Raiders of the Lost Mud: The geology behind drilling incidents within the Balder Formation around the Corona Ridge, West of Shetland

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Abstract: The Faroe-Shetland Basin, NE Atlantic continental margin, hosts a number of important hydrocarbon fields, though deep water and narrow weather windows mean drilling costs are considerably higher than other parts of the UK Continental Shelf. Any additional drilling complications are therefore important to predict and negate as such issues can result in avoidable multi-million pound cost implications. This study focuses on the Corona Ridge, an intra-basinal high which contains the Rosebank Field, where a plethora of drilling issues, of enigmatic origin, are common within a key stratigraphic marker known as the Balder Formation. Drilling fluid loss, bit balling, wellbore breakouts, and wellbore "ballooning", where lost drilling fluid returns to the wellbore, are all recognised within the Balder Formation along the Corona Ridge. We find that many of the drilling incidents can be traced back to both the lithological character of the Balder Formation, and the mid-Miocene tectonic inversion of the Corona Ridge. Moreover, we find that this geological explanation has wider implications for exploration in the region, including mitigation of drilling incidents in future wells through drill bit selection.

The Faroe-Shetland Basin, located on the NE Atlantic continental margin, represents one of the last remaining exploration frontiers of the UK Continental Shelf, with arguably the greatest remaining potential for significant new discoveries (Ellis & Stoker 2014; Austin *et al*. 2014). One particularly prospective area of the Faroe-Shetland Basin is the Corona Ridge (Fig. 1), an intra-basinal high which hosts a number of oil and gas discoveries, notably the ~240 million barrels of oil equivalent Rosebank Field (Austin *et al*. 2014). A challenging aspect of exploring around the Corona Ridge area, though, is high drilling costs associated with deep water (up to 1.5 km in places) and extreme weather conditions (Austin *et al*. 2014), necessitating the use of either fifth generation semi-submersible drill rigs ($125,000/day) or dynamically positioned drillships ($145,000/day) (IHS Markit 2018) in order to drill exploration and appraisal wells. Further exploration costs result from a myriad of drilling complications, particularly through thick volcanic sequences. Previous research has focused on drilling efficiency through these volcanic sequences, emphasising how key lithological properties contribute to different drilling and well control issues (Archer *et al.* 2005; Millet *et al.* 2014; Millet *et al.* 2015; Millet *et al.* 2016; Mark *et al.* 2018). However, a critical aspect of drilling operations around the Corona Ridge that has been overlooked is drilling issues encountered within a volcanic unit in the uneconomic overburden: specifically, the Balder Formation, an early Eocene aged unit consisting of interbedded volcanic tuffs (lithified ash), claystone and siltstone (Watson *et al.* 2017). These drilling issues have included drilling fluid loss, bit balling (clogging), borehole breakouts and wellbore "ballooning", where lost drilling fluid later returns to the wellbore. We propose that these drilling events can be linked back to the regional geological history, particularly given their concentration along, or close to, the Corona Ridge. By synthesising these findings with wider regional knowledge, we highlight that many of the drilling issues can be traced back to the tectonic event that enhanced the Corona Ridge. Furthermore, our findings have wider implications for future exploration in the region, including suggestions for mitigation of drilling issues (leading to cost reduction) in future exploration wells, for example through selecting a PDC drill bit as opposed to a tricone bit.

Geological setting

The Faroe-Shetland Basin (FSB) is located along the NE Atlantic continental margin, situated between the Faroe Islands and the Shetland Islands (Fig. 1). The FSB is a series of SW-NE trending sub-basins, formed through multiple phases of Palaeozoic to Cenozoic rifting (Ritchie *et al.* 2011). These sub-basins are delineated by intra-basinal highs of Precambrian crystalline basement capped by Mesozoic sediments (Lamers & Carmichael 1999). During the Palaeocene to early Eocene the FSB was characterised by widespread volcanism, associated with the presence of a mantle plume and the commencement of rifting and crustal thinning between Greenland and NW Europe (White & McKenzie 1989; Schofield *et al.* 2015; Hardman *et al.* 2018a). Later, during Eocene-Miocene times, the FSB experienced several punctuated phases of compression, resulting in large scale inversion of the intra-basinal highs, and the formation of elongate anticlines with four-way closure at Cretaceous-Cenozoic level (Boldreel & Andersen 1993; Dore *et al.* 2008; Ritchie *et al.* 2008; Holford *et al.* 2009;

Holford *et al.* 2016). This study adopts the lithostratigraphy of Ritchie *et al.* (2011) and Stoker & Varming (2011) (Fig. 2).

Corona Ridge exploration history

The FSB has been the focus of petroleum exploration since the 1970s. The basin hosts the prolific Kimmeridge Clay marine source rock, thought to be responsible for sourcing the majority of the hydrocarbons discovered in the region (Scotchman *et al.* 2006; Scotchman *et al.* 2016). A number of hydrocarbon fields are present throughout the basin, generally overlying or close to intra-basinal highs (Fig. 1a). This study concerns the Corona Ridge, an intra-basinal high located in the centre of the basin (Fig. 1b). Figure 3 shows a seismic line cross-section running parallel through the Corona Ridge, depicting the location of wells and structures examined in this study; the details of the seismic line can be found in the methodology section of this work.

The first well located along the Corona Ridge was drilled in 1998 and tested the Eribol Prospect (well 213/23-1), which encountered oil shows within Lower-Middle Carboniferous sandstones. The Tobermory prospect (214/4-1), drilled in 1999, marked the first discovery of sizeable quantities of hydrocarbons, when it encountered dry gas in Mid-Eocene turbidite fan sandstones. In the year 2000 the Bunnehaven exploration well (214/9-1, 17 km south of Tobermory) encountered oil (and associated gas) within Palaeocene-Eocene fluvial-deltaic sandstones in addition to gas in Upper Cretaceous marine sandstones. At present Bunnehaven and Tobermory are undeveloped, being classed as uneconomic (as of 2018), though further nearby exploration (e.g. Lyon Prospect to be drilled in 2019; Siccar Point Energy 2018) may lead to an economic cluster of gas fields in the north of the FSB.

In 2004, 140 km southwest of Bunnehaven, the Chevron exploration well 213/27-1 encountered oil and associated gas within Palaeocene-Eocene sandstones present between basalt lava flows (Rosebank prospect), and oil within Upper Jurassic sandstones (Lochnagar prospect) (Duncan *et al.* 2009; Helland-Hansen 2009; Schofield & Jolley, 2013; Poppit *et al.* 2016; Hardman *et al.* 2018b). A further six wells, two exploration and four appraisal, have established the extent of the Rosebank

Field, though has yet to be developed; Lochnagar is planned to remain undeveloped (Poppit *et al.* 2016). Later North Uist (213/25c-1), drilled in 2012, encountered significant gas shows above background within the Balder Fm., the Kimmeridge Clay and the Carboniferous. Finally well 6104/25-1, drilled in 2014 within the Faroese sector, encountered only water-bearing sediments, within the Early Eocene Colsay (Sula prospect) and Hildasay targets (Stelkur prospect). In terms of trapping mechanisms, generally the Palaeocene-Eocene plays along the Corona Ridge, such as Rosebank, rely on inversion-induced anticlines. Meanwhile, older Mesozoic plays, principally the Jurassic, are hosted within tilted fault blocks sealed by Cretaceous mudstones (Duncan *et al.* 2009) (Fig. 3).

Within several of the wells drilled along the Corona Ridge, however, a variety of drilling issues are recorded within the Balder Formation (see text boxes in Fig. 3), which in practical terms forms part of the overburden. The cause of these drilling issues, which this study investigates, is currently unknown, and have a significant cost implication given that future exploration wells near Bunnehaven and the potential development wells of the Rosebank Field, will both have to drill through the Balder Formation to reach intended targets.

Data and Methodology

The main dataset used for this study is the released commercial borehole data from wells drilled in the UK Continental Shelf, from the Common Data Access (CDA). The wells used as case studies are listed in Table 1. For consistency with previous work (Mark *et al.* 2018), a table detailing definitions of the terminology adopted by the offshore exploration and drilling industry is provided (supplementary material). Several seismic lines are also exhibited in this study, which are from the regional Faroe-Shetland PGS MegaSurvey Plus 3D seismic dataset, to place the wells examined in a tectono-stratigraphic context.

Well	Prospect/ Field name	Year Drilled	Balder depth [m MDBRT] (& Calculated Thickness [m])	Drilling fluid	Drill bit through Balder	Issues/notes within the Balder

205/1-1	Rosebank (Main)	2007	2472-2537 (55)	WBM	PDC	None
213/26-1*	Rosebank (Main)	2007	2448-2514 (66)	WBM	Tricone	Drilling fluid loss
213/27-1*	Rosebank (Main)/ Lochnagar	2004	2395-2465 (70.5)	WBM	Tricone	Drilling Fluid loss
213/27-2	Rosebank (Main)	2007	2471-2532 (56)	WBM	PDC	Cement loss during liner placement
6104/25-1	Sula/Stelkur	2014	2471-2535 (63.5)	WBM	Hybrid	Drilling fluid losses and break-outs
213/27-3	Rosebank (North)	2008	2440-2471 (43.7)	WBM	PDC	None
213/23-1	Eribol	1998	2644-2677 (32.3)	WBM	Tricone	LOT- weak formation
213/25c-1*	North Uist	2012	3017-3076† (69.1)	WBM & OBM‡	Tricone	Fluid losses, hole collapse, BHA lost in hole
214/27-1	Flett Ridge	1985	2301-2367 (67.1)	WBM	Tricone	Cement loss during casing
214/9-1	Bunnehaven	2000	3524-3726 (189)	WBM	Tricone	Drilling fluid loss & ballooning.
214/4-1	Tobermory	1999	3456-3734 (80)	WBM	Tricone	Drilling fluid losses & pack offs

Table 1: List of well case studies from south to north within the FSB. Note the drilling parameters, which will be referred to in the results section of this work. Depths are in Measured Depth Below Rotray Table (MDBRT). * = includes sidetracks. † = base depth projected from deviated sidetrack. WBM = water based mud, which in each instance is a KCl polymer. ‡ = OBM, Oil-based mud, used in

final side-track where no drilling issues recorded. PDC = Polycrystalline diamond compact, a type of drill bit. BHA = Bottom Hole Assembly. LOT = Leak Off Test.

Character and identification of the Balder Formation

The Balder Formation is an early Eocene lithostratigraphic unit, characterised by an interbedded assemblage of siltstone, claystone, and volcanic tuffs (lithified ash) (Knox & Holloway 1992; Mudge 2014; Watson *et al.* 2017). During burial the volcanic tuffs are almost entirely altered to smectitic or bentonitic clays (Knox & Morton 1983; Malm *et al.* 1984; Knox & Morton 1988). As a consequence of the original volcanic component, the Balder Formation has a prominent well log character (Fig. 4), manifested as low gamma akin to sandstone (Fig. 4a), resistivity moderately higher than shale (4b), a density/neutron positive separation of a shale (4c), and a fast interval transit time that has a bell-shaped log signature (4d) (Watson *et al.* 2017). The Balder Formation is also laterally extensive and a prominent seismic marker (due to a marked acoustic impedance contrast with the surrounding claystones).

