Overpressure Transmission through Interconnected Igneous Intrusions

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Abstract

In situ overpressures in sedimentary basins are commonly attributed to disequilibrium compaction or fluid expansion mechanisms, though overpressures in shallow sedimentary sequences may also develop by vertical transfer of pressure from deeper basins levels, for example via faults. Mafic sill complexes are common features of sedimentary basins at rifted continental margins, often comprising networks of interconnected sills and dykes that facilitate the transfer of magma over considerable vertical distances to shallow basinal depths. Here we document evidence for deep sills (depths >5 km) hosting permeable, open fracture systems which may have allowed transmission of overpressure from ultra-deep basin (>6-7 km) levels in the Faroe-Shetland Basin (FSB), NE Atlantic Margin. Most notably, well 214/28-1 encountered overpressured, thin (<8 m) and fractured gas-charged intrusions, which resulted in temporary loss of well control. Whilst the overpressures could reflect local gas generation related to thermal maturation of Cretaceous shales into which the sills were emplaced, this would require the overpressures to have been sustained for unfeasibly long timescales (>50 Myr). We instead suggest that transgressive, interconnected sill complexes, such as those penetrated by well 214/28-1, may represent a previously unrecognized mechanism of transferring overpressures (and indeed hydrocarbons) laterally and vertically from deep to shallow levels in sedimentary basins, and that they represent a potentially under-recognised

hazard to both scientific and hydrocarbon drilling in the vicinity of subsurface igneous complexes.

Introduction

Abnormally high pore-fluid pressure, commonly referred to as overpressure, is a common occurrence within sedimentary basins, occurring when the pore-fluid pressure is greater than the hydrostatic pressure expected at a given depth (Osborne and Swarbrick, 1997; Tingay et al., 2007). Encountering unexpected overpressure zones during drilling operations can pose a significant risk to both human life and the environment; such zones can result in an influx of high pressure gas and fluid into and up the wellbore (known as a 'kick'), and in a worst-case scenario a 'blowout' (Grace, 2017). Accurate prediction of pore pressures when drilling hydrocarbon wells fundamentally underlies safe drilling operations; the lack of adequate understanding and subsequent response to higher than expected pore pressures during drilling of the Macondo Well in the Gulf of Mexico was one of the fundamental underlying causes of the blowout that led to the Deepwater Horizon disaster (Board, 2012).

It is generally accepted that overpressure cannot be sustained for long periods of geological time (>50 Ma) within a sedimentary basin, with the overpressure dissipating via fluid leakage (Osborne and Swarbrick, 1997; Swarbrick et al., 2001; Tingay et al., 2007; Luo and Vasseur, 2016). Critically, it is also generally assumed that overpressure exists close to where it is generated (Osborne and Swarbrick, 1997). The transfer of overpressure horizontally or vertically within sedimentary basins has not been widely documented, with a notable exception being Tingay et al., (2007) who demonstrated the likely vertical transfer of overpressure up normal faults within the inner shelf of the Baram Delta, Borneo. Another notable area where such pressure transfer is documented is that of the Northern Carnarvon Basin, Northwest Australia Shelf (van Ruth et al. 2000; Dodds et al. 2001; Tingate et al. 2001).

Here we detail the occurrence of overpressure within igneous intrusions in the Faroe-Shetland Basin, using a combination of subsurface datasets. We propose a new mode of overpressure transfer via inter-connected networks of fractured igneous intrusions. We then discuss the ramifications of such an 'overpressure' transfer mechanism for both hydrocarbon and scientific drilling in sedimentary basins containing extensive igneous intrusions, emphasising the need to plan for the possibility of encountering significantly higher than expected pore-fluid pressures in the vicinity of igneous sheet intrusions.

Geological History of the Faroe-Shetland Basin (FSB)

The FSB is located between the Faroe and Shetland Islands on the Atlantic passive continental margin of NW Europe (Fig. 1). The basin can be sub-divided into a series of SW-NE trending sub-basins and is contiguous with the Rockall Trough to the SW and the Møre Basin to the NE (Hitchen and Ritchie, 1987). The sub-basins consist of Mesozoic to Recent sediments bounded by basement highs comprised of Precambrian crystalline rocks capped by Palaeozoic and Mesozoic sediments (Lamers and Carmichael, 1999). The FSB has undergone several stages of rifting between the Devonian and Paleocene, followed by Cenozoic episodes of inversion (Smallwood and Maresh, 2002; Sorensen, 2003; Ritchie et al., 2011). Critically, the FSB underwent several phases of high magnitude extension during the Cretaceous, as a result of the northwards propagation of the Central Atlantic Rift system (Fleet and Boldy, 1999; Stoker, 2016).

Following the cessation of Cretaceous extension, the FSB experienced considerable igneous activity during the Late Palaeocene-Early Eocene as a result of the impinging proto-Icelandic plume coinciding with continental break-up of the North Atlantic (White and McKenzie, 1989). This igneous activity is expressed by the eruption of extrusive basaltic sequences and the emplacement of a pervasive suite of mafic sills and dykes into the sedimentary basins flanking the NE Atlantic Margin (Fig. 2) (Gibb and Kanaris- Sotriou, 1998, Schofield et al., 2015). Mafic intrusions are identified throughout the FSB where they are collectively termed the Faroe-Shetland Sill Complex (FSSC), and extending northwards into the Møre basin and south into the Rockall Trough (Ritchie et al., 2011; Schofield et al., 2017). Critically the FSSC, and the sills in other Atlantic Margin basins, are observed to preferentially intrude the Cretaceous and Lower Paleocene sedimentary succession, which is predominantly composed of marine shales (Stoker et al., 2016) and represents a significant low-permeability sealing unit (Ogilvie et al., 2015).

Overpressure Development within the Faroe-Shetland Basin

Understanding the interplay of sub-surface pressures and their impact on hydrocarbon generation/migration during basin evolution is essential for any hydrocarbon exploration and has particular importance in the Faroe-Shetland Basin due to the tectonic complexity of the basin (Iliffe et al., 1999). Despite extensive exploration activity in the FSB, a full quantitative analysis of the depth-pore pressure relationships remains poorly documented in the literature. However, some broad conclusions can be drawn about the pressure history of the FSB.

