig.4.jpg

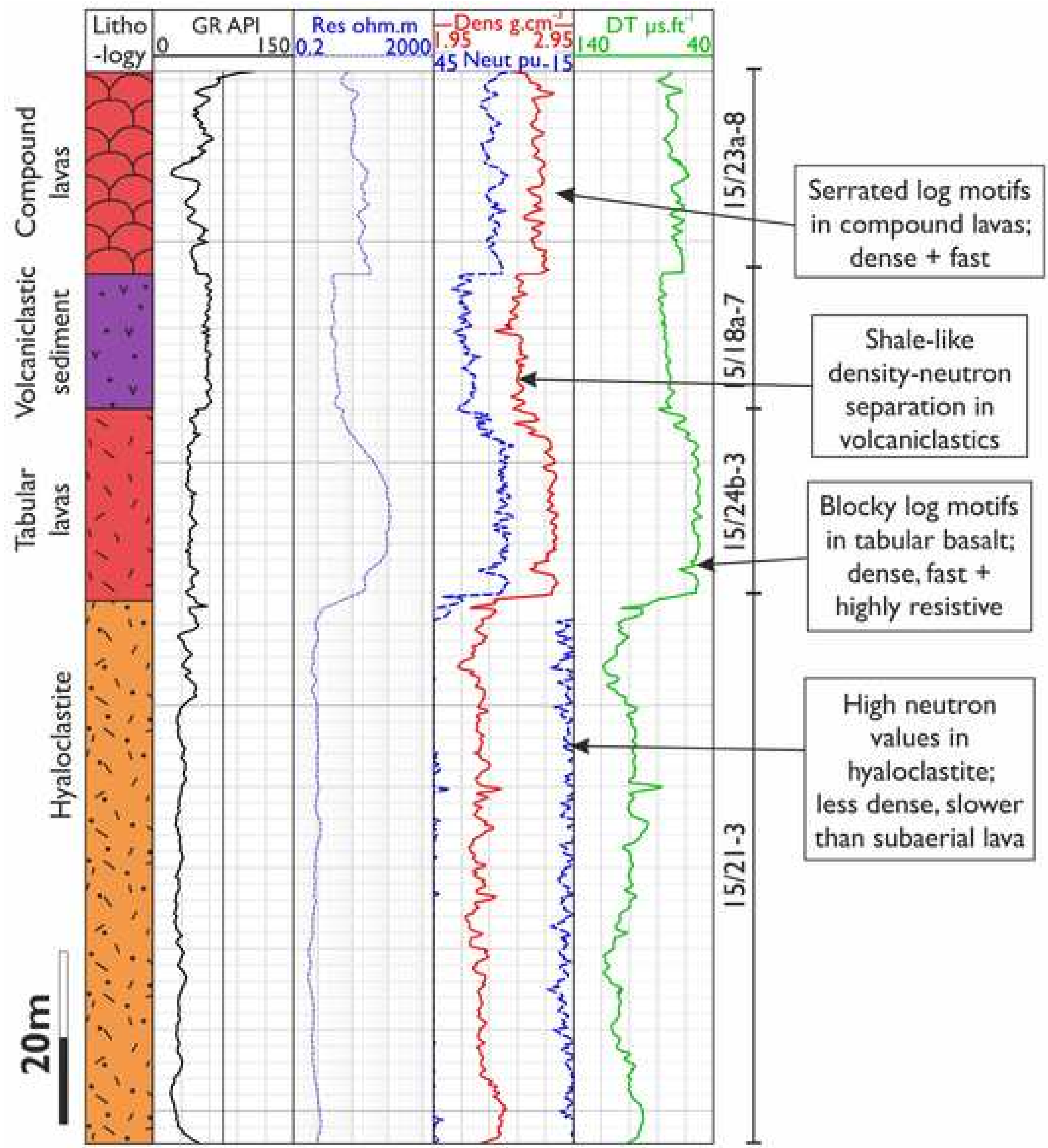

Fig. 5

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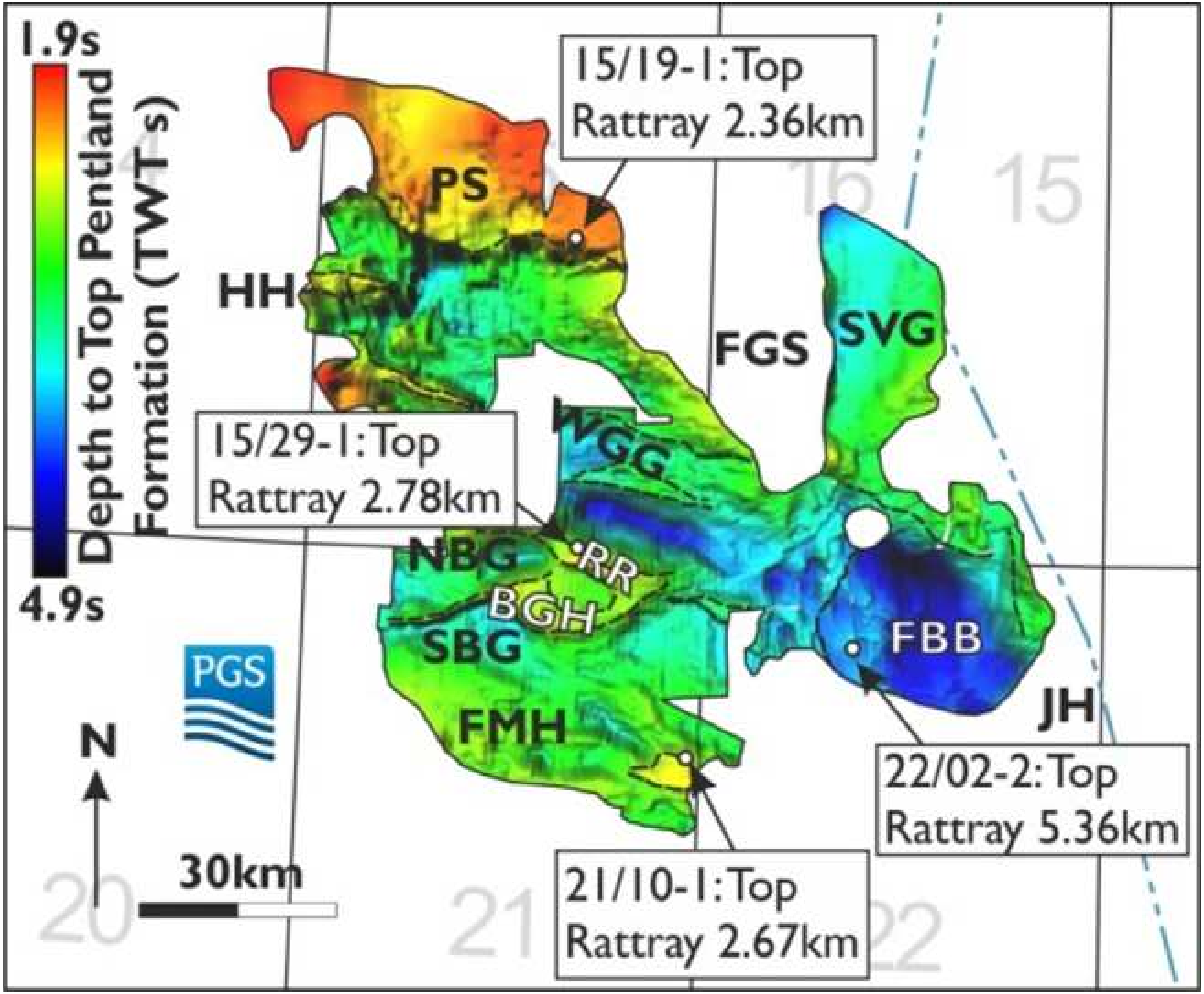