Drilling the Balder Formation

A major focus of this study is drilling behaviour through the Balder Formation, which is best understood in the context of the drilling window (Fig. 5). The drilling window is a wellbore pressure profile governing safe drilling, bounded on the lower limit by pore pressure, and the fracture pressure on the upper limit (Cook *et al.* 2011). The wellbore pressure profile is represented by the mud pressure, governed by the weight of the drilling fluid (expressed in pounds per gallon [ppg]) (Cook *et al.* 2011). When examining drilling issues recorded within the Balder Formation, we either utilised a pre-existing drilling window (present in end of well reports), or constructed our own, to help establish the cause of particular drilling problems.

Pore pressure is the pressure exerted by the fluids within the rock and represents the lower limit of the drilling window (Osborne & Swarbrick 1997). If the mud pressure is set too low, below the pore pressure, then there is a danger of an unwanted influx of fluid from the wellbore, known as a "kick" (Cook *et al.* 2011). The most reliable way to determine pore pressure is from Wireline

Formation Tester (WFT) data, where pressures are measured from the formation directly downhole (Rider & Kennedy 2011). Marked increases in rates of penetration (ROP), known as "drilling breaks", are also helpful in highlighting potential zones of overpressure (Ablard *et al.* 2012).

The fracture pressure, the upper limit of the drilling window, represents the mud pressure above which the tensile strength of the rock is exceeded causing failure and hydraulic fracturing of the formation (Osborne & Swarbrick 1997; Cook *et al.* 2011; Millet *et al.* 2016). A consequence of unintentionally fracturing the formation can be the loss of drilling fluid, which is both costly (as mud is often on loan to the operator of a well), and unsafe as the wellbore pressure may drop, leading to loss of the pressure barrier and the influx of formation fluid (i.e. a kick). In order to establish the fracture pressure a Formation Integrity Test (FIT) or Leak-off Test (LOT) is performed at the start of each new section of a well. A LOT is where the well is shut in, and a surface pressure is applied on top of the pressure of the drilling mud column. The surface pressure is increased gradually until the pressure is sufficiently high to fracture the formation, causing *leaking off* of drilling fluid. If the test is stopped before fracturing then it is an FIT, providing an upper limit for the mud weight (the Equivalent Circulating Density [ECD]) used when drilling the next section (Gaarenstroom *et al.* 1993).

Drill bits and drilling fluids

Drilling issues which occur through the Balder Formation occur in some wells (e.g. 213/26-1) but not in others (e.g. 205/1-1), even when in relatively close proximity (both examples within Rosebank Main), suggesting that drilling parameters play a crucial role in operational complications. Two important drilling variables between different wells, outwith of the geology, is the type of drill bit and type of drilling fluid used. Drill bit selection is a critical pre-drill consideration as different bits perform more effectively in different lithologies. The two most common drill bit types are (1) roller cone bits and (2) fixed cutter bits. *Roller cone* bits (Fig. 6a) consist of three (a tricone bit) or four cone shaped steel noses that turn on the rock surface at the bottom of the wellbore as the bit rotates. *Fixed cutters* (Fig. 6b) consist of a single head that rotates with no separately moving parts (Schlumberger 2018), chipping and cutting away at the rock surface. A third, less common drill bit variant is a *hybrid drill bit* (Fig. 6c), which consists of a fixed head cutter and 2 or 3 roller cones.

Roller cone bits are predominantly used to drill mixed successions of soft (e.g. coal and shale) and moderately hard lithologies (such as sandstone and limestone) (Warren 1987). Fixed cutter bits, such as Polycrystalline Diamond Compacts (PDC), are typically more expensive than roller cones, though have more durable wear and therefore are more effective in very hard and abrasive formations such as chert (German *et al.* 2015) and crystalline volcanic rocks (Grindhaug 2012). Hybrid bits are used to drill an interbedded succession of very hard (e.g. basalt) and markedly softer rocks (e.g. claystone) (Rickard *et al.* 2014). Of note within the separate drill bits utilised, are the location of the nozzles, which pump out the drilling fluid at the front of the drill bit, in a similar fashion to the nozzle on a garden hose. In both roller cone and hybrid drill bits, the nozzles tend to be located above and slightly to the side of the main cutting cones, whereas the nozzles in a fixed cutter bit are more centrally located and closer to the cutting surface (Fig. 6).

In terms of drilling fluids, the most common types used are water-based mud (WBM) and oil-based mud (OBM). OBM provides greater wellbore stability, as clay bearing formations can interact with WBM and cause swelling and ultimately formation damage (McLean & Addis 1990). In terms of drilling in the UK Continental Shelf, OBM is generally reserved for drilling reservoir intervals. Additives, such as potassium chloride (KCl) are often added to WBM in order to inhibit clays from swelling (Caenn & Chillingar 1996).

Results: Drilling characteristics of the Balder Formation around the Corona Ridge area

Geomechanical properties

An important initial step in determining the cause of drilling issues within the Balder Formation is to establish its drilling window parameters; chiefly, what the pore pressure and fracture gradient of the formation is across the Corona Ridge, and what mud weight was used to drill through the formation in each well.

Any evidence of overpressure, i.e. pore fluid pressures in excess of hydrostatic pressure at a specific depth (Osborne & Swarbrick 1997; Zoback 2010), is important to recognise as it is linked to a number of drilling incidents, such as kicks and drilling fluid losses, which have been historically encountered in wells in the FSB (Mark *et al.* 2018). There is, however, a lack of WFT data within the Balder Formation as the lithologies such as tuffs and claystones present have permeability too low to be measured with conventional WFTs. We therefore examined WFT data acquired from a variety of formations throughout the Corona Ridge, in order to establish the study area pore pressure profile around the depths at which the Balder Formation is intersected. When plotted, these WFT points indicate that the depth zone at which the Balder Formation is encountered around the Corona Ridge is normally pressured (e.g. Fig. 5), that is, it follows a normal hydrostatic gradient that would be anticipated for pore connection up to the seabed. However, low permeability Palaeogene-aged shales globally commonly exhibit overpressure beyond depths of 1500 m (Swarbrick & Osborne 1998).

There is also a scarcity of FIT and LOT data, the most reliable way to determine fracture gradients, within the Balder Formation in the FSB, owing to the fact casing points are rarely set within the Balder Formation itself. In this study we therefore examined a number of individual LOTs acquired within the Balder Formation from five wells within the FSB and a further 7 wells from the contiguous North Sea Basin; the latter of which hosts the Balder Formation and is lithologically similar to the FSB (Mudge 2014; Watson *et al.* 2017). When plotting these LOT points (Fig. 7), the fracture gradient measured within the Balder Formation displays a gradual increase with depth, as would be expected. The fracture pressure measured along the Corona Ridge, acquired within the Balder from the Eribol well (213/23-1), represents a marginal departure from this trend line, hydraulically fracturing 274 psi (1.9 MPa) lower than the fracture gradient projected from the regional trend.

Drilling phenomena which occur within the Balder Formation

There is a variety of drilling problems recorded through the Balder Formation around the Corona Ridge, such as bit balling (clogging up of the bit) and drilling fluid losses, which contribute to non-productive time (NPT) for drilling activity and even necessitate pulling out of the hole (POOH), at great cost to troubleshoot and solve the problem. One "trip", the process of pulling the drill string out of the hole, can take up to 24 hours to complete, equating to $125,000 in cost at the current semi-submersible drill rig daily rate (IHS Markit 2018). The following section details specific drilling issues encountered within the Balder Formation around the Corona Ridge, though with particular emphasis on the Rosebank wells, all of which were drilled within the last 15 years and therefore have a good selection of publicly available data, including drilling mechanics logs and wellbore image logs, with which to investigate the nature and cause of drilling problems. In the southern part of Rosebank Main (e.g. 213/26-1z) these drilling incidents typically occur within narrow ranges (~20 m) (Fig. 8).

Bit Balling

The initial drilling issue to occur in this narrow, 20 m depth range through the Balder Formation is bit balling, which is when the formation interacts with the drilling fluid, and then proceeds to swell and stick to the drill bit (Fig. 9) (Cheatham & Nahm 1990). Bit balling can significantly reduce rates of penetration (ROP), preventing the drill bit from contacting the formation, and the built up mass of clay can make the bottom hole assembly behave like a piston in a cylinder, producing additional surge and swab pressures (Hariharan & Azar 1996). Unless balling is treated downhole, it may require pulling out of the hole (POOH) to clean the drill bit, resulting in non-productive drilling time.

Bit balling is noted in drilling reports throughout Rosebank Main (213/26-1, 213/26-1z & 213/27-1z) and in the Bunnehaven (214/9-1) well. In Rosebank Main well 213/27-1z, bit balling was recognised through the Balder Formation as ROP dropped to <1 m/hour at 2417.7 m measured depth, after only the top 20 meters of the Balder Formation having been drilled. Forty-Five barrels (6,120 litres) equivalent worth of caustic material and seawater was put down the hole, in an attempt to breakdown the build-up of swelling materials. However, the unballing strategy was unsuccessful and eventually required POOH to clean the drill bit, resulting in approximately 24 hours of NPT. Taken as a proportion of the £14.09 million total well cost of 213/27-1z, drilled over 51.6 days, cleaning of the bit due to balling equates to a cost of £273,062 (1.94% of the entire well cost). A full suite of drilling mechanics logs is not available for well 213/27-1z. However, drilling mechanics logs are available for well 213/26-1z (Rosebank Main), drilled three years later, where balling was again encountered within the Balder Formation. Within the drilling mechanics logs, balling causes a reduction in the rate of penetration (ROP) (Fig. 8a), despite the weight on bit (WOB) being increased (Fig. 8b). Significantly, the balling is concomitant with a gradual increase in standpipe pressure (Fig. 8c) (which represents pressure in the circulating drilling fluid system), which eventually spikes (at 2582 psi), just prior to the commencement of drilling fluid losses (Fig. 8d).

Drilling fluid losses and gains (ballooning)

In the narrow, 20 m depth range in 213/26-1z within the Balder Formation, dynamic drilling fluid loss (losses as the drilling fluid is circulating during drilling) occurs immediately after the spike in standpipe pressure associated with bit balling (Fig. 8c&d). Fluid losses also occur further down in the Balder and in total occur in three separate zones (149 bbl/hr at 2522.8 m; 90 bbl/hr at 2529 m; 298 bbl/hr at 2575.6 m) (Fig. 8), categorising them as moderate, minor and severe losses, respectively (Millet *et al.* 2016). In an attempt to "cure" the losses, 110 barrels (14,960 litres) of Lost Circulation Material (LCM) was pumped down the hole to plug the permeable zones. However, the resulting reduction in mud supplies, in combination with a deteriorating weather forecast, resulted in POOH. During the subsequent bad weather, 100 hours of NPT were ultimately accrued before the recommencement of drilling; when taken as a proportion of the 57 days taken to drill 213/26-1z, this equates to £1.16 million. Including sidetracks, drilling fluid loss is recorded within the Balder Formation in six out of the eleven wells (54.5 %) along the Corona Ridge: in 6104/25-1 (Sula/Stelkur), in 213/26-1 & 213/27-1 (Rosebank Main), North Uist (213/25-1c), Tobermory (214/4-1) and in Bunnehaven (214/9-1). In total, more than 550 barrels (74,800 litres) of drilling fluid have been lost to the Balder Formation in these Corona Ridge wells, equating to ~ £25,300 cost for just the mud alone.