Measured reservoir pressure data show that the majority of the wells in the West of Shetlands region exhibit normally pressured or near-normally pressured gradients (Iliffe et al., 1999; Lamers and Carmichael, 1999; Edwards et al., 2012). However, overpressure is known to occur within Mesozoic sections at depths >3000 m, with lower Cretaceous sequences generally exhibiting the largest formation overpressures (Iliffe et al., 1999; Tassone et al., 2014). The distribution of overpressure within the FSB is, however, not uniform with both normally pressured and overpressured high permeability sands occurring at similar depths. This implies that a complex basin plumbing and fluid drainage system is in operation within the FSB (Edwards et al., 2012). It is generally accepted that disequilibrium compaction, as a result of high sedimentation rates in the Cenozoic, is the dominant mechanism that has created the large magnitude (> 20 Mpa) overpressure within the Mesozoic sections of the FSB (Iliffe et al., 1999).

Overpressured Intrusions

Well 214/28-1 – Flett Ridge

Well 214/28-1, drilled in the FSB in 1984 to a total depth of 5124 mBRT, was designed to test Palaeocene and Jurassic targets. However, the well encountered substantial issues with overpressured mafic intrusions between 4596 mBRT and 5013 mBRT (Fig. 3), which required the expenditure of considerable time and effort to control the overpressure and gas influx (Mark et al., 2017). The intrusions penetrated by Well 214/28-1 form a series of vertically stacked intrusions that extend down towards the centre of the Flett Basin and the base of the Cretaceous sequence (Schofield et al., 2015) (Fig. 2).

Using direct (e.g. Wireline Formation Tester and Repeat Formation Tester) and indirect (e.g. mud weights), pressure data indicates a consistent picture of broadly hydrostatic pressures to depth of ~3200 m within the Middle Paleocene. Below this depth, RFT (Repeat Formation Tester) and MDT (Modular Formation Dynamic Tester) data begin to indicate a departure from normal hydrostatic conditions and occurrence of overpressure, which increased gradually with small deviations (e.g. 4100 mBRT). However, on encountering a 6.1 m thick intrusion at a sub-seabed depth of 4,596 mBRT (Fig. 3, 4, and 5), a large magnitude overpressure was encountered associated with high pressure gas influx into the wellbore and 44% Total Gas (Methane, Ethane, Propane and Butane) (Fig. 4 and 5). Using the static mud weight pressure as a proxy for pore pressure in absence of direct pressure data (e.g. RFT) at this interval (van Ruth et al., 2002), the mud weight had to be increased to control the pore pressure increase and associated gas from around 57 MPa (8,267 Psi; 10.5 ppg) to over 71

MPa (10,296 Psi; 13.1 ppg) (Fig. 4 and 5). On continuation of drilling, two further intrusions where penetrated at 4,788 mBRT and 4,931 mBRT respectively, without any issues (Fig. 5). However, at a depth of 5,013 mBRT, a 7.6 m thick overpressured intrusion was encountered (Fig. 5), with mud weights having to be raised further to counteract estimated pressure of over 82 MPa (11,893 Psi; 13.9 ppg). Associated with this intrusion was 51% Total Gas (Methane), which when expanding at the surface led to mud flowing out over the Kelly Bushing and partial loss of well integrity. After penetration of the 7.6 m thick intrusion, connection gas values remained at 30-45 % even at the increased levels of mud-weight to the base of hole at 5124 mBRT.

Well 219/28-2z – Northern FSB

Well 219/28-2z was drilled in the north east of the FSB and southern extension of the Møre Basin, approximately 20 km northwards of the Margarita Spur. The well penetrated a 36 m thick intrusion at 3148 mBRT (~3.1 sec TWT) (Fig. 6 and 7). On seismic data, the intrusion is poorly imaged due to the deep depth of imaging and inclined (approximately 40°) nature of the intrusion. However, the intrusion can be seen to connect sub-vertically to a series of sills intruded into the lower Cretaceous succession. Although initially, the intrusion (which was associated with a small gas peak ranging from 0.78 to 1.92%), was estimated to have a pore pressure of between 39 Mpa (5706 Psi; 10.5 ppg) and 40 Mpa (5923 Psi; 10.9 ppg), a direct RFT measurement taken at the lower intrusion contact gave a pore pressure measurement of 48 Mpa (6956 Psi; 12.8 ppg) (Fig. 7 and 8) with the well completion report noting "Evidence also indicated that this [high pore pressure] was probably confined entirely to the sill as the adjacent claystone appears to have a substantially lower pressure gradient".

Discussion

Overpressure Generation

Kerogen to gas maturation is regarded as the only fluid expansion mechanisms in which high magnitude overpressure, equivalent to that formed by disequilibrium compaction can be generated (Swarbrick and Osborne, 1998; Tingay et al., 2007). The emplacement of mafic, Paleogene-age intrusions into the Cretaceous claystone sequences of the FSB could lead to gas generation, as a result of localized maturation of organic matter by the intrusions (Aarnes et al., 2010; Muirhead et al., 2017). However, we argue against this mechanism for the overpressure witnessed within the intrusions penetrated in 214/28-1 and 219/28-2Z. Overpressures are inherently unstable, with pore fluid pressures always attempting to return to hydrostatic equilibrium (Osborne and Swarbrick, 1997). If the overpressure was a result of gas generation caused by heating of the host rock by intrusions, this would require the overpressure to have been maintained within the vicinity of the intrusions from the time of igneous activity at ~58 Ma (Schofield et al., 2015). This residence time exceeds the generally accepted upper maximum timescale which overpressure is thought to be sustainable within most sedimentary basins (~50 Myr); for overpressure to be maintained over a longer period, seal permeability would have to be in the range of 10^{-23} to 10^{-25} m^2 (1^{-11} to 1^{-13} Darcy), less than the lowest permeabilities ever recorded in shales globally (Deming, 1994).

Fractures within Intrusions

Exposed sill intrusions are often pervaded by open fractures, in the form of cooling joints (Senger et al., 2015). However, because of the unloading associated with the exhumation of such intrusions to contemporary surface levels, it is often difficult to assess whether open fractures visible in surface outcrops (e.g. Senger et al., 2015), would still be open and interconnected in deeply buried intrusions.

Direct constraints on the physical properties of in situ subsurface igneous intrusions (i.e. those that have not undergone any substantial tectonism or uplift and are close to their emplacement depths) are often sparse. However, within the FSB, there are several lines of evidence indicating that igneous intrusions contain open and interconnected fracture systems, even at deep basinal levels (>5 km).