Fig. 6

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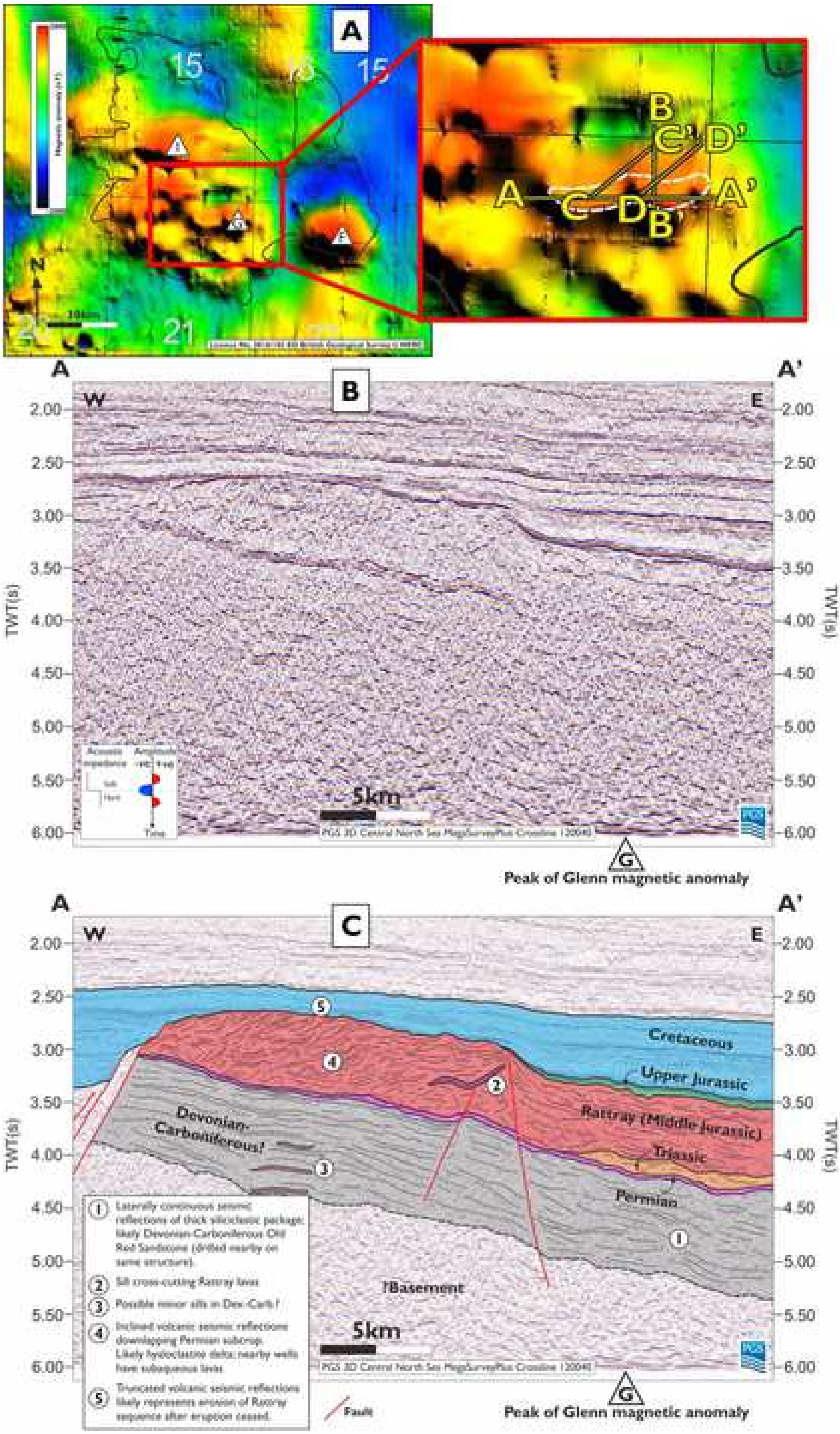