Within three of these Corona Ridge wells which encountered drilling fluid losses through the Balder Formation (213/26-1, Rosebank Main; 214/4-1, Tobermory; 214/9-1, Bunnehaven), the lost drilling fluid later returned to the wellbore in a process called wellbore ballooning (Helstrup *et al.* 2004). Ballooning can be problematic as returning drilling fluid can be interpreted wrongly as an influx of formation fluid (known as a "kick"). In the case of misinterpretation as a kick, consequently mud weights may be increased to compensate for this influx, with the inadvertent effect of fracturing the formation, and exacerbating drilling fluid loss (Helstrup *et al.* 2004; York *et al.* 2009). During connections (the process of adding more pipe to the drillstring) circulation of the drilling mud is stopped, and only the pressure of the static mud column holds back formation fluids from entering the wellbore, which includes any lost drilling mud. Ballooning can therefore occur as the pressure of the static mud column can be lower than the pressure of the lost drilling mud within the formation (Ward & Clark 1998).

Drilling Fractures

The Balder Formation is characterised from mud logs as a series of low permeability interbedded mudstone, siltstone and volcanic tuffs in wells around the Corona Ridge. Drilling fluid losses within the Balder Formation therefore appear to be linked to several sets of electrically conductive fractures recognised within Rosebank Main, specifically 213/26-1 and its sidetrack 213/26-1z where losses occurred through the Balder. In well 213/26-1 these fractures appear as thin, electrically conductive fractures sub-parallel with the wellbore, 180° apart (Fig. 10a), characteristic of drilling induced fractures (Zoback *et al.* 2003). In well 213/26-1z, a more complex fracture pattern is recognised, with "one winged" drilling induced, or at least enhanced, fractures (i.e. a single sub-parallel fracture with no pair) (Fig. 10b) (Barton *et al.* 1995; Jepson *et al.* 2018) and several smaller fracture splays exhibiting an irregular, dendritic pattern.

The fractures within 213/26-1 are typical of drilling induced fractures, though the fracture network within 213/26-1z is more complex to characterise. One way to determine whether the fractures within 213/26-1z are natural, i.e. pre-existing before drilling, is to examine whether background gas increases in that interval, which is otherwise impossible with drilling induced fractures (Rider & Kennedy 2011). Drilling fluid losses can complicate gas readings whilst drilling, though in 213/26-1z electrically conductive fractures are also observed deeper, where no drilling fluid losses occurred. Between 2522-2525 m, where the fractures are located, methane levels increase from 1000 ppm at 2522 m, to 1900 ppm at 2525 m. Smaller pre-existing fractures are also recognised in well 205/1-1 in Rosebank Main (Fig. 10c) where the Balder Formation was drilled incident free. These fractures are also associated with a small increase in background gas (methane increases from 4000 ppm at 2514 m, to 7000 ppm at 2515 m), suggesting they are, at least in part, pre-existing, fractures that have been drilling enhanced (Rider & Kennedy 2011). Ultimately, there appears to be both drilling induced and enhanced fractures in wells where losses occur (213/26-1 & 213/26-1z), and smaller pre-existing fractures in wells where no drilling incidents were observed (e.g. 205/1-1).

Drilling induced and enhanced fractures also provide important evidence of regional stress, and hence their underlying tectonic origin, which has important economic implications given that these fractures are associated with costly drilling fluid losses. Fracture enlargement, including induced and enhanced fractures, forms parallel to contemporary maximum horizontal stress (S_{Hmax}) (Fig. 11) (Dart & Zoback 1989; Hillis & Williams 1992). The drilling induced (213/26-1) and drilling enhanced fractures (213/26-1z) within the Balder Formation overlying the Corona Ridge are orientated NW-SE (Fig. 10a) and NNW-SSE (Fig. 10b), respectively, approximately parallel with the predominant present day stress field of WNW-SSE (Holford *et al.* 2016).

Unfortunately, drilling mechanics logs, including mud weights, are not available for well 213/26-1, though are available from the sidetrack 213/26-1z. An unusual aspect of the drilling induced and/or enhanced fractures within 213/26-1z is that the mud weight used (ECD of ~2407 psi) does not appear to have exceeded the fracture gradient of the Balder Formation around the Corona Ridge (~2539 psi) (Fig. 8).

Discussion

Synthesising geology and drilling data - why the drilling issues occur

In this study we have outlined how a number of drilling incidents encountered within the Balder Formation occur in a narrow, ~20m depth range (e.g. Fig. 8). Image logs from Rosebank Main (Fig. 10) highlight that within this zone there are large conductive fractures, up to 15 m long, interpreted as either drilling induced (213/26-1) or enhanced (213/26-1z), which likely represent the source of permeability by which the drilling fluid escapes from the wellbore. However, the mud pressure does not appear to have exceeded the modelled fracture gradient of the Balder Formation, suggesting an alternative mechanism for hydraulically fracturing the Balder is in effect.

Notably, examination of the standpipe pressure (pressure in the drilling fluid system) can be seen to markedly increase from background readings, spiking just prior to occurrence of loss of drilling fluid. When plotted, the pressure combination of mud pressure (ECD) and the excess in standpipe pressure exceeds the modelled fracture pressure of the Balder (Fig. 12). Operationally, this is interpreted as the bit baling creating a restricted flow, causing a spike in mud pressure which reaches the fracture pressure, leading to drilling induced or enhanced fractures. We therefore suggest that the drilling issues- including bit balling, drilling induced/enhanced fracturing, drilling fluid losses and ballooning- occur in an inter-related chain reaction (visually depicted in Fig. 13) and detailed below:

1. Normal drilling conditions within the Balder Formation, no operational issues initially.
2. Balder Formation clays start to swell, causing balling of the drill bit and leading to a reduction in ROP. An increase in WOB likely exacerbates this effect (akin to a car continuing to accelerate wheels stuck in mud). Tricone and hybrid bits are more adversely affected by this balling, as their drilling nozzles are located at the side of the bit and are therefore less effective at clearing away the build-up of clay material.
3. The swelling clays cause restriction of flow, preventing communication between the area in front of the drill bit (where the cuttings are being generated) to the rest of the wellbore (termed a "pack-off"). When the well packs off the trapped pressure causes the formation below the pack-off to be subject to higher pressure than calculated by mud weight and ECD, to the point where the natural fractures within the Balder are enhanced. Drilling fluid is then lost to those fractures.
4. The drilling fluid losses are "cured" by putting Lost Circulation Material (LCM) pills pumped down the hole, plugging the facture network and allowing drilling to recommence.

5. The lost fluid later returns to the wellbore (ballooning), often during drill pipe connections as only the static mud column is holding back formation fluids (which includes lost drilling mud).

Wider geological context- Why drilling issues occur around the Corona Ridge

In this study we have detailed a range of drilling incidents observed within the Balder Formation around the Corona Ridge area of the FSB. There are two critical features of the Balder Formation observed in these wells: the formation is both (1) highly swelling and (2) a NW-SE principal stress orientation.

The swelling aspect can clearly be linked back to the lithological character of the Balder Formation, particularly the volcanic tuffs which are now largely altered to smectite (Knox & Morton 1983), a clay type particularly prone to swelling (Norrish 1954; Cheatham & Nahm 1990). An important aspect of the Balder Formation tuffs is that their distribution is regionally variable, particularly when associated with marginal to non-marine deposition compared to marine settings (Watson *et al*. 2017). In marginal to non-marine settings (Fig. 14), such as the southern (e.g. quads 204, 205) and eastern (e.g. Rona Ridge) flanks of the basin, tuff preservation is more limited, appearing within discontinuous, relatively thin (2-12 m thick) packages. In marine settings such as the Flett Sub-basin and the Corona Ridge, in contrast, tuffs are better preserved within predominantly siltstone and claystone rich successions.

The drilling induced and enhanced fractures recognised within the Balder Formation along the Corona Ridge document a principal horizontal stress orientated NW-SE. This orientation is parallel with the dominant horizontal stress within the basin (Holford *et al*. 2016), and also coincident with the orientation of Miocene-aged North Atlantic ridge-push compression, a postulated mechanism for the inversion of SW-NE trending anticlines such as those overlying the Corona Ridge (Boldreel & Andersen 1993; Ritchie *et al*. 2008). We therefore propose that the compression event that caused inversion of the Corona Ridge lead to horizontal stresses sufficient to induce brittle deformation within the Balder Formation, manifested as a fracture network that is later enhanced during the drilling process.

Therefore, specifically in the case of the Corona Ridge, it appears that the combination of (1) marine Balder Formation with tuffs that are susceptible to swelling during drilling and (2) a mechanically weak Balder Formation subjected to NW-SE horizontal stress overlying intra-basinal highs, result in drilling issues related to the opening of pre-existing fractures (Fig. 14). To the south-west of Rosebank, wells around the Cambo intra-basinal high (e.g. Cambo Field) have not experienced drilling issues through the Balder Formation likely due to Cambo's closer proximity to the Balder palaeocoastline (Hardman *et al*. 2018a) and therefore more marginal marine sedimentation (greater proportion of non-tuffaceous siltstone and sandstone less prone to swelling).

Mitigation against drilling issues for future wells

Issues related to drilling through the Balder Formation around the Corona Ridge have led to a number of highly undesirable operational events, such as reduced ROP and loss of drilling fluid. Cumulatively, in total >550 barrels (74,800 litres) of drilling fluid have been lost, and at least 124 hours of NPT have been accrued, whilst drilling the Balder Formation around the Corona Ridge, which equates to approximately £1.5 million in cost. Therefore any mitigations which can be put in place to minimise drilling issues within the Balder Formation have a significant efficiency and monetary implication. Table 2 summarises a number of mitigations to prevent drilling issues through the Balder, addressed in further detail below.

Operation Mitigations	Selection	Impact
Mud type	Oil-based mud (OBM)	No reaction with swelling clays.
Bit choice	PDC bit	PDC bit nozzles more centrally located, likely more effective at clearing away build-up of swelling clays.
Mud pressure	Reduced mud pressure through the Balder	In the event of a sudden downhole increase in pressure, a lower mud pressure would provide a wider drilling window.

Weight on Bit (WOB)	Not immediately increasing WOB if ROP drops through Balder	Drop in ROP through Balder can indicate bit balling, which would only be exacerbated by an increase in WOB.
Fracture characterisation	Acquire LWD image logs through the Balder	Identification of fracture networks within the Balder prone to drilling issues.
Casing points	Avoid setting casing points within the Balder	Interbedded, mechanically weak formations make poor locations for casing points.

Table 2: List of actions to mitigate against encountering drilling issues through the Balder Formation around the Corona Ridge area.