Multiple intrusions encountered within the FSB have caused substantial mud losses during drilling (Rateau et al., 2013; Mark et al., 2017). In an extreme case, nearly 4 million litres (~7 tonne) of drilling mud was lost into a 60 m thick, fractured intrusion in the FSB (208/15-1A; Mark et al., 2017). In total, of the 29 wells that have encountered intrusions in the FSB, >80% have suffered some degree of mud loss when drilling through intrusions (Rateau et al., 2013; Mark et al., 2017).

Additionally, open fractures within intrusions along Atlantic Margin have been inferred to control the location of oil/gas accumulations (e.g. Tormore Field), by acting as migration 'super-highways' through low permeability Cretaceous sequences (Rateau et al., 2013; Schofield et al., 2015; Schofield et al., 2017). In Svalbard, the intrusions and surrounding contact metamorphic aureoles have been inferred to control fluid flow and gas escape structures adjacent to intrusions on the seafloor (Senger et al., 2013).

The open nature of fractures within subsurface igneous intrusions, even at depth, can be substantiated directly, when available, from borehole image resistivity logs (e.g. FMI, GeoXplorer, AFR, OMRI). In Figure 9, a FMI log through an igneous intrusion encountered at 3265 mBRT within the subsurface shows clear evidence of open fractures within a 27 m thick intrusion. Additionally, core obtained from intrusions within the FSB have also been shown to contain open natural (i.e. not induced by drilling) fracture sets (Rateau et al., 2013).

Associated with the fractures observed in the FMI log in Figure 9 is an increase in separation between the logged medium and deep resistivity within the wireline logs. In the areas of clear fracturing on the FMI Log (Fig. 9), the medium resistivity, which measures the physical properties of rocks close to the wellbore (~1.5 m), is lower due to the invasion of the water based mud into the sill via the fractures (thus reducing resistivity). The deep resistivity, however, remains high as it is measuring the virgin formation further away from the borehole where the formation has not been invaded by the water-based mud. Using this resistivity separation relationship, it is possible to infer the presence of fractures in other igneous intrusions within the subsurface where FMI logs, or core are not available.

In the case of well 214/28-1, FMI logs are not available, but within the suite of intrusions that overpressure was encountered (Fig. 5), a clear separation in resistivity is visible within two of the sills implying open fractures within the intrusions exist in the sills at this depth. Interestingly a large separation is not visible within the two overpressured intrusions (detailed previously) that where encountered at 4,596 mBRT and 5,013 mBRT (Fig. 5). This lack of resistivity separation is most likely the result of the drilling mud being unable to invade into the fracture network of the intrusion, due to the outward force of the high-pressure gas that was exiting from the fractures into the wellbore, thus preventing the resistivity contrast. Within well 219/28-2Z, the resistivity separation appears to indicate clear fracturing within the intrusion where the elevated pore pressure was recorded (Fig. 7).

In summary, a broad array of direct subsurface evidence, such as loss of circulation events, image and resistivity logs, confirms the presence of extensive, open fracture networks within many igneous intrusions at sub-seabed depths of up to at least 5 km within the FSB.

The intrusions within the FSB have never been exhumed or substantially uplifted since their emplacement, and therefore this suggests fractures formed at depth, probably the result of normal cooling and contractional processes within the intrusions at the time of emplacement (Bemudez and Delpino, 2008). When the fractures became open is more difficult to assess and still unclear, although compressional inversion did occur within the FSB from the Miocene-Oligocene, mainly focused along major basin bounding faults (Ritchie et al. 2008).

However, what is demonstrably clear is that within the FSB (and presumably other sedimentary basins), even at deep basinal levels within impermeable sequences (e.g. Cretaceous along the Atlantic Margin), fracture pathways can be open within intrusions which have never been exhumed or undergone major tectonic activity.

'Overpressure' transmission via fractured sills

Igneous intrusions within sedimentary basins often form highly interconnected complexes; Cartwright and Hansen (2006) astutely documented this phenomenon on the Norwegian Margin, showing a complex of interconnected sill intrusions extending over 12 km vertically and 20 km horizontally. Similar, highly interconnected complexes of mafic intrusions are also observed in the FSB (Schofield et al., 2015) (Fig. 2)

In the specific case of the intrusions penetrated by well 214/28-1, seismic reflection mapping shows that the overpressured intrusions form part of a larger, interconnected intrusive complex that can be traced toward the centre of the basin, rooting at depths >6 km (Fig. 10) (Schofield et al., 2015; Mark et al. 2017). A continuous path can be traced from the 6 m thick overpressured intrusion penetrated by well 214/28-1 at 4,596 m, via the interconnected intrusion to over 6 km in depth (Fig. 10).

In well 219/28-2Z, the overpressured sill can be seen to be connected from ~3148 mBRT, where it was penetrated by the well to a saucer shaped intrusion situated in the lower Cretaceous at a depth of ~4300 mBRT (Fig. 6). The saucer-shaped intrusion can be seen to be connected to a further inclined intrusion that extends down to a depth of ~7 km within the lower Cretaceous (Fig. 6).

Therefore, given the interconnected nature of intrusions, coupled with the evidence supporting the occurrence of open fracture systems within the intrusions, it seems plausible that intrusions may act as fractured conduits, hydraulically connecting separate pressure regimes within a basin. This would lead to apparent 'overpressure' if intersected within the subsurface, even though the overpressure is the result of pressure transmission from a deeper sequence.

A common concept used to explain the presence of overpressure within reservoir sand units is that of the centroid (Fig. 11) (Traugott and Heppard, 1994; Swarbrick and Osborne, 1998), where lateral pressure transference occurs through a sand body which has become inclined (Swarbrick and Osborne, 1998). The centroid is the depth where the pore pressure in the reservoir and bounding shale are in equilibrium, above the centroid, the pore pressure in the reservoir is higher than that of the bounding shale. Below the centroid, the reservoir pressure will be less than the surrounding shale (Traugott and Heppard, 1994). Tingay et al. (2007) adapted this concept to illustrate that overpressures could be transferred if an overpressured compartment comes into hydraulic communication with another less pressured and isolated compartment either by cap-rock fracturing or active faulting.