Fig. 7

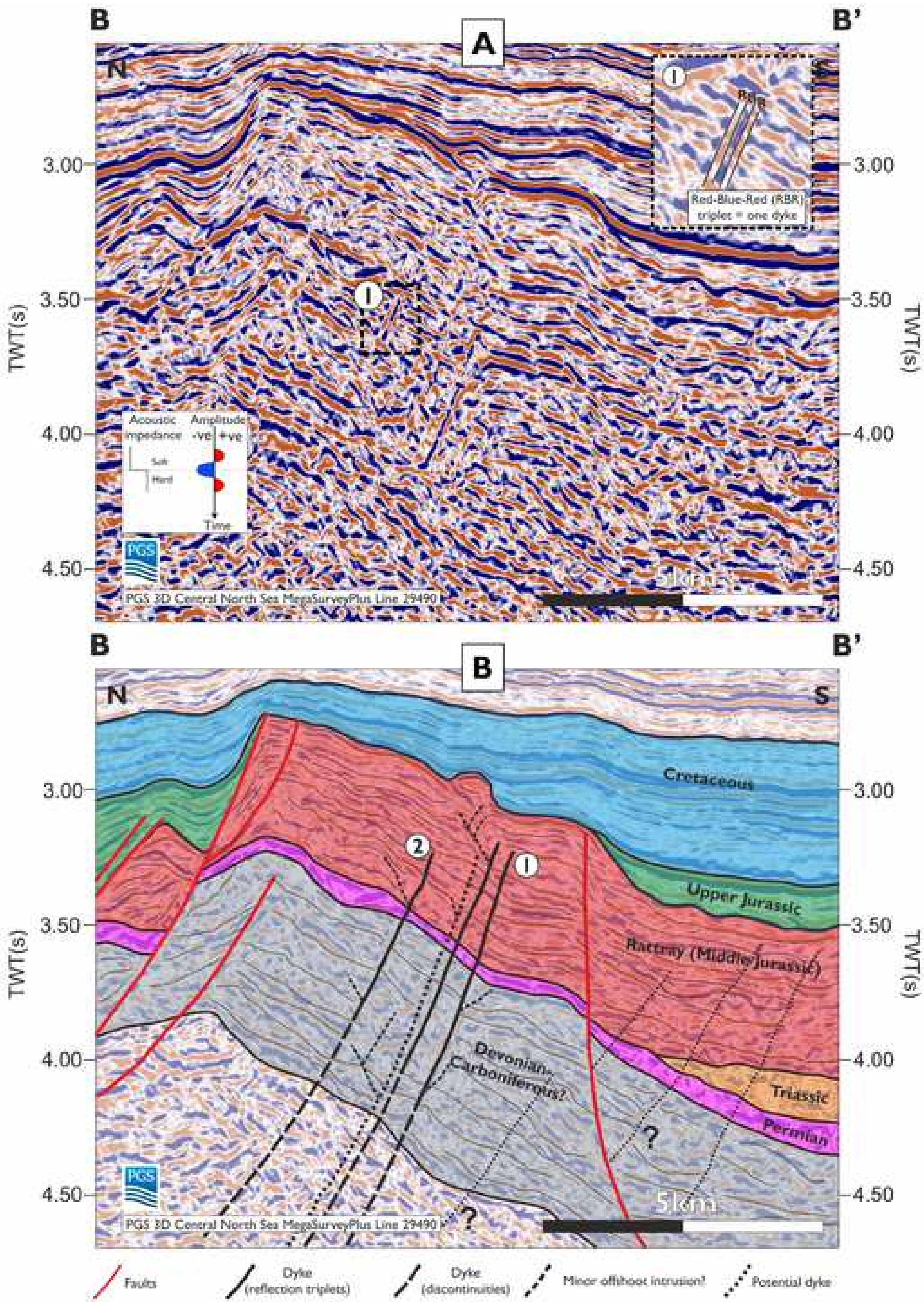
B
B'
A
N
S
TWT(s)
3.00
3.50
4.00
4.50
Red-Blue-Red (RBR) triplet = one dyke
Acoustic impedance
Amplitude -ve +ve
Soft
Hard
Time
PGS
PGS 3D Central North Sea MegaSurveyPlus Line 29490
5km
B
Cretaceous
Upper Jurassic
Rattray (Middle Jurassic)
Devonian-Carboniferous?
Triassic
Permian
Faults
Dyke (reflection triplets)
Dyke (discontinuities)
Minor offshoot intrusion?
Potential dyke