Swelling clays and bit balling have been reported through the Balder Formation in a number of the Corona Ridge wells examined (e.g. 213/26-1) despite the use of KCl water-based mud (KCl being an additive meant to inhibit clay swelling). Oil-based muds (OBM) eliminate water from the external phase and therefore would offer greater clay swelling inhibition for future wells drilling through the Balder around the Corona Ridge.

In the majority of the wells where drilling issues occur a tricone drill bit was used, with the exception of the Sula/Stelkur well (6104/25-1) in the Faroese sector, where a hybrid bit was used (combination of fixed cutter and roller cone). A key feature of both tricone and hybrid bits is that the nozzles which expel the drilling fluid are located slightly behind and to the side of the drill bit, and are therefore less effective at clearing away a build-up of swelling clays. Therefore, use of a PDC drill bit with central nozzles through the Balder may help retard bit balling, a phenomenon which appears to precede fracture enhancement and drilling fluid loss; see Table 1 where all three uses of PDC bits has not lead to the problems associated with other bits. However, the use of a PDC bit often can lead to a degradation in cuttings quality, and consequently biostratigraphic observations, which has shown to be a critical component in correlating reservoir intervals along the Corona Ridge (Schofield & Jolley 2013; Hardman *et al.* 2018).

A further drilling consideration for future wells around the Corona Ridge is the placement of casing points. Formations which are interbedded and mechanically weak, such as the Balder Formation around the Corona Ridge, tend to form poor locations to set casing shoes. Future wells around the Corona Ridge therefore may be best cased off before or after the Balder Formation is penetrated. Future studies could also examine the impact a weakened Balder Formation may have on the stability of the overlying Stronsay Group sediments. The North Uist well (213/25-1c) along the Corona Ridge for instance, had major difficulties getting casing through the base of these Stronsay Group sediments, just above a potentially weakened Balder Formation.

Wider Implications for the Petroleum System

The widespread occurrence of drilling fluid losses in wells around the Corona Ridge betrays the presence of permeability within the Balder Formation. The exact nature of this permeability away from the wellbore is unclear, be it within pre-existing fractures, fractures enhanced during drilling or permeable turbidite sediment stringers. However, an increase in background gas within the Balder both in North Uist (213/25-1c) and in Rosebank Main (205/1-1) associated with smaller fractures where no drilling issues occur signifies that the permeability is to an extent natural, and not solely drilling induced. The presence of permeability within the Balder Formation is slightly counter intuitive as it is a laterally extensive formation composed of relatively low permeability claystone, siltstone and volcanic tuffs.

It is well established that the Balder Formation forms an effective top seal in other parts of the UK Continental Shelf, notably within the Bressay Discovery in the contiguous North Sea Basin (Underhill 2001). When comparing the Bressay and Rosebank structures side-by-side (Fig. 15), the sands underlying the Balder at Rosebank are water-bearing, despite being within a four-way closure, in contrast to the oil charged sands of Bressay. Fluorescence is, however, reported in ditch cuttings from the Hildasay Member in Rosebank well 213/27-3, suggesting hydrocarbons have migrated through the Hildasay. Notably the Bressay structure has an entirely different genesis to Rosebank and the Corona Ridge. Bressay formed as a result of differential compaction due to an incised fluvial channel (which forms the reservoir) which the Balder Formation drapes (Underhill 2001). Traps formed through differential compaction, or "drape anticlines", form shortly after reservoir deposition and without tectonic disturbance (Allen & Allen 2005; p. 483). In contrast, inversion anticlines, such as the Rosebank trap (Duncan *et al.* 2009), form due to the reversal of extensional faults during compression (Williams *et al.* 1989). The compressional tectonism associated with the formation of the Rosebank anticline trap therefore may have generated a permeable fracture network which ultimately retarded the sealing capability of the Balder Formation.

Application to other sedimentary basins

This study deconstructs the chain-reaction of events which occur whilst drilling the Balder Formation, which in the study area specifically is prone to swelling. These drilling events all occurred with the use of a water-based drilling mud, which despite the presence of KCl as an inhibitor, still caused the Balder to swell and ball the bit. The swelling within the Balder Formation is linked to the presence of smectitic clays, which are a product of alteration of the original volcanic ash (Knox & Morton 1983; Malm *et al.* 1984; Knox & Morton 1988). In addition to volcanic input, smectite-rich sedimentary successions can also be sourced from drainage of large continents (Griffin *et al.* 1968). Within the Gulf of Mexico, for example, swelling smectite clays are termed “gumbo shale” and widely known for drilling issues such as low rates of penetration (Allred & McCaleb 1973; Klein *et al.* 2003; Sameni & Chamkalani 2018). This study’s multidisciplinary approach of placing drilling incidents within the context of regional geological observations, including the tectonic history and environment of deposition, could therefore be applied to other sedimentary basins where similar drilling issues are recorded. We emphasise the need to properly integrate the geological understanding with drilling planning and parameters. This is important in the current exploration drilling backdrop where water-based drilling muds are being increasingly deployed because they are viewed as more environmentally acceptable (Anderson *et al.* 2010), and therefore the prospect of swelling clays will continue to be a risk during drilling operations.

Conclusions

A myriad of drilling incidents have been observed whilst drilling the Balder Formation around the Corona Ridge area of the FSB, including bit balling, drilling fluid loss, wellbore ballooning and wellbore collapse, often with multi-million pound cost implications. These drilling phenomena appear linked, effectively forming a drilling chain reaction- bit balling preceding drilling fluid loss, followed by wellbore ballooning. These drilling events can be linked back to the geological history of the basin, in particular to Miocene compression which appears to have inherently weakened the Balder Formation along the Corona Ridge. However, these drilling issues can be mitigated by drill bit selection, particularly through the use of a PDC bit, rather than a tricone (Table 2). Furthermore, the recognition of a permeable Balder Formation around the Corona Ridge has important ramifications for quantifying risk in exploration of the Hildasay sandstone play.

Ultimately, this study highlights the importance of integrating regional geological observations, such as tectonic histories, to help fully understand the origin of drilling issues. This multidisciplinary approach, between geology and drilling operations, could be applied to other sedimentary basins globally where drilling issues such as swelling clays and mud losses are reported.

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Figure Captions

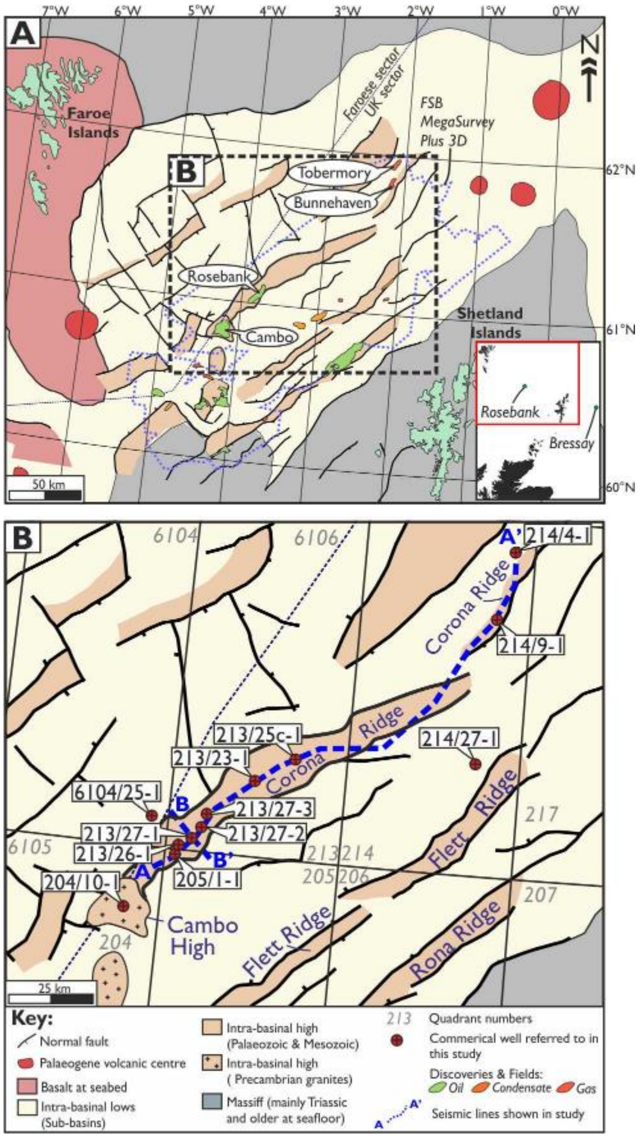

Fig. 1. (**A**) Map of the Faroe-Shetland Basin with main tectonic elements. (**B**) More localised map, showing the location of this study's focus, including the wells and seismic lines described in this paper. Base map adapted from Ellis *et al*. (2009), and Corona Ridge elements modified based on Hardman *et al*. 2018b.

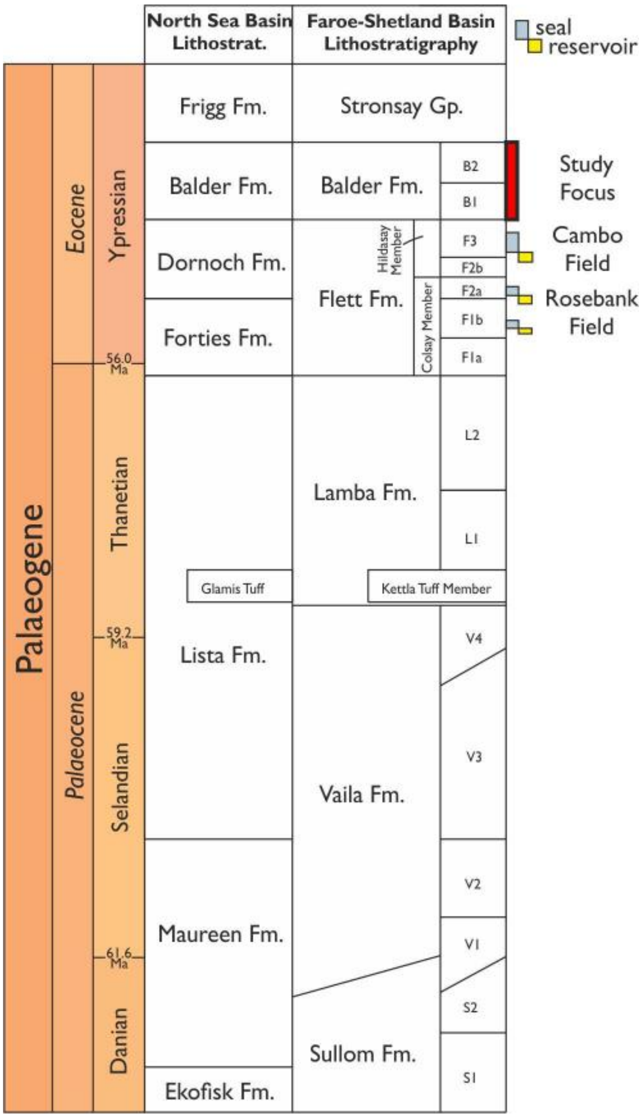

Fig. 2. Lithostratigraphy of the Palaeocene to lower Eocene in the FSB, and their lateral equivalents in the North Sea. Chart adapted from Ritchie *et al*. (2011), with revision of Colsay and Hildasay members of the Flett Fm. from Schofield *et al*. 2017.