In the case of the abnormally pressured intrusions within wells 214/28-1 and 219/28-2Z, both suites of intrusions were penetrated by the wells situated near to the intrusion tip and therefore the shallowest depth of the entire intrusive complexes, which can be seen to have climbed sub-vertically, cross-cutting the stratigraphy over distances >1 km. Given the known overpressure that occurs within the shale-dominated Cretaceous succession of the FSB (Illiffe et al., 1999), it seems plausible that transference of pressure is occurring through the fractured intrusions, under a similar mechanism as proposed by Tingay et al. (2007). However, whereas the models of Tingay et al. (2007) and others are primarily concerned with generally sub-vertical to vertical transfer of overpressure, because of the highly interconnected, laterally extensive nature of the intrusive complexes, overpressures in the FSB could potentially be transferred laterally (and vertically) through a basin up to 10's of km's away from its point of origin. Additionally, unlike the concept of the centroid, which relies on recent tilting of the sand body to produce differential pressures, in the case of intrusions, it is their cross-cutting nature and tendency to intrude sub-vertically which leads to the pressure transfer and drainage (Fig. 11).

It is important to acknowledge that open fracture systems within intrusions are not universally prevalent within the FSB, and fractures can often be infilled by later fracture filling cements (Rateau et al. 2013). Additionally, even if fractured, not all intrusions will carry overpressure. Out of the 29 wells which drilled intrusions within the FSB, only two of the wells, listed in this study, penetrated intrusions that had overpressure associated with them. Even within well 214/28-1, over the space of only 600 m, two sills appeared to be transmitting overpressure, whereas two others were drilled through without any issues or abnormal pressure (Fig. 5), despite appearing on the seismic data as all being part of the same family of inclined intrusions (see Fig. 3).

For an intrusion to become overpressured in the subsurface, it must satisfy several criteria. It must contain an open an extensive fracture network, be connected into a deeper pressure regime, and also be sealed by a suitable sealing lithology. If the intrusion intersects a permeable sand sequence, the overpressure will potentially bleed off into that sequence.

Drilling Hazards: Are there safety and potential environmental issues with Hydrocarbon and Scientific (IODP) exploration in volcanically-influenced basins?

Accurate prediction of subsurface fluid pressures is a critical element of oil industry drilling, underpinning the design of safe wells (Board, 2012). Pressure control within a well consists of two main methods; the first is the primary barrier, which is the weight of the drilling mud within the wellbore, which counters the upward force of the pressure at depth. However, in the event of encountering abnormal subsurface pressures, the secondary barrier, or Blowout Preventer (BOP), which consists of a series of valves and other devices, can close off the well bore, whilst at the same time resisting the upward pressure emanating from the well bore (often thousands of Psi). This secondary barrier is critical, as increasing the mud weight by adding dense material and chemicals to counteract abnormal pressure takes time to circulate and equalise the pressure in the well. Critically, pore pressure prediction underpins the well design. For example, the maximum pressure tolerance of a blowout preventer, and even the amount of barite and other chemicals kept on board a drilling rig to enable a rapid change in mud density, are all reliant on predicting the pressure at a given depth. In mature basins, such as the North Sea, UK, or established areas of the Gulf of Mexico, where abundant primary well data exists, such prediction is generally well constrained, but in frontier areas, with sparse well control, pore pressure prediction can be highly challenging.

Hydrocarbon exploration wells are designed to be able to deal with (within a given tolerance) excess pore pressures. Scientific drilling, such as IODP expeditions utilising the JOIDES Resolution, are generally drilled with open hole condition, meaning no primary (other than seawater) or secondary barrier exists to contain a potentially overpressured zone of fluids. The risk of encountering sub-surface overpressure on IODP expeditions drilling in such conditions is usually minimised as zones of known potential overpressure (e.g. accretionary wedges; Westbrook and Smith, 1983) are avoided, and many expeditions target the seabed to shallow targets, which can be assumed to be in hydrostatic equilibrium from seabed to the eventual termination point of the well. However, IODP drilling in basins effected by volcanism may be at risk from intersecting intrusions connected to a deeper pressure regime, especially in deeper targets (>1000 meters below sea floor), where the strength of host rock and sealing capacity may be sufficient to support overpressure connection via an interconnected intrusion to a deeper pressure compartment.

The maximum overpressure that can occur at a given depth is reliant on the sealing capacity of the host lithology in which an overpressured body is situated (Cartwright et al., 2007). The most effective lithologies at containing pressure are those with low permeabilities, including shales and mudstone.

The maximum overpressure that can be supported by a rock unit can be expressed in terms of the fracture gradient of the host rock (e.g. Fig. 4), beyond which hydraulic fracturing will take place and any overpressure can be assumed to dissipate. Following this scenario, a well being drilled in a sequence containing interconnected sill complexes, may have only planned to go to a depth of e.g. 4,000 mBRT. However, if a fractured intrusion that is part of an interconnected complex plumbed into a deeper overpressure zone was penetrated, a overpressure magnitude up to the fracture gradient of the host rock could be encountered (Fig. 12).

If during planning of the well, this scenario has not been identified, then the well design may not have the inbuilt tolerances to resist and deal with the abnormal pressures, leading to a worst-case scenario of a blowout, which brings a substantial risk to human life and the environment, as was seen in the Deep Water Horizon.

Recommendation for both Scientific (e.g. IODP) and Hydrocarbon Drilling

Sill intrusions have a fundamental underlying geological relationship in terms of thickness that directly impacts on their ability to be imaged successfully using seismic reflection data. From studies of both well and field data, around 60% of intrusions fall under 10m in thickness within sedimentary basins globally (Button and Cawthorn, 2015, Schofield et al. 2015; Mark et al. 2017; Eide et al. 2018; Svensen et al. 2018). This aspect, on its own may not appear significant, but when it is considered in the context of the limitations of imaging of seismic reflection data, this can become an issue. Vertical seismic resolution in seismic surveys is typically in the range of 10's of metres (Cartwright et al. 2005), and at deep basin levels, e.g. 3-4 km's, vertical resolution can drop to 40-80m range (Schofield et al. 2015). The aspects of thin sills and limited seismic resolution, combine to create an unfavourable scenario where many of the intrusions within the subsurface will possess thicknesses which fall well below the ability for them to be imaged or even detected within seismic reflection data (Schofield et al. 2015; Mark et al. 2017). In the case of potential pressure transmission via intrusions, this is troublesome, as it means that even if intrusions cannot be confidently interpreted from seismic reflection data in the vicinity of a well, they may still be present. This is illustrated in well 214/28-1, where the pressure kicks emanated from intrusions that were 6 and 7.3 m thick respectively.