Fig. 8 Click here to access/download;figure;Quirie Fig.8.jpg

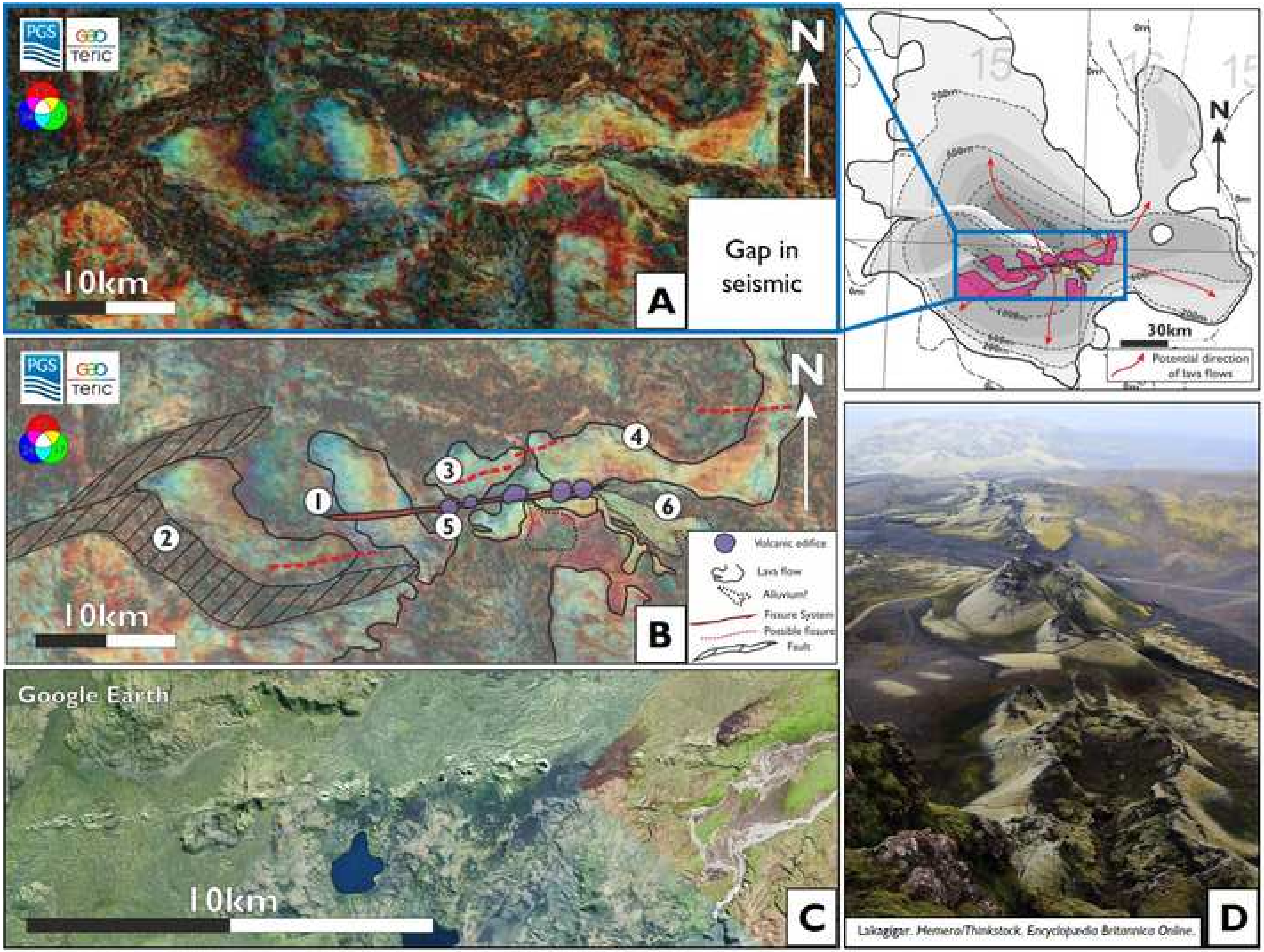

Fig. 9

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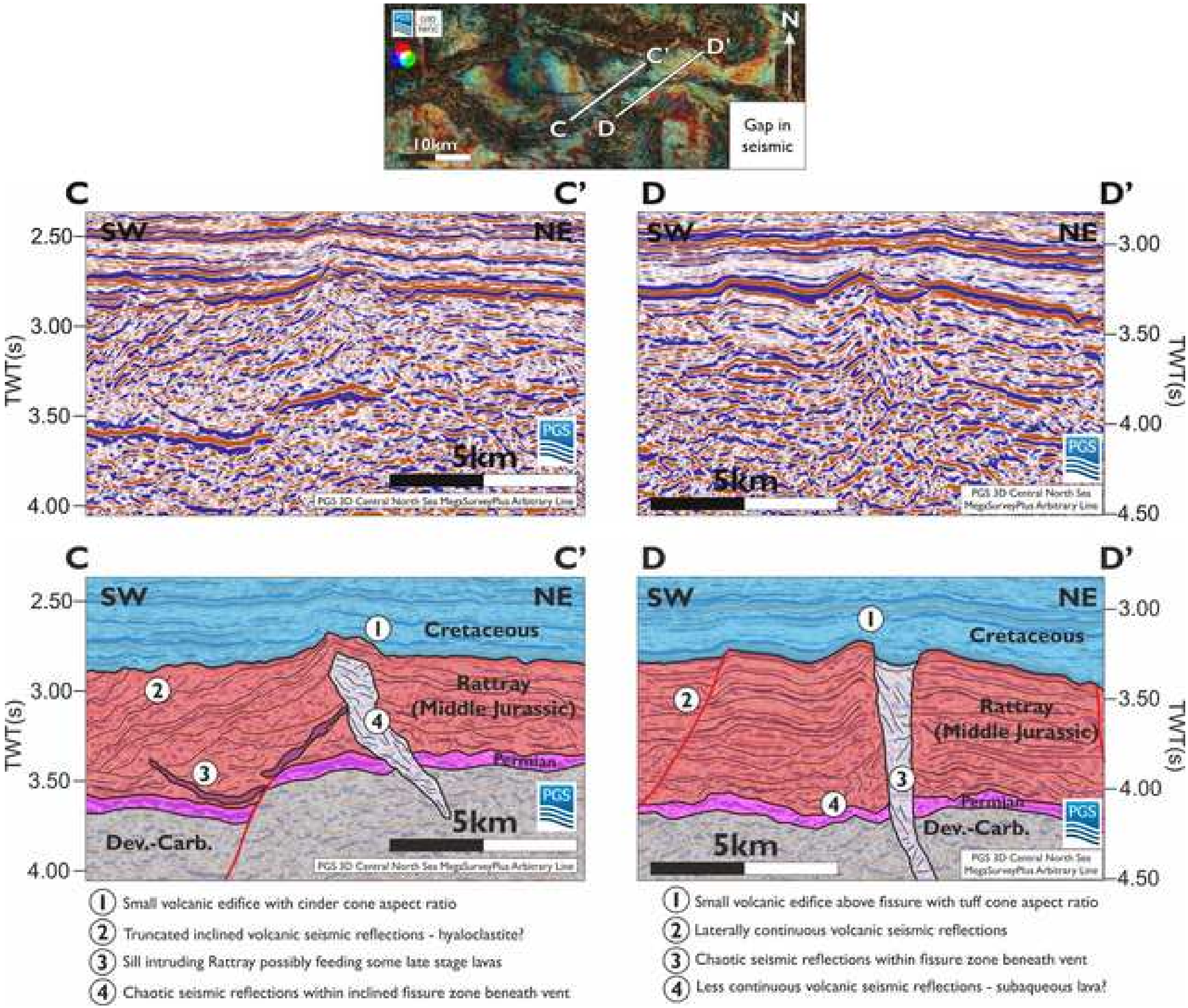