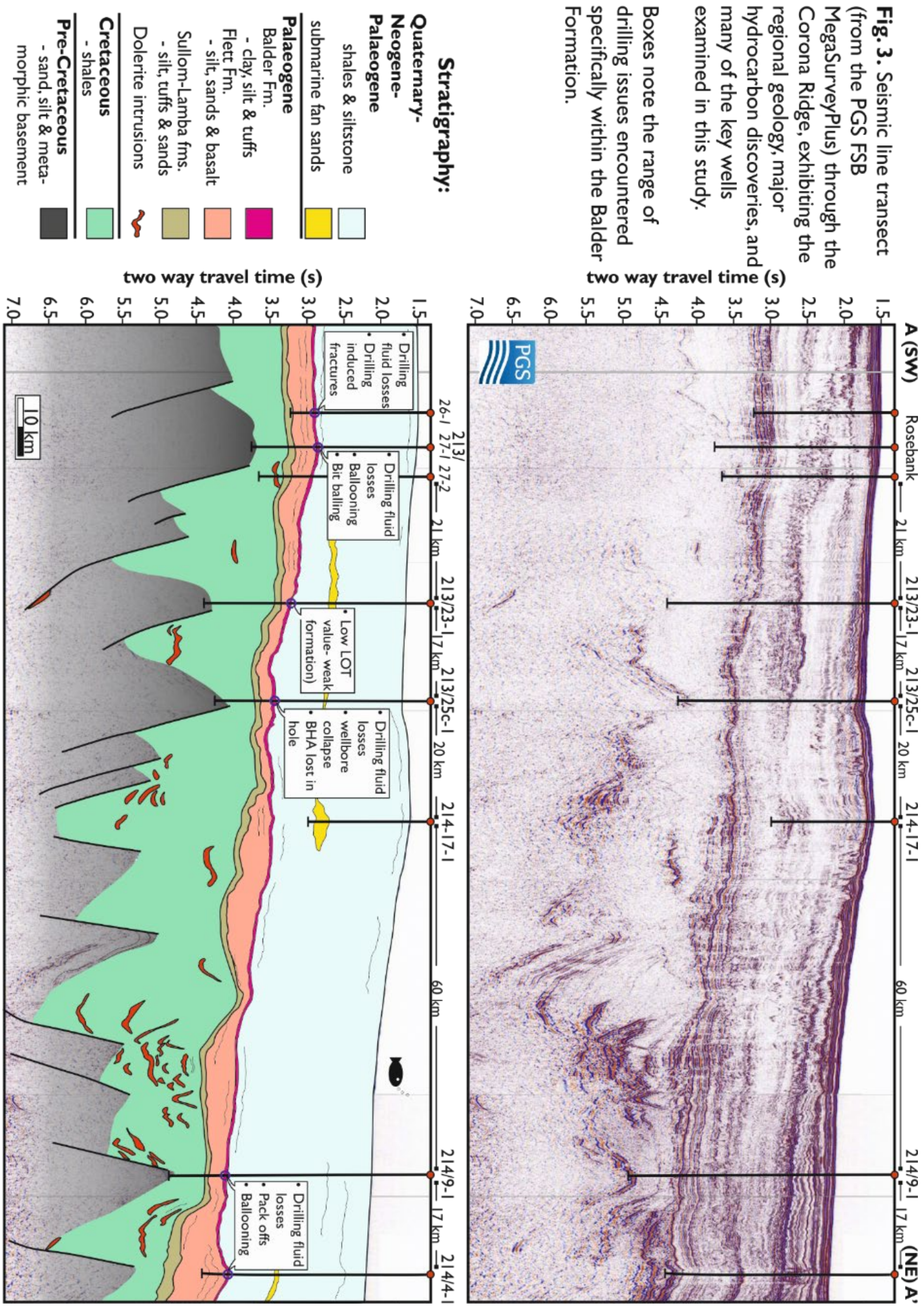

Fig. 3. Seismic line transect (from the PGS FSB MegaSurveyPlus) through the Corona Ridge, exhibiting the regional geology, major hydrocarbon discoveries, and many of the key wells examine

in this study. Boxes note the range of drilling issues encountered specifically within the Balder Formation.

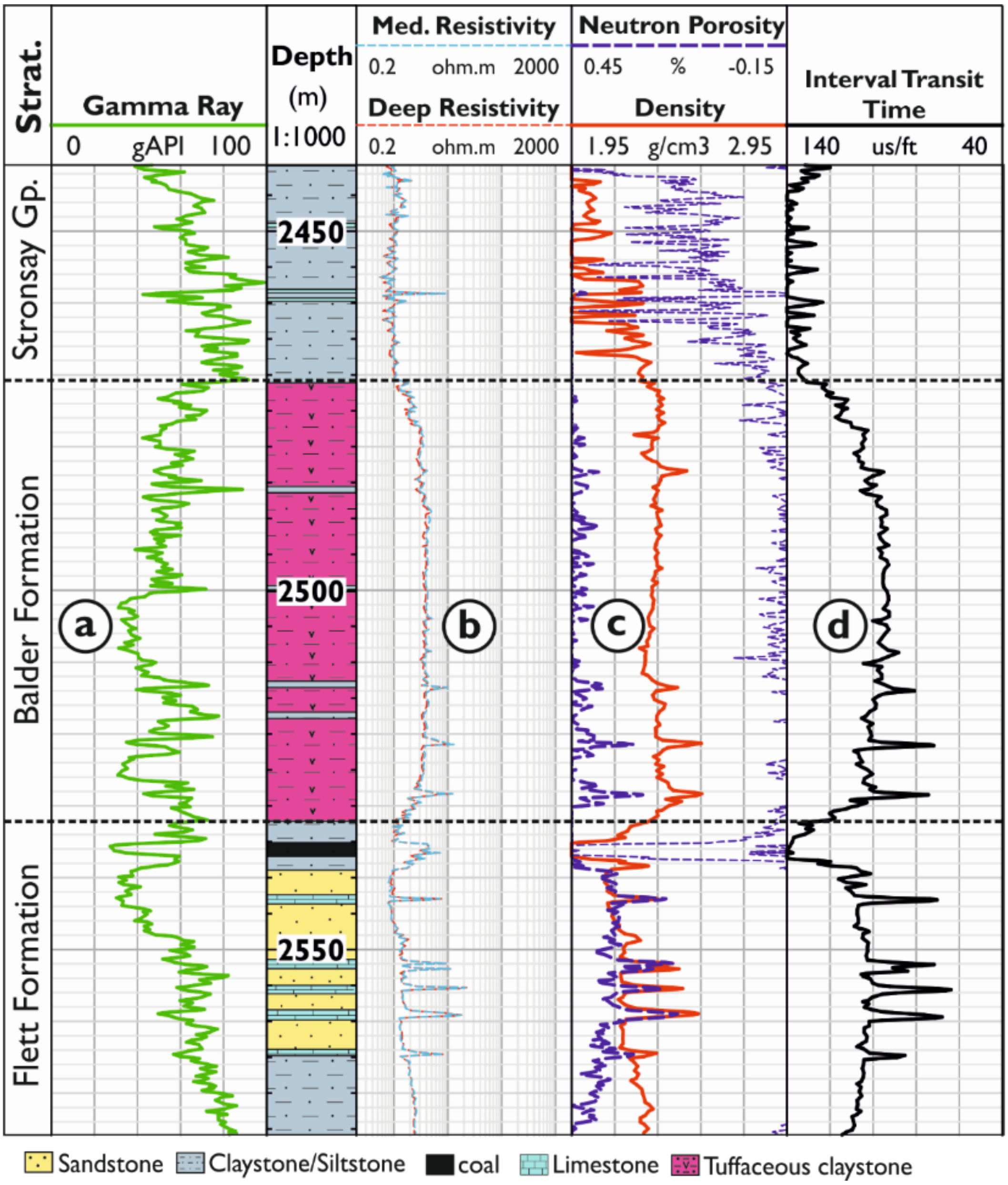

Fig. 4. Typical well log character of the Balder Formation in the FSB, from well 6104/25-1, manifested in a low, serrated gamma profile (**a**), resistivity slightly higher than shale (**b**), a density/neutron separation typical of shale (**c**) and a bell-shaped interval-transit time profile (**d**).

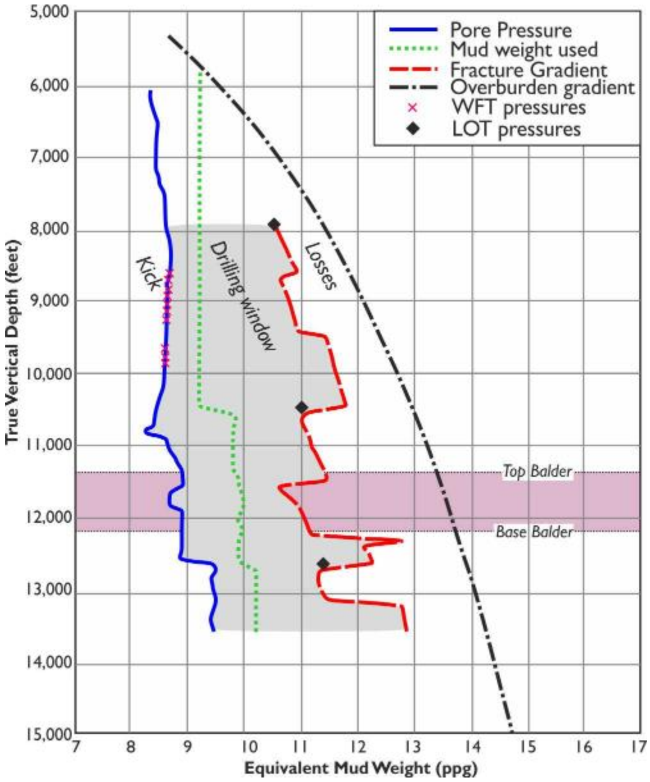

Fig. 5. An example of a drilling window plot, from Tobermory (well 214/4-1) End of Well Report. In this example, as well as all other wells examined, the mud weight (pounds per gallon [ppg]) does not appear to be set higher than the fracture gradient of the Balder Formation, yet drilling fluid losses still occurred.