Even on the most recent, high resolution seismic reflection data (Fig. 3), although the sills can be detected, their thin nature means that without the benefit of 'hard data' from well 214/28-1 to differentiate the bodies as intrusions, it would be extremely hard to identify them in a pre-drill scenario.

In areas containing pervasive subsurface intrusions, mitigating and predicting the risk of which intrusions may be fractured and overpressured is challenging. Detailed seismic mapping of intrusions may indicate deep connectivity, allowing some degree of mitigation during the well planning phase. During drilling activities, look-ahead resistivity tools (Constable et al., 2016) have the potential to alert drillers to the presence of sub-seismic intrusions before they are encountered. However, look-ahead resistivity tools are in a fledging stage of development (Constable et al., 2016) and there is a paucity of data on the look-ahead resistivity response of intrusions to permit assessment to whether an intrusion is either fractured, not fractured or fractured and overpressured.

In both scientific and commercial drilling operations in basins affected by intrusive volcanism, decisions should be underpinned by the recognition that the majority of intrusions will not be visible on seismic data, and that intrusions in the region of a few metres are potentially capable of pressure transmission (Schofield et al. 2015; Mark et al. 2017).

Conclusions

We have detailed the occurrence of overpressure within intrusions of the FSB, and propose a new mechanism for overpressure transfer within sedimentary basins, namely the lateral and vertical transmission of pressure via vertically interconnected, fractured igneous intrusions. This mechanism is previously unrecognized and may represent a significant hazard to both scientific (e.g. IODP) and hydrocarbon drilling in the vicinity of interconnected transgressive igneous intrusive complexes.

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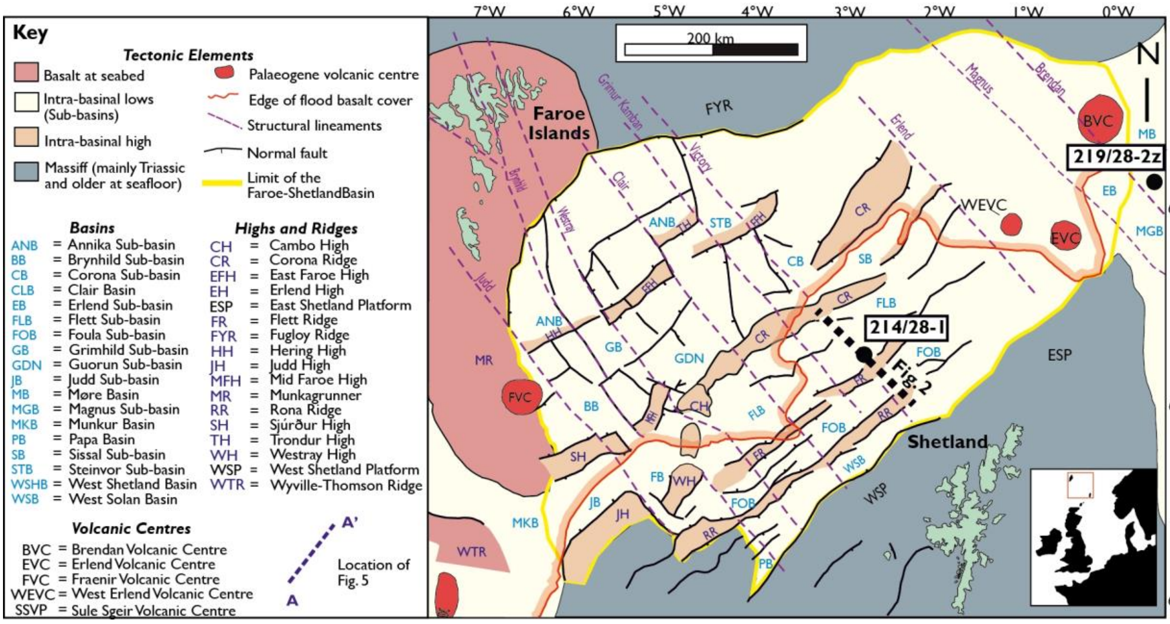


Figure 1 - Tectonic elements of the Faroe-Shetland Basin. Adapted from Ellis et al. (2009), Mudge (2014), Watson et al. (2017) and Hardman et al. (2018a,b). Wells that contain evidence for overpressured intrusions are labelled.