Fig. 10

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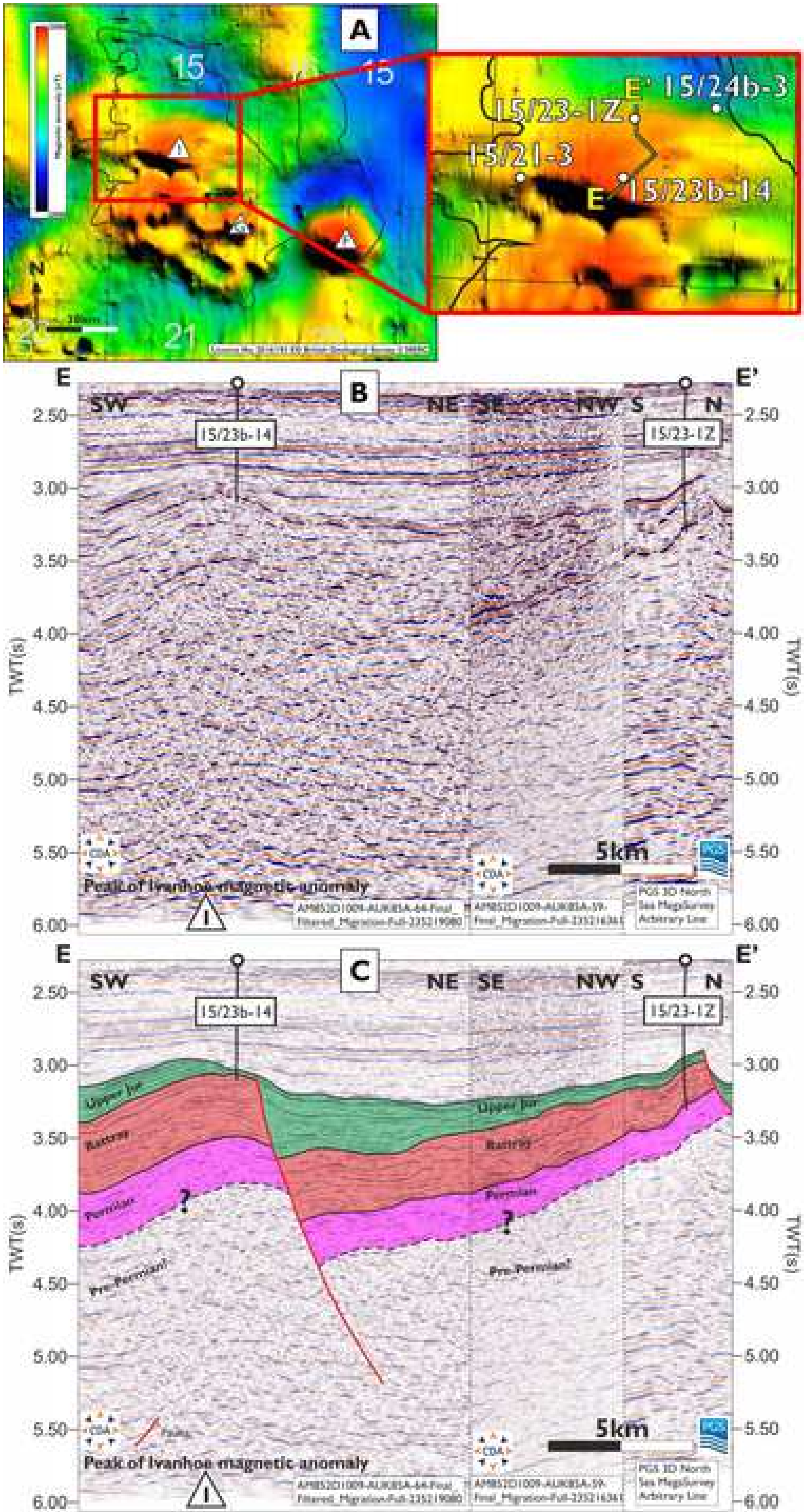