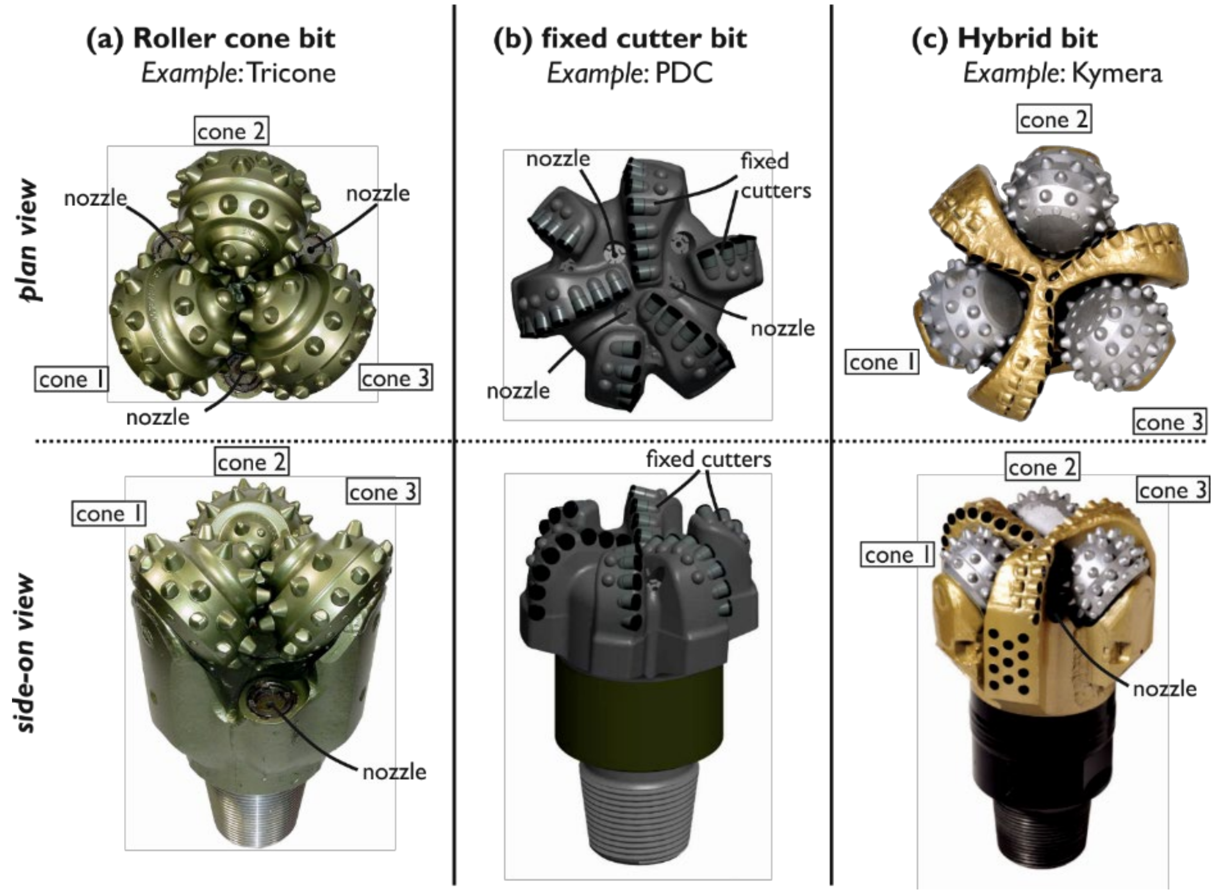

Fig. 6. Different types of drill bit commonly used to dill through the Balder Formation around the Corona Ridge. The nozzles in (**a**) tricone and (**c**) Kymera bits are located to the side and further back from the front of the bit, compared to a (**b**) PDC bit. Tricone and PDC bits from Schlumberger drilling catalogue (2018), and hybrid bit from Baker Hughes catalogue (2018).

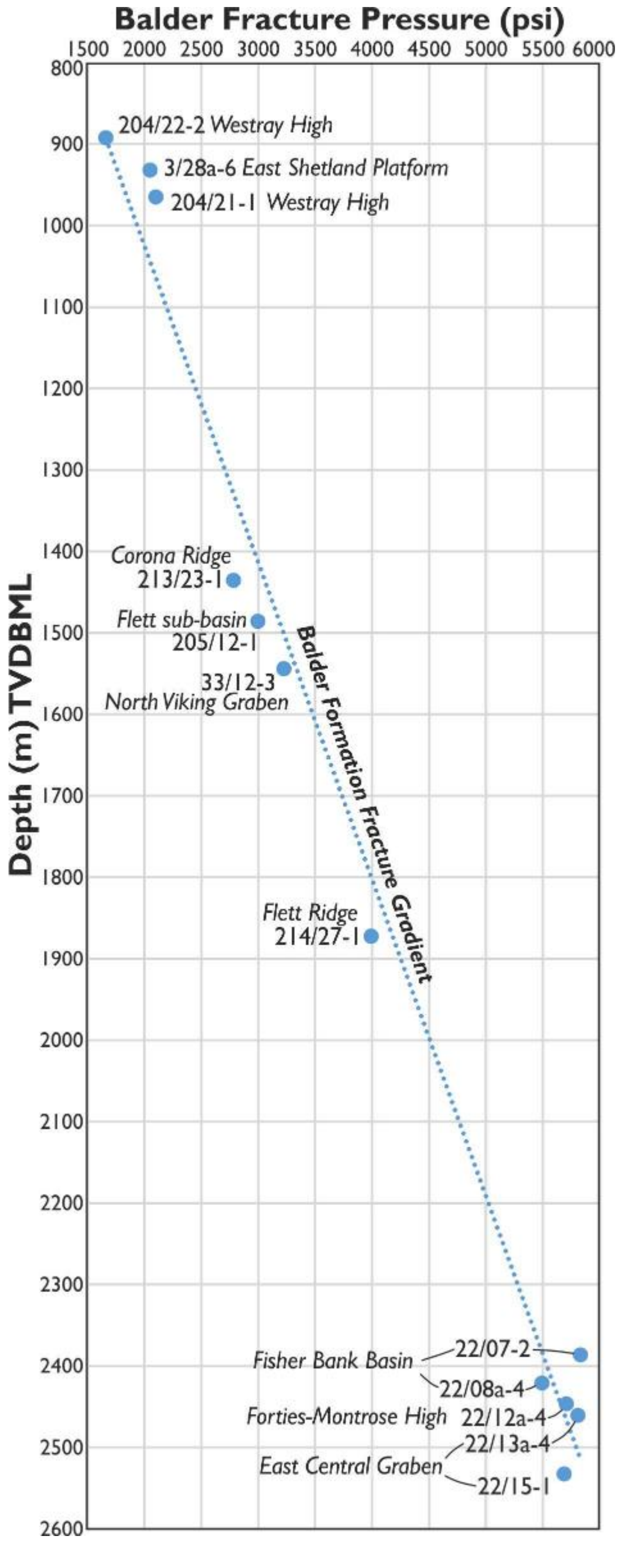

Fig. 7. Regional fracture pressure gradient for the Balder Formation around the Corona Ridge. The LOT data is from the Balder Formation from wells in the FSB and North Sea.

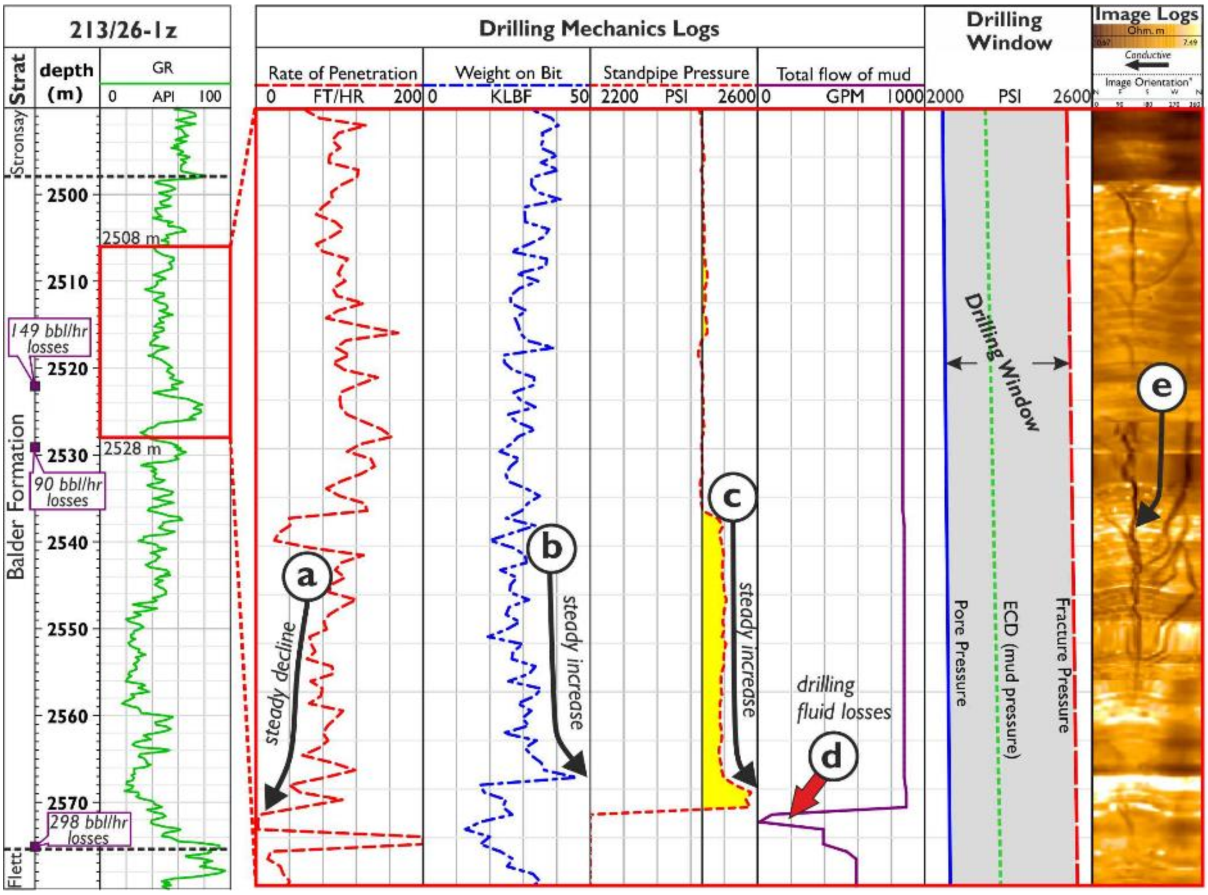

Fig. 8. Drilling properties through the Balder Formation in well 213/26-1z. A notable reduction in the rate of penetration is observed (**a**), despite the fact the weight on the bit (**b**) is increased. The increase in standpipe pressure (**c**) in therefore indicative of bit balling. Drilling fluid loss (**d**) is initiated shortly after the recognition of bit balling. The fluid losses are associated with a conductive fracture network (**e**), recognised in image logs. Three separate zones of drilling fluid loss occur (highlighted on the depth track on the left).