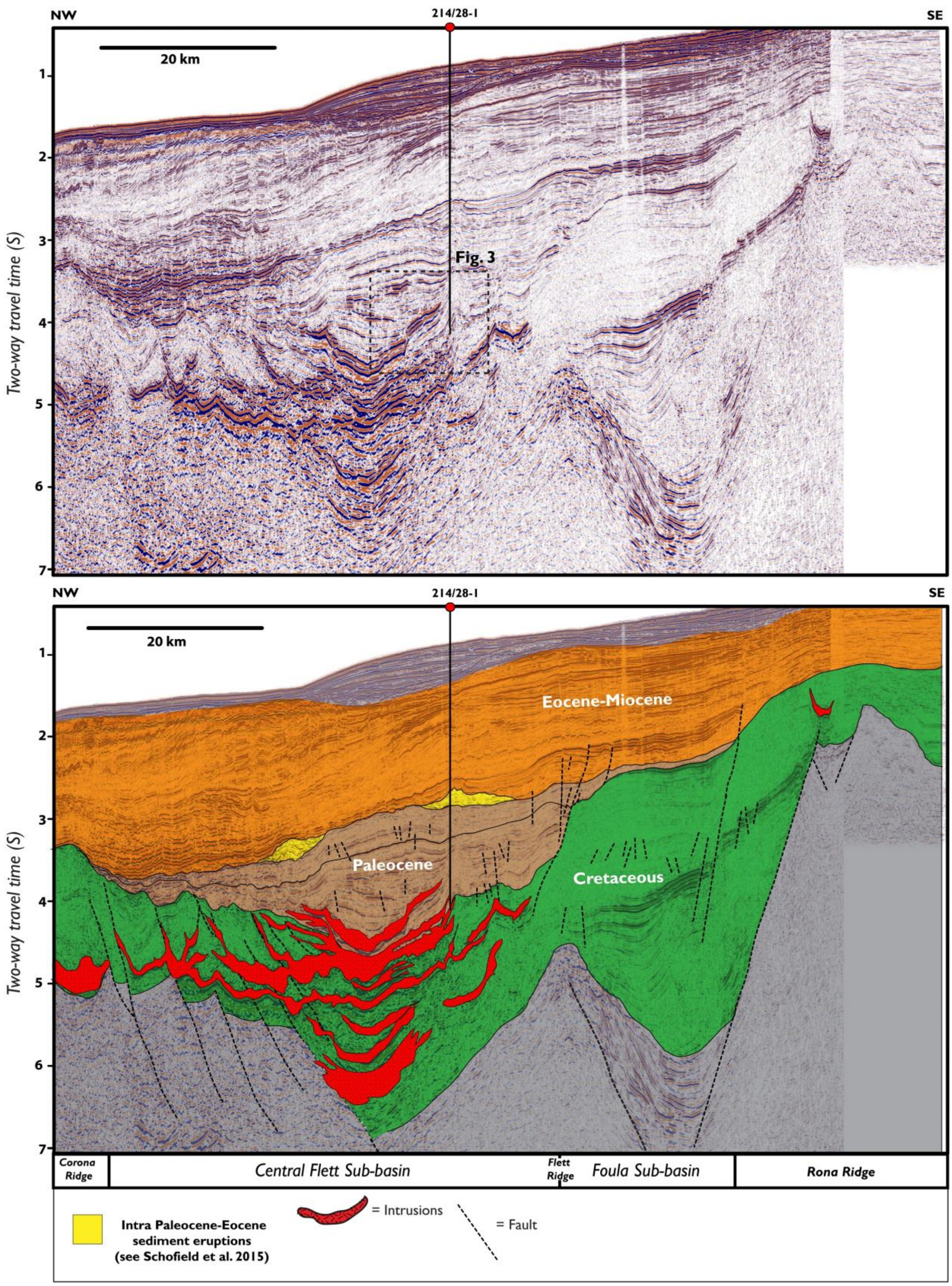


Figure 2 - Regional seismic line through well 214/28-1, modified from Schofield et al. (2015).

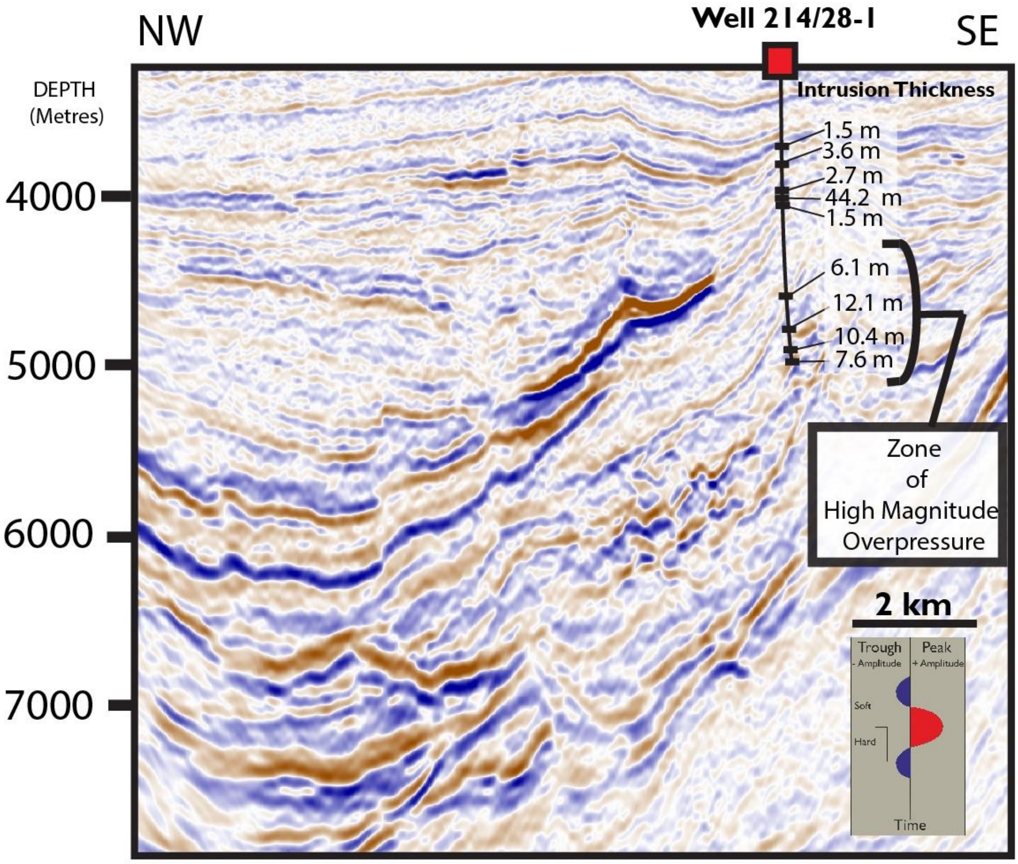


Figure 3 - Seismic line through Well 214/28-1 located in the Faroe-Shetland Basin, offshore NW Scotland. The seismic line is from a 3D cube acquired 2011-2012 and reprocessed to Pre-Stack Depth Migration in 2016. The lower zone of intrusions, where overpressure was encountered (Fig. 4), extend in a down-dip direction towards a depth of ~ 6.5 km.