Fig. 11 Click here to access/download;figure;Quirie Fig.11.jpg

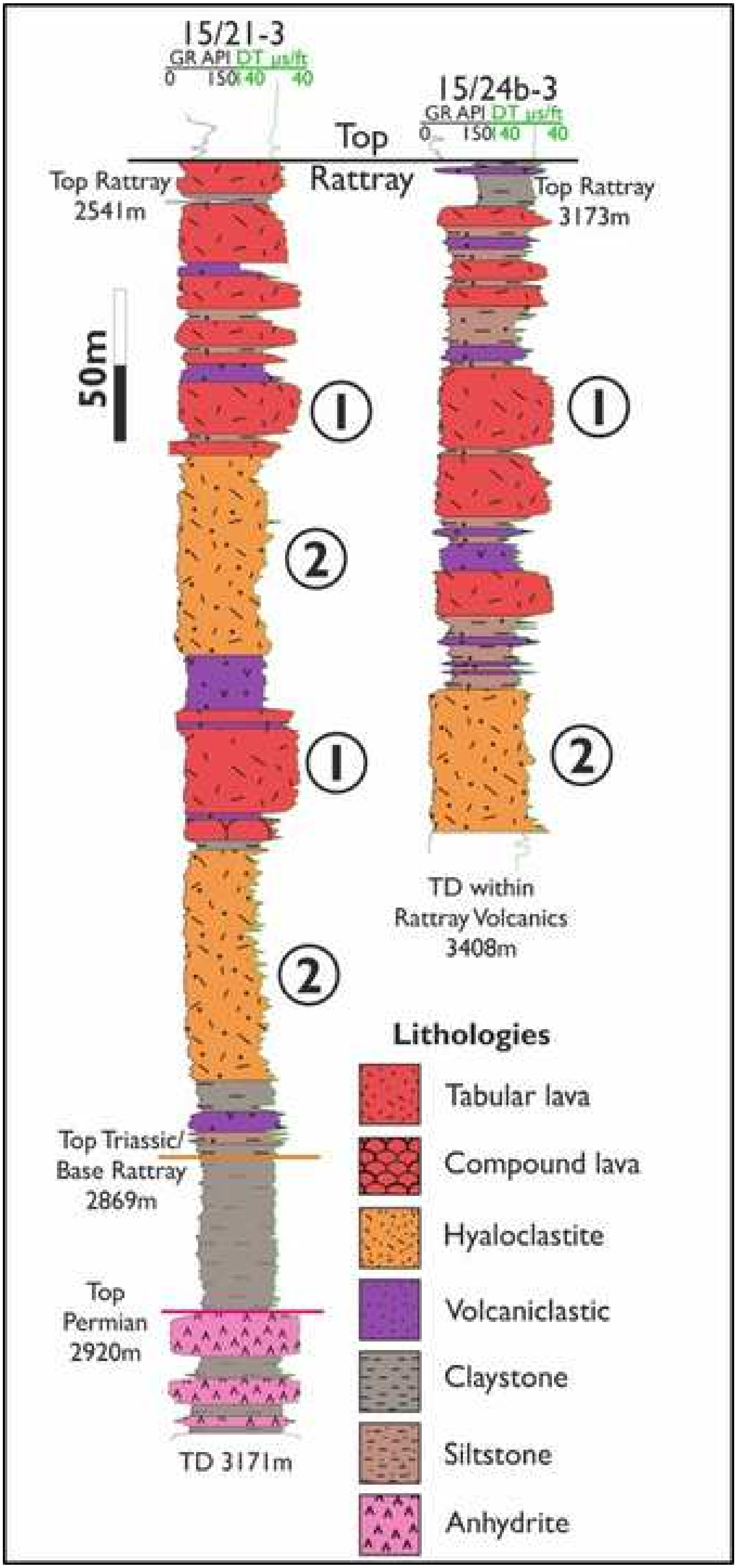


Fig. 12 Click here to access/download;figure;Quirie Fig.12.jpg

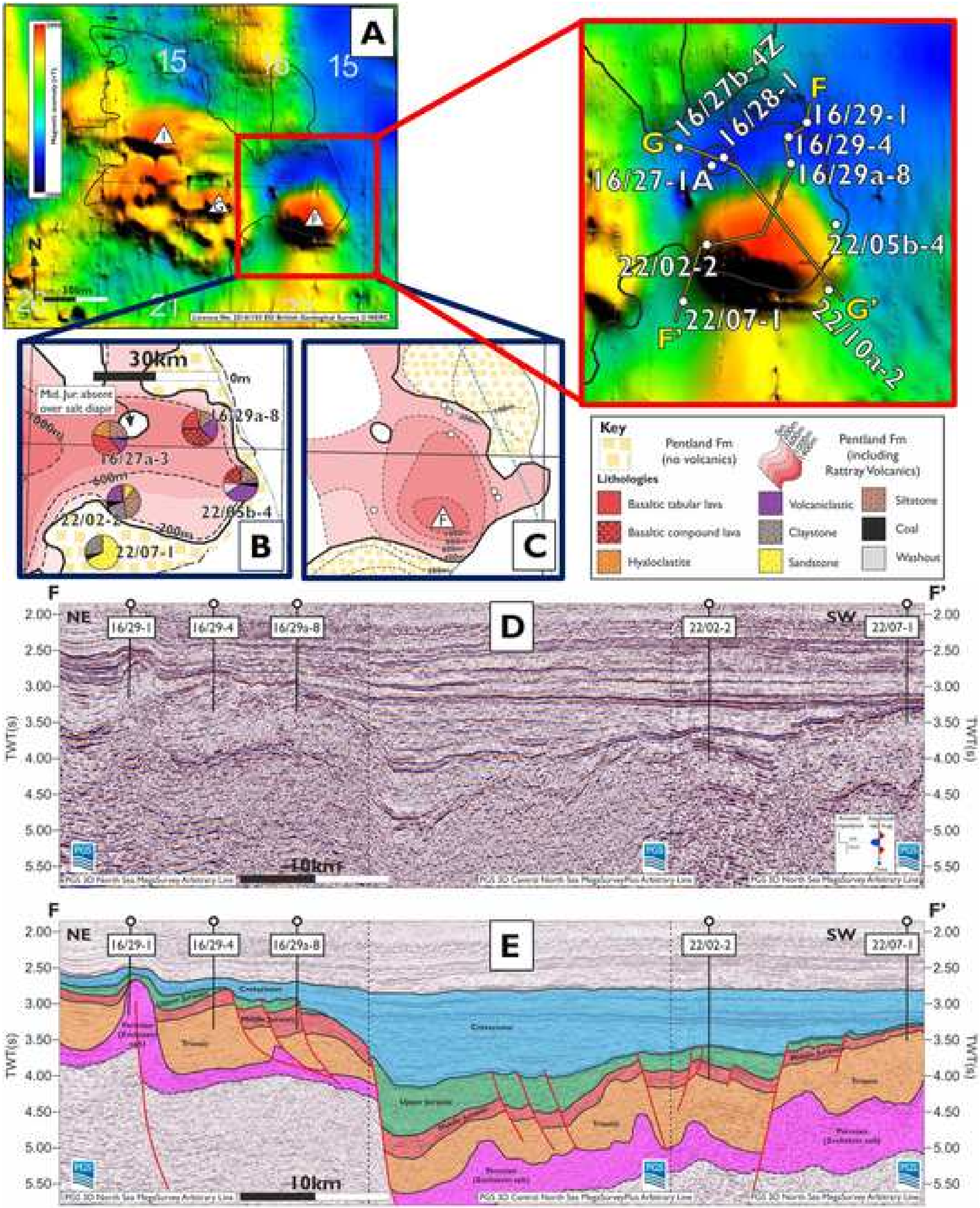


Fig. 13

Click here to access/download;figure;Quirie Fig.13.jpg

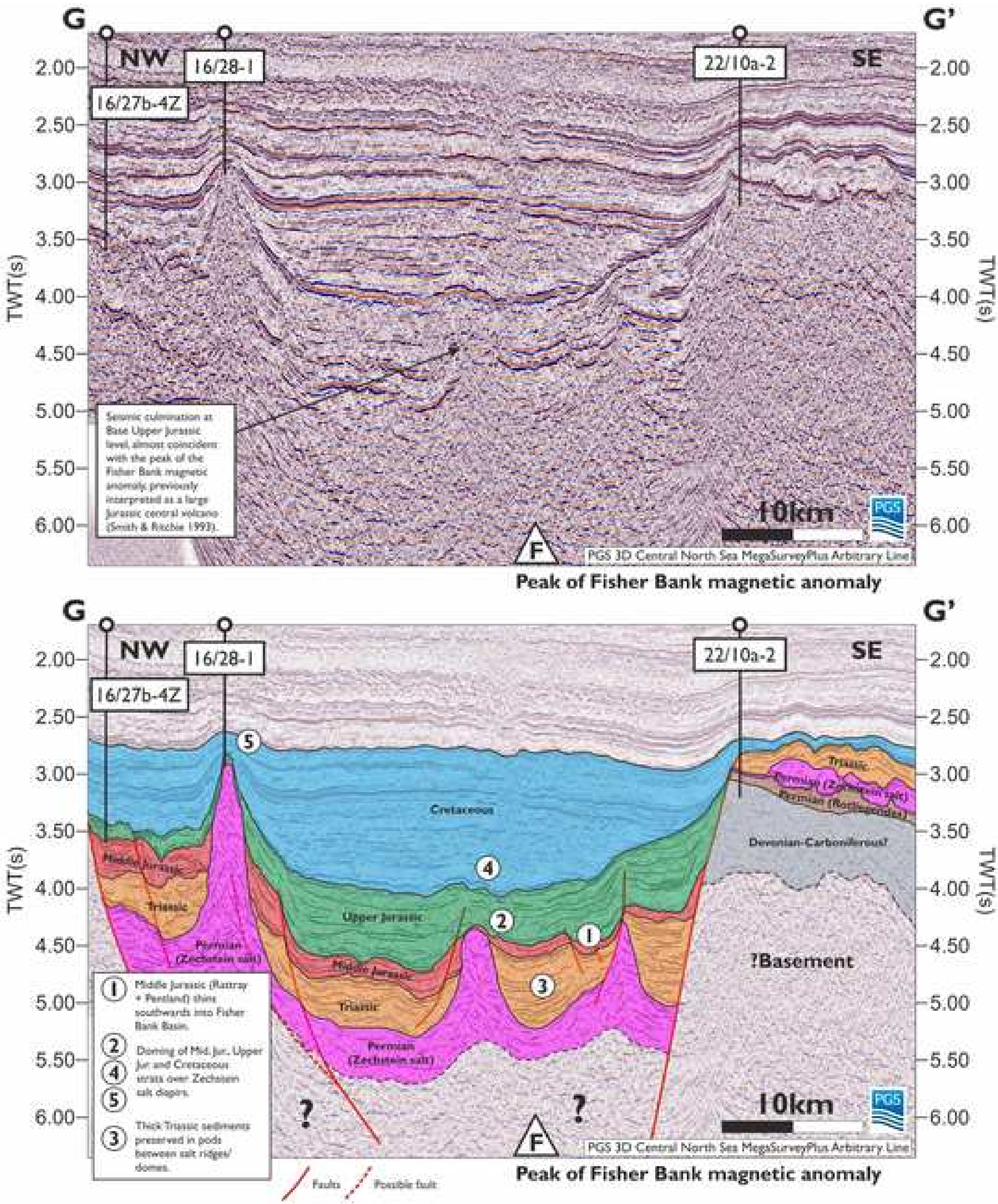


Fig. 14

Click here to access/download;figure;Quirie Fig.14.jpg