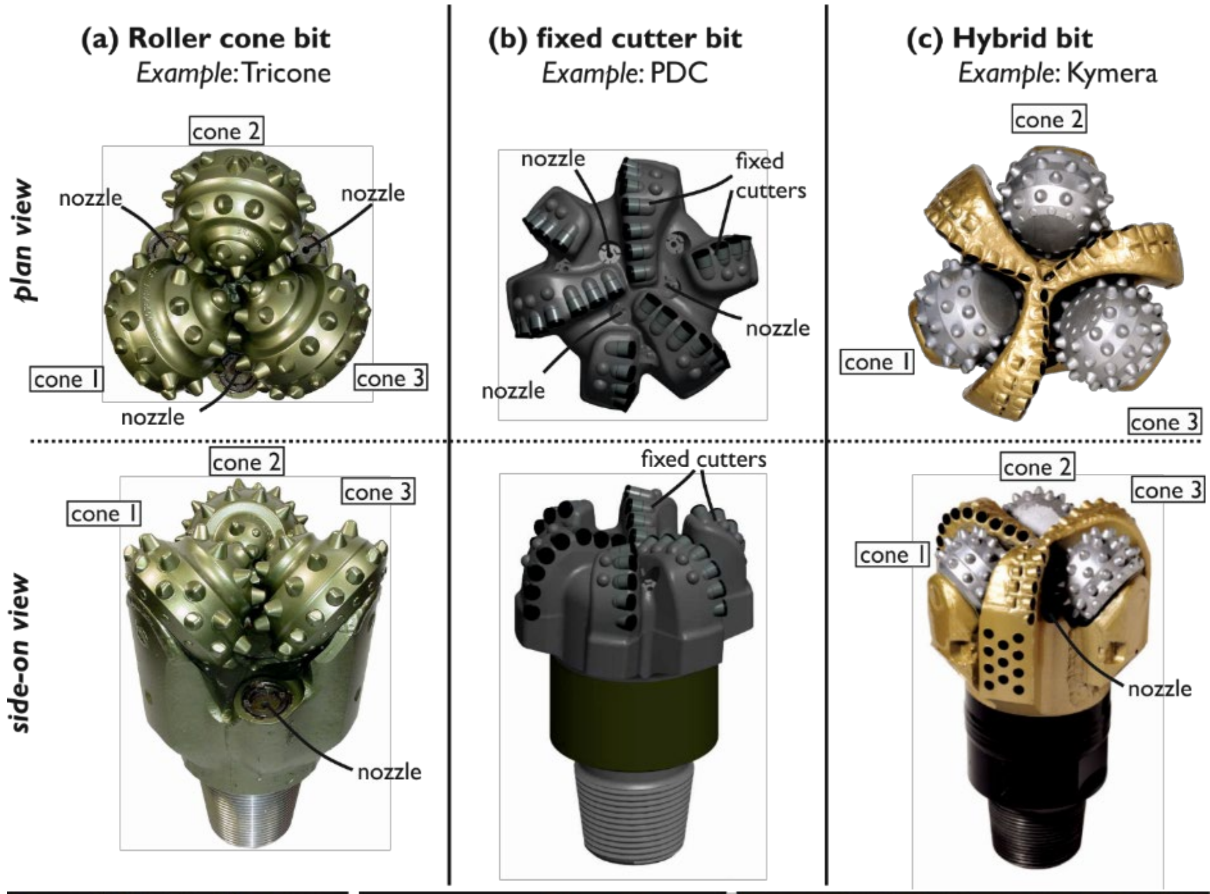

Fig. 9. Examples of bit balling of a tricone drill bit. Images courtesy of John Jong & Jon Royds, JX Nippon Oil & Gas Exploration.

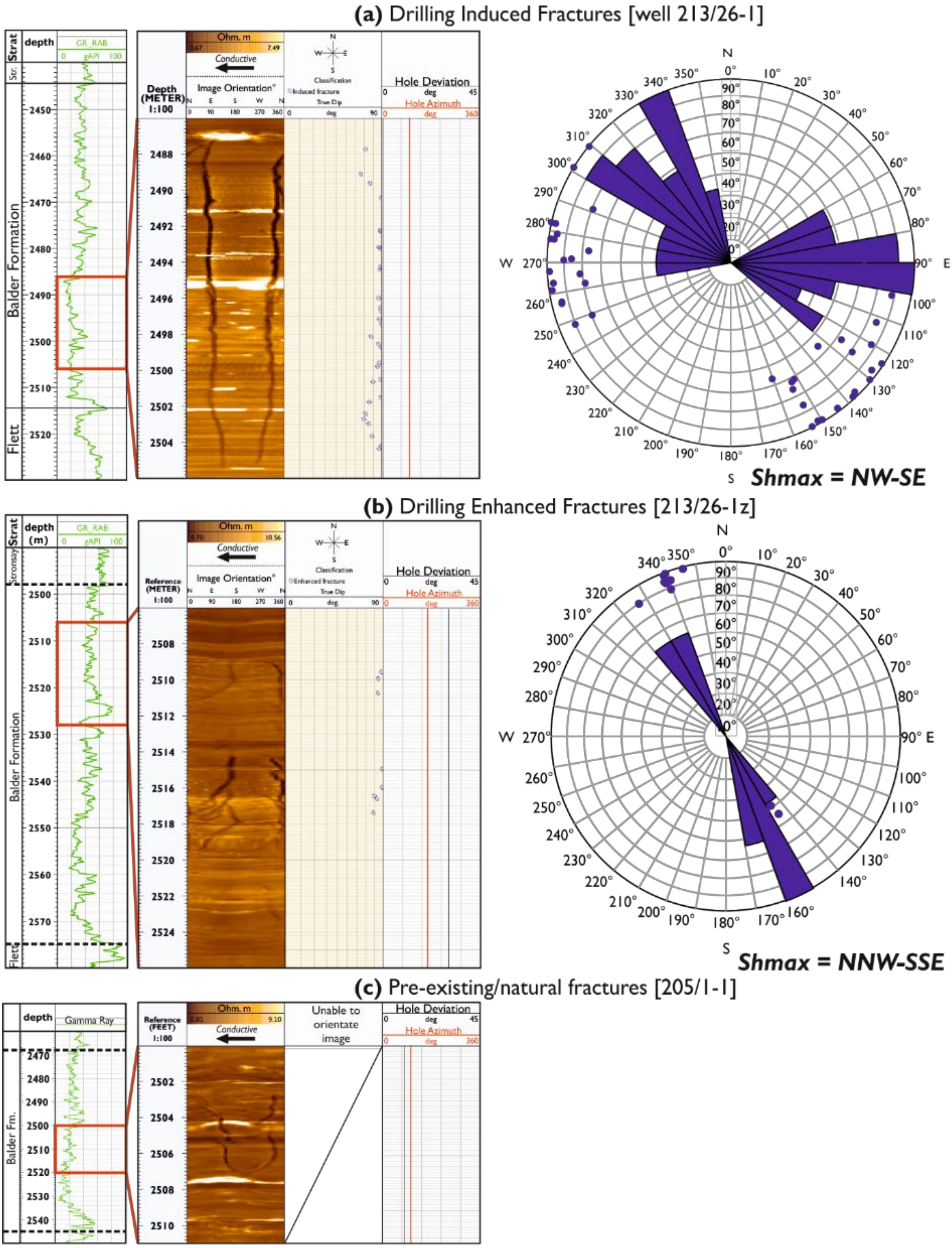

Fig. 10. The drilling induced fractures within 213/26-1 (**A**) are orientated NW-SE, implying a maximum compressive stress (σHmax) in the same direction. Drilling enhanced fractures within 213/26-1z (**B**) are orientated NNW-SSE. There are also natural fractures (**C**) within the Balder in 205/1-1; note this image log was not able to be orientated.

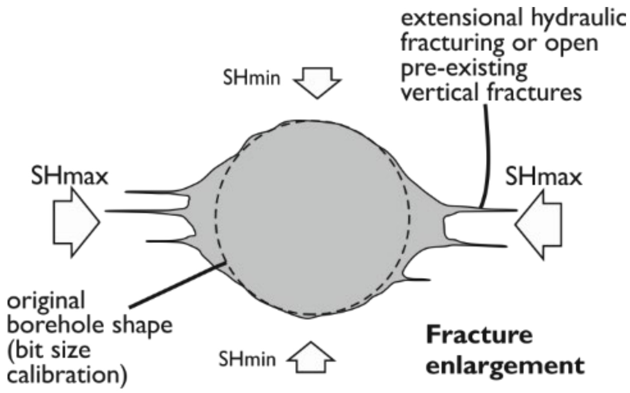

Fig. 11. Fracture enlargement (i.e. drilling induced and enhanced fractures) form parallel with the maximum horizontal stress (SHmax). From Hillis & Williams (1992).

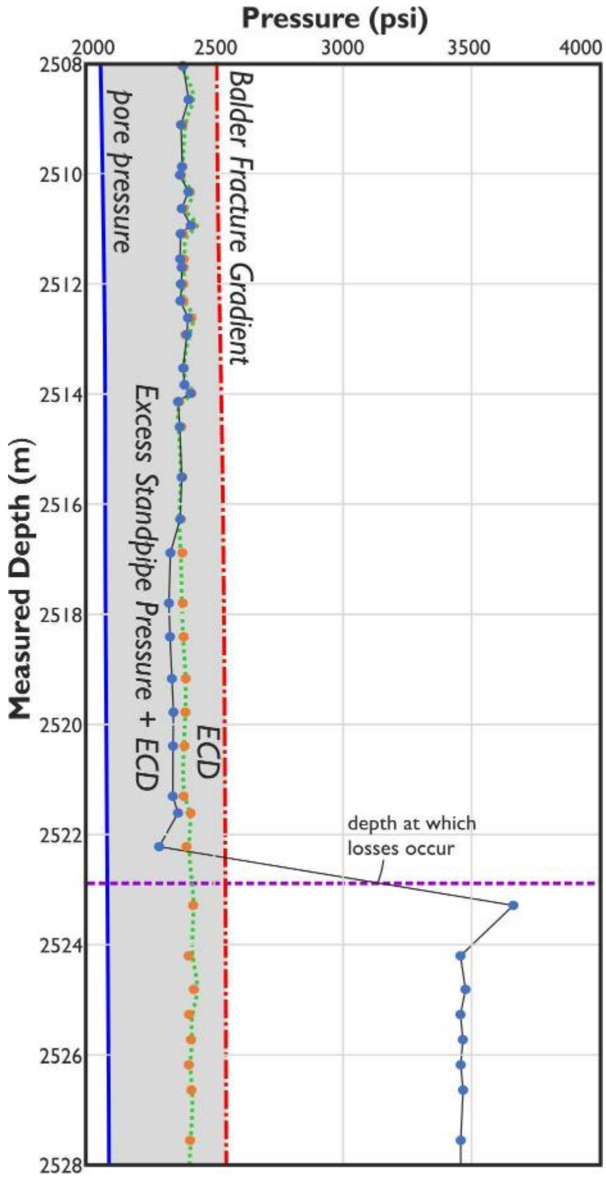

Fig. 12. Drilling window plot for well 213/26-1z with geomechanical explanation behind drilling induced fractures within the Balder Formation. The mud pressure (the ECD, in ppg) is not set

sufficiently high to induce fractures within the Balder Formation (i.e. it is below the regional Balder fracture pressure gradient). However, when the observed marked increase in standpipe pressure (called the *Excess Standpipe Pressure* in this plot) is combined with the ECD, then this pressure would exceed the anomalously low fracture pressure gradient of the Balder Formation around the Corona Ridge, at the exact depth where the losses occur.