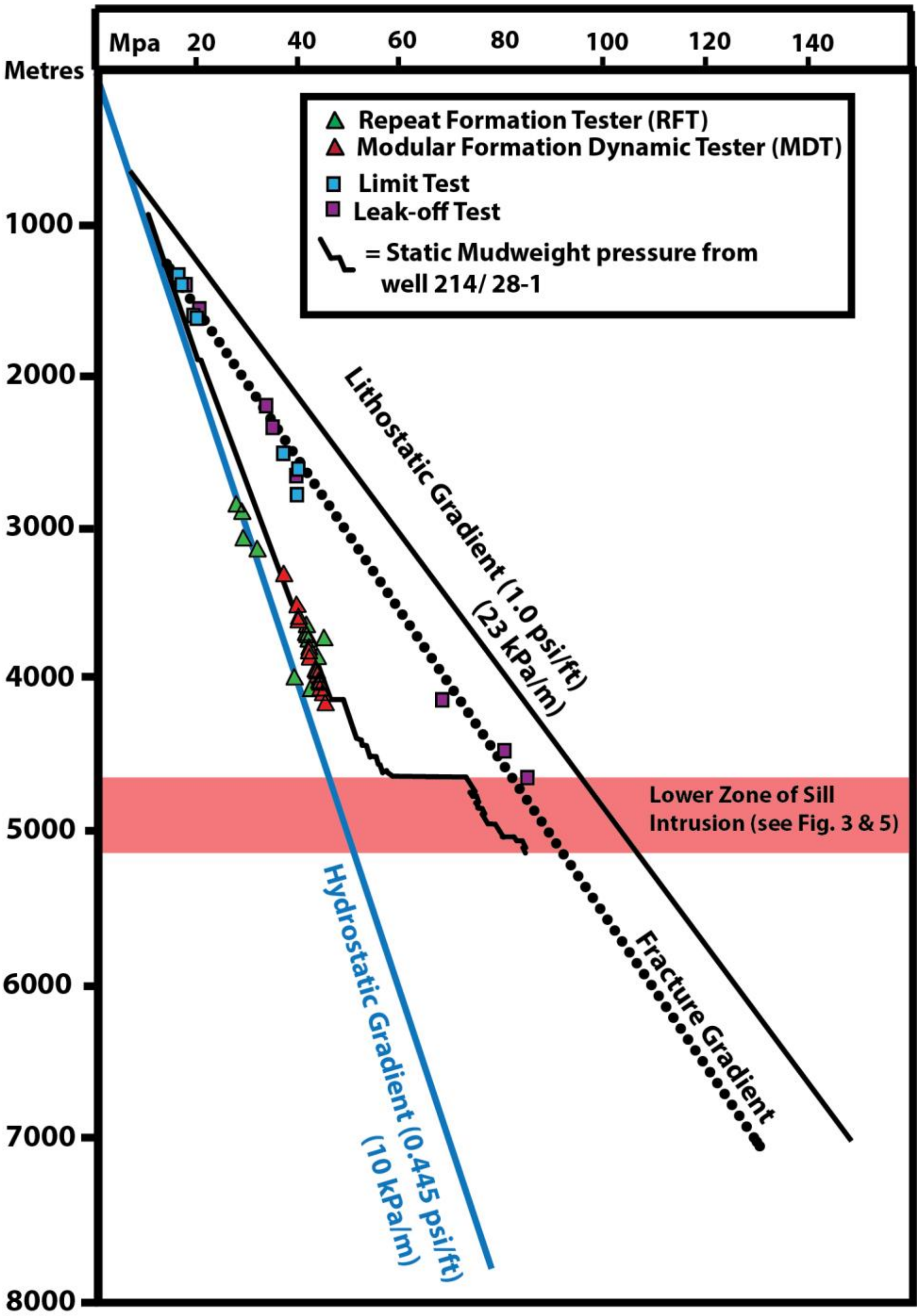


Figure 4 - Pressure vs depth plot. Direct pressure data (e.g. RFT) from well 214/28-1 and well 214/27-1 (located 10 km away, that penetrated same stratigraphic succession).

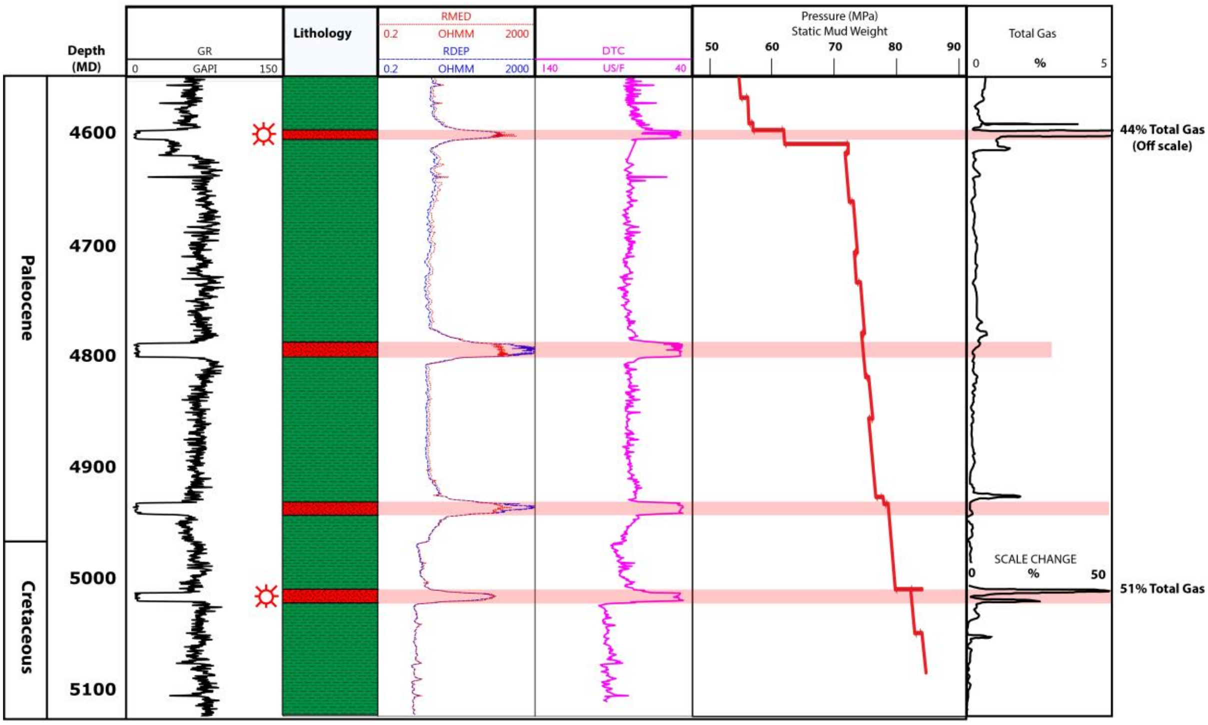


Figure 5 – Diagram showing log responses, static mud weight (MPa) and total gas from the lower zone of intrusions where overpressure was encountered in well 214/28-1.

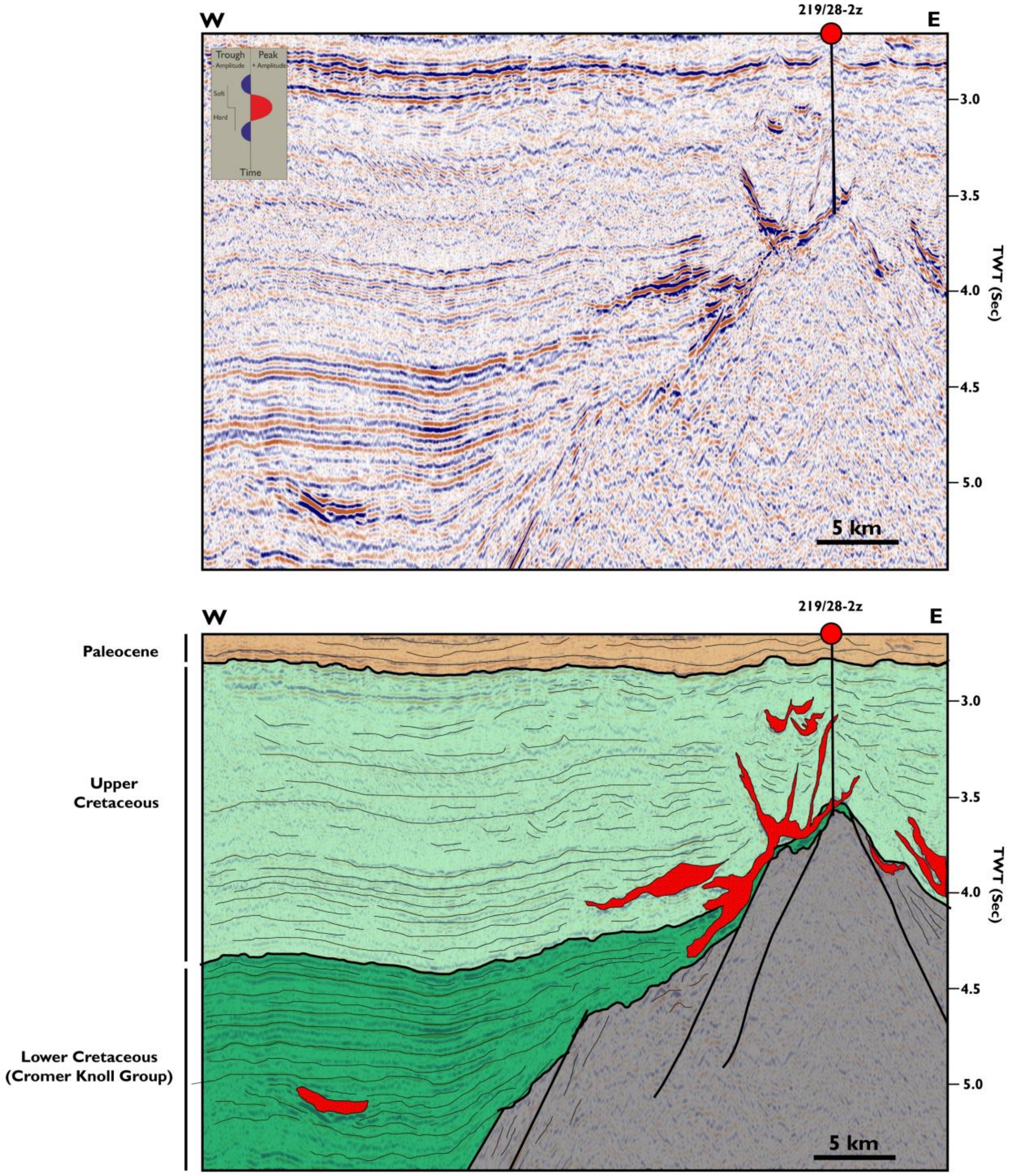


Figure 6 – 2D seismic line (NS92202) across Well 219/28-2z, showing inclined intrusion which was penetrated at 3048 mBRT (~ 3.1 sec TWT).

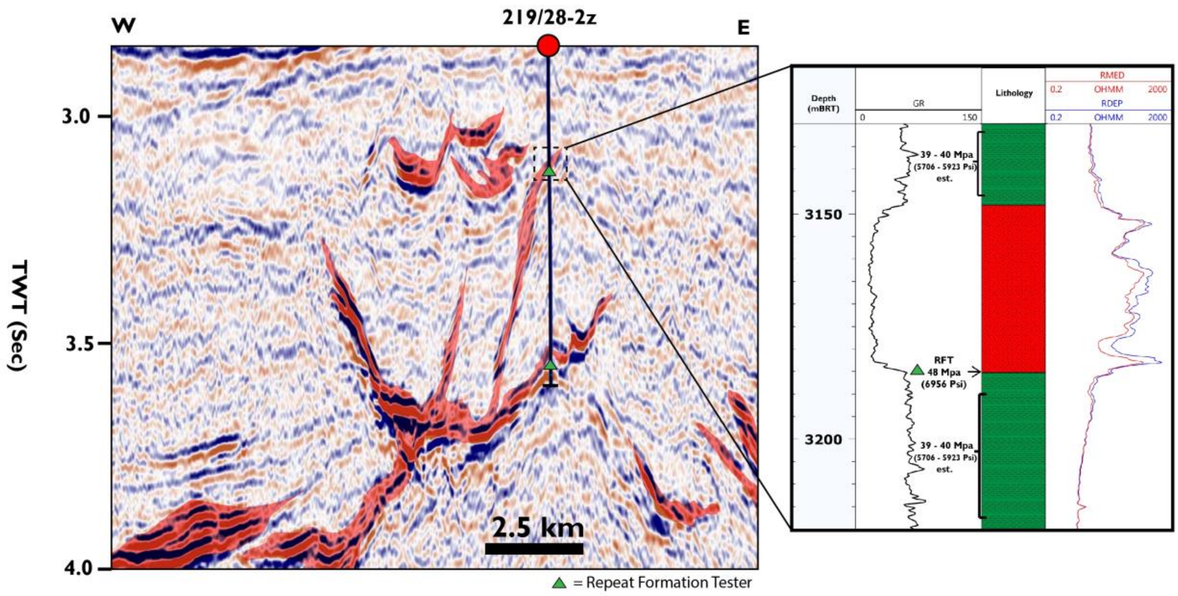