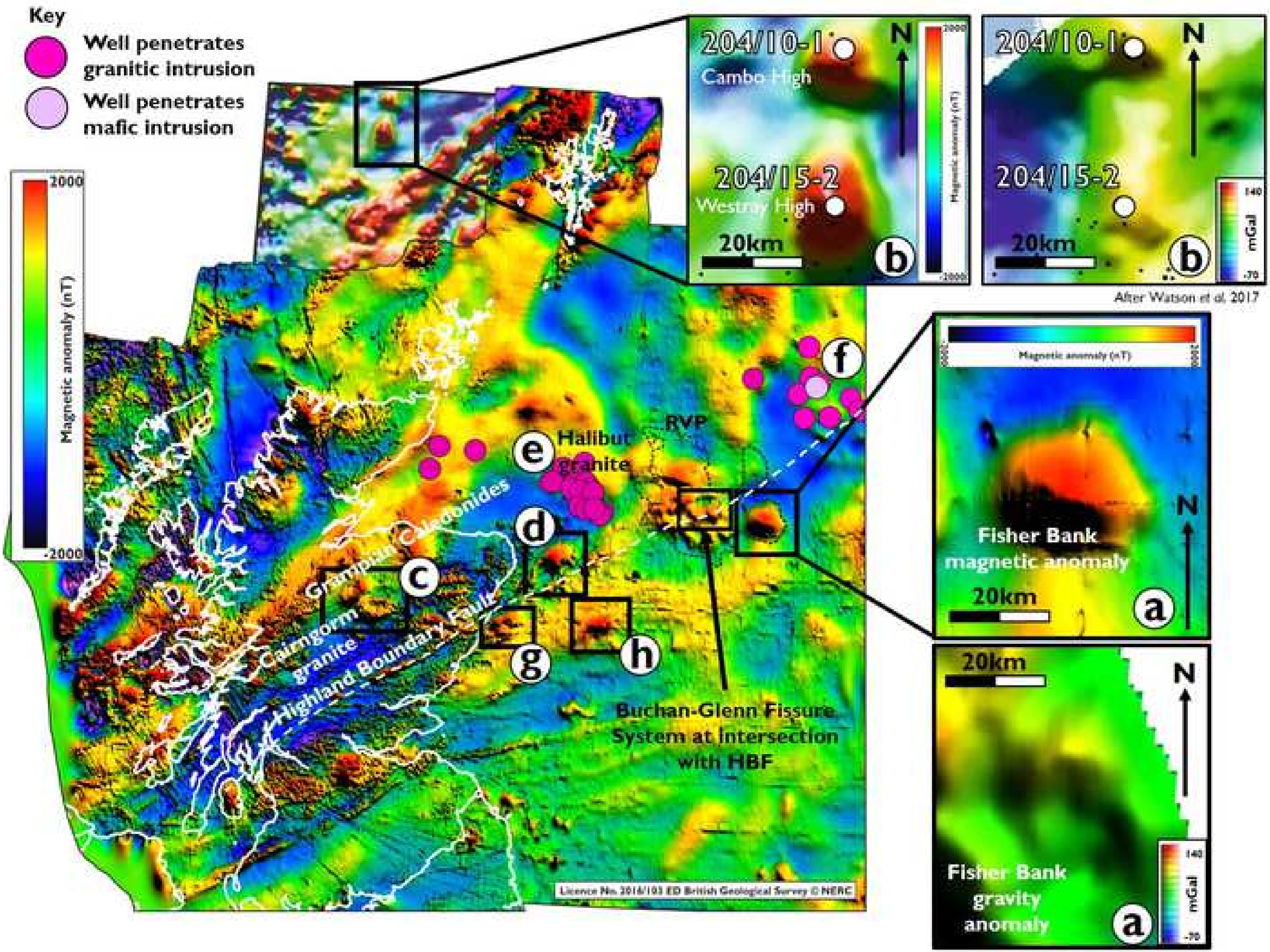
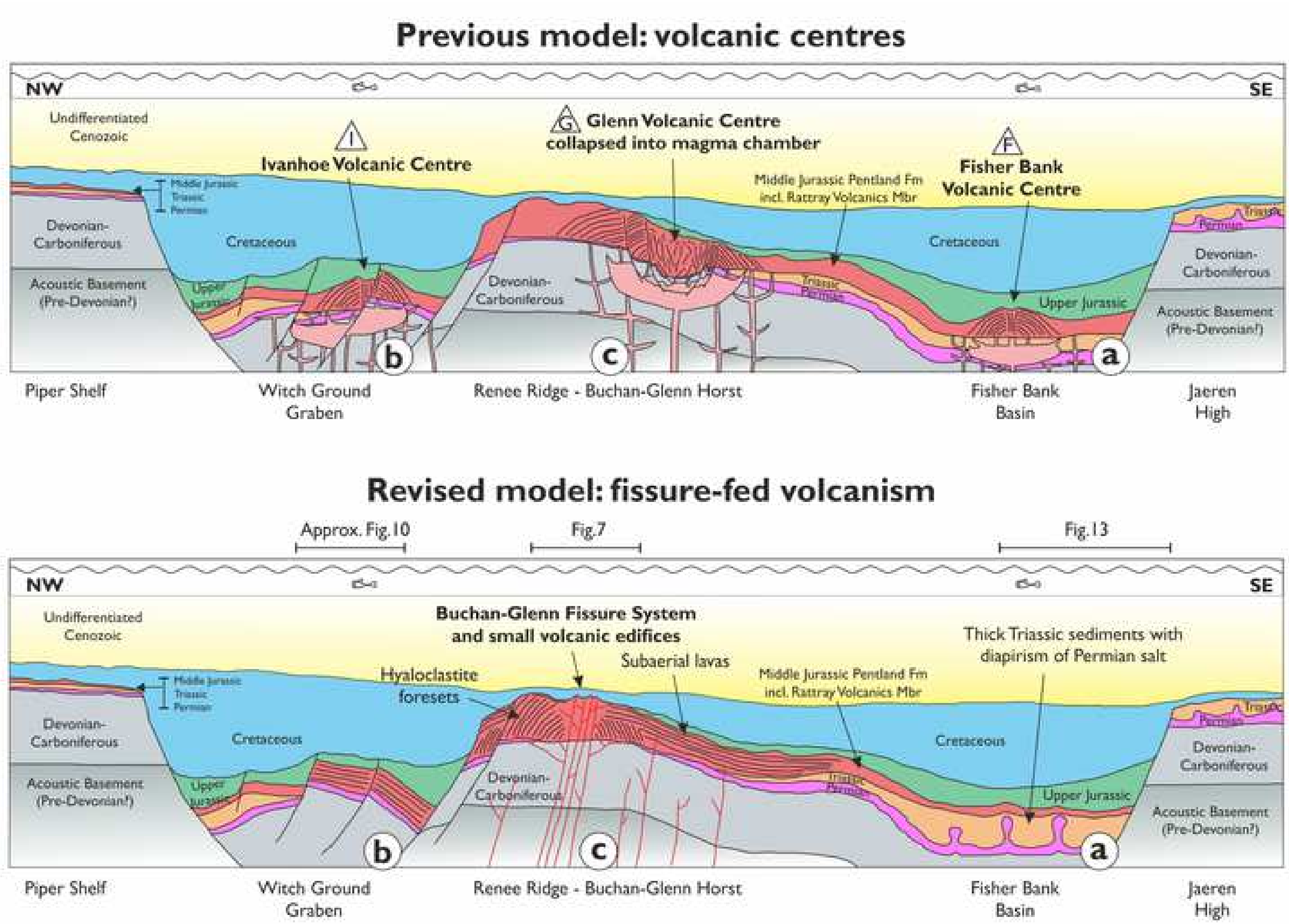


Fig. 15



Previous model: volcanic centres
NW
SE
Undifferentiated Cenozoic
Ivanhoe Volcanic Centre
Glenn Volcanic Centre collapsed into magma chamber
Fisher Bank Volcanic Centre
Middle Jurassic Pentland Fm incl. Rattray Volcanics Mbr
Middle Jurassic
Triassic
Permian
Devonian-Carboniferous
Cretaceous
Acoustic Basement (Pre-Devonian?)
Upper Jurassic
b
c
a
Piper Shelf
Witch Ground Graben
Renee Ridge - Buchan-Glenn Horst
Fisher Bank Basin
Jaeren High
Revised model: fissure-fed volcanism
Approx. Fig.10
Fig.7
Fig.13
Buchan-Glenn Fissure System and small volcanic edifices
Subaerial lavas
Hyaloclastite foresets
Thick Triassic sediments with diapirism of Permian salt