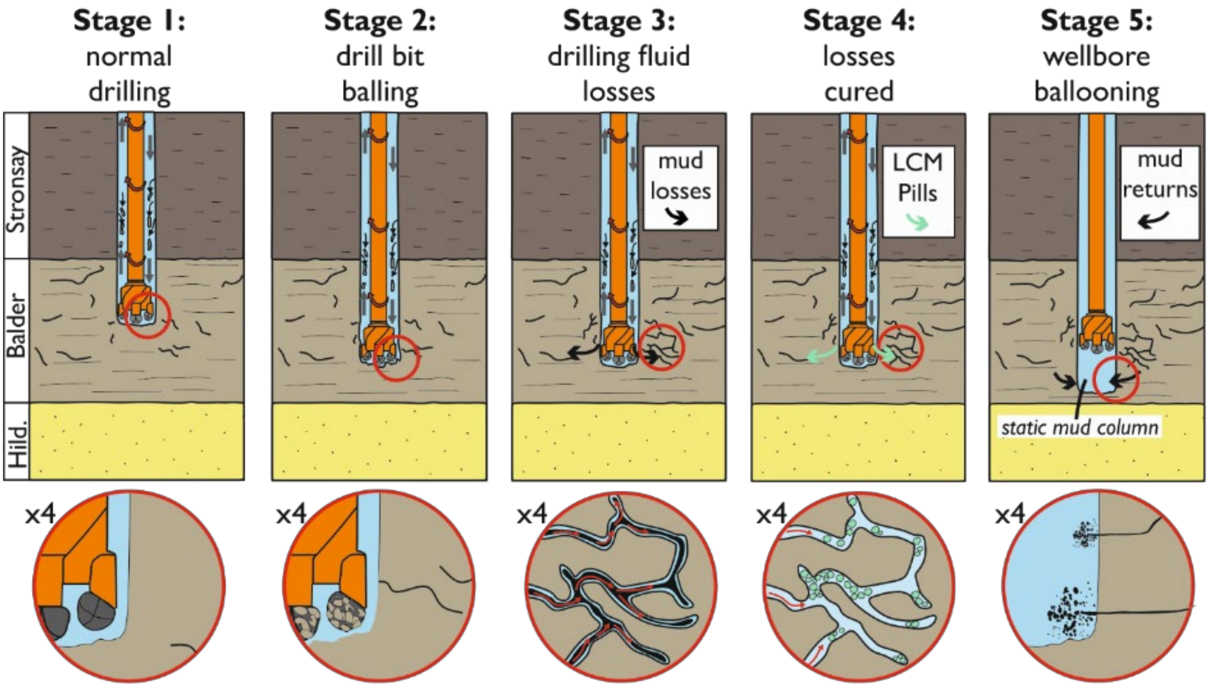

Fig. 13. Sequence of events leading to drilling issues encountered in the Balder Formation along the Corona Ridge. **Stage 1** represents normal drilling conditions, though by **Stage 2** the Balder Formation begins to react with drilling fluid and balls the drill bit, clogging the nozzles at the front of the bit, and leading to plugging of the wellbore above the bit and nozzles (a pack off), trapping pressure below. In **Stage 3** the trapped pressure below the pack-off causes the underlying formation to be subject to shock, causing pressures higher than measured and a drilling enhancement of natural fractures. Drilling fluid is lost to the fractures. These losses are cured (**Stage 4**), and drilling continues, though the drilling mud later returns to the wellbore (**Stage 5**), likely during connections (when more pipe is added to the drillstring) as the only thing holding back the formation fluids (including the drilling fluid lost earlier) is the pressure of the static mud column.

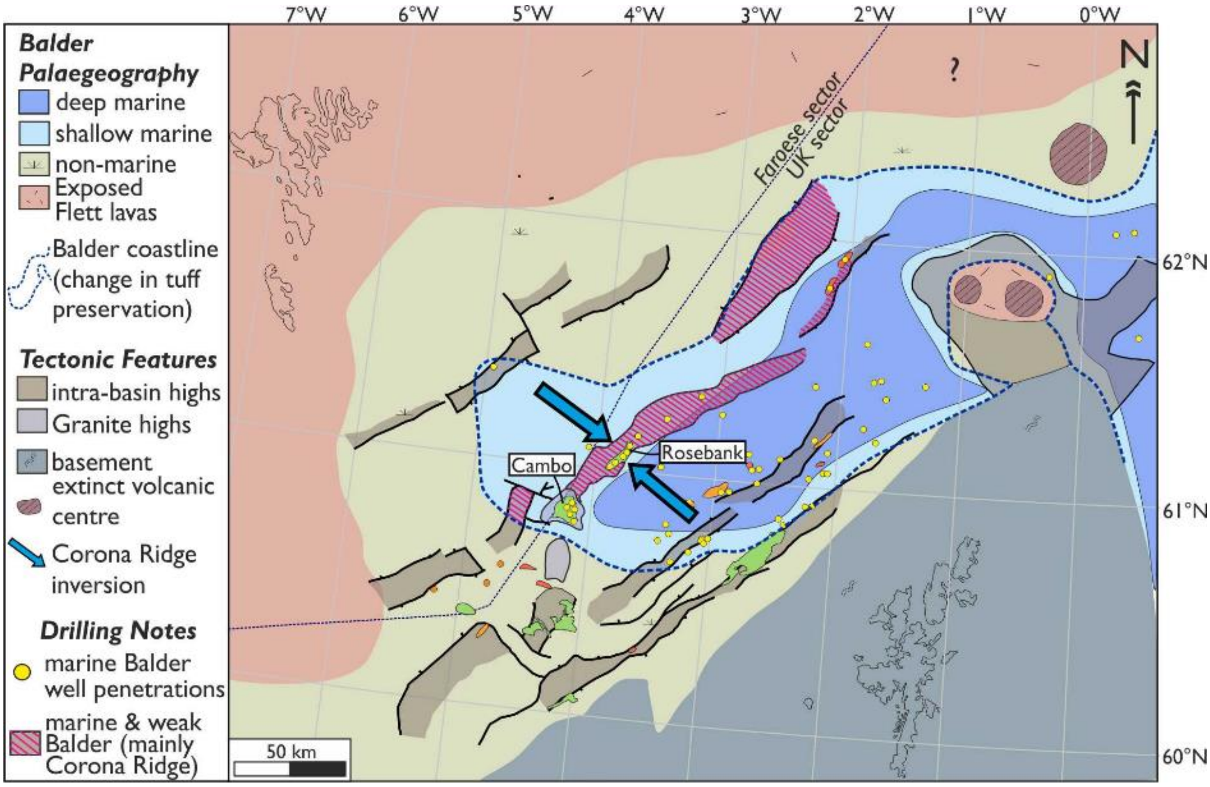

Fig. 14. Balder palaeogeography (adapted from Watson *et al*. 2017) showing areas of high risk of drilling issues through the Balder Formation (dashed red), corresponding to a marine setting overlying the Corona Ridge.

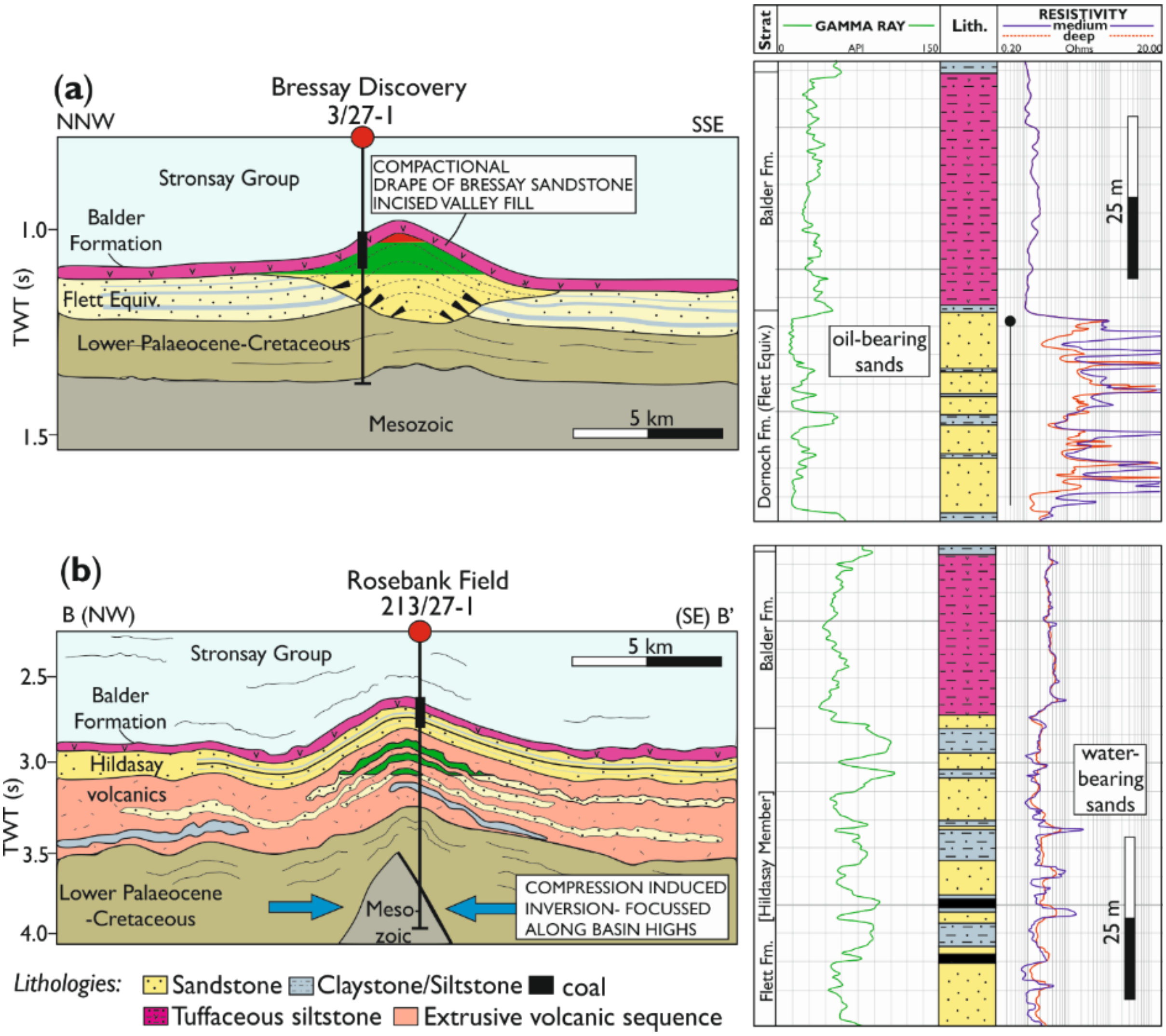

Fig. 15. Geoschematic comparison between the Bressay (a) and Rosebank (b) structures (location of Bressay and Rosebank displayed on Fig. 1). The Bressay structure formed as a result of differential compaction, with the Balder Formation acting as the top seal. In Rosebank, the structure formed tectonically due to regional compression, resulting in horizontal stresses that may have exceeded the fracture gradient of the Balder Formation. This fracture network, and associated permeability, would account for the water-bearing sandstones below the Balder Formation at Rosebank. Bressay cross-section adapted from Underhill (2001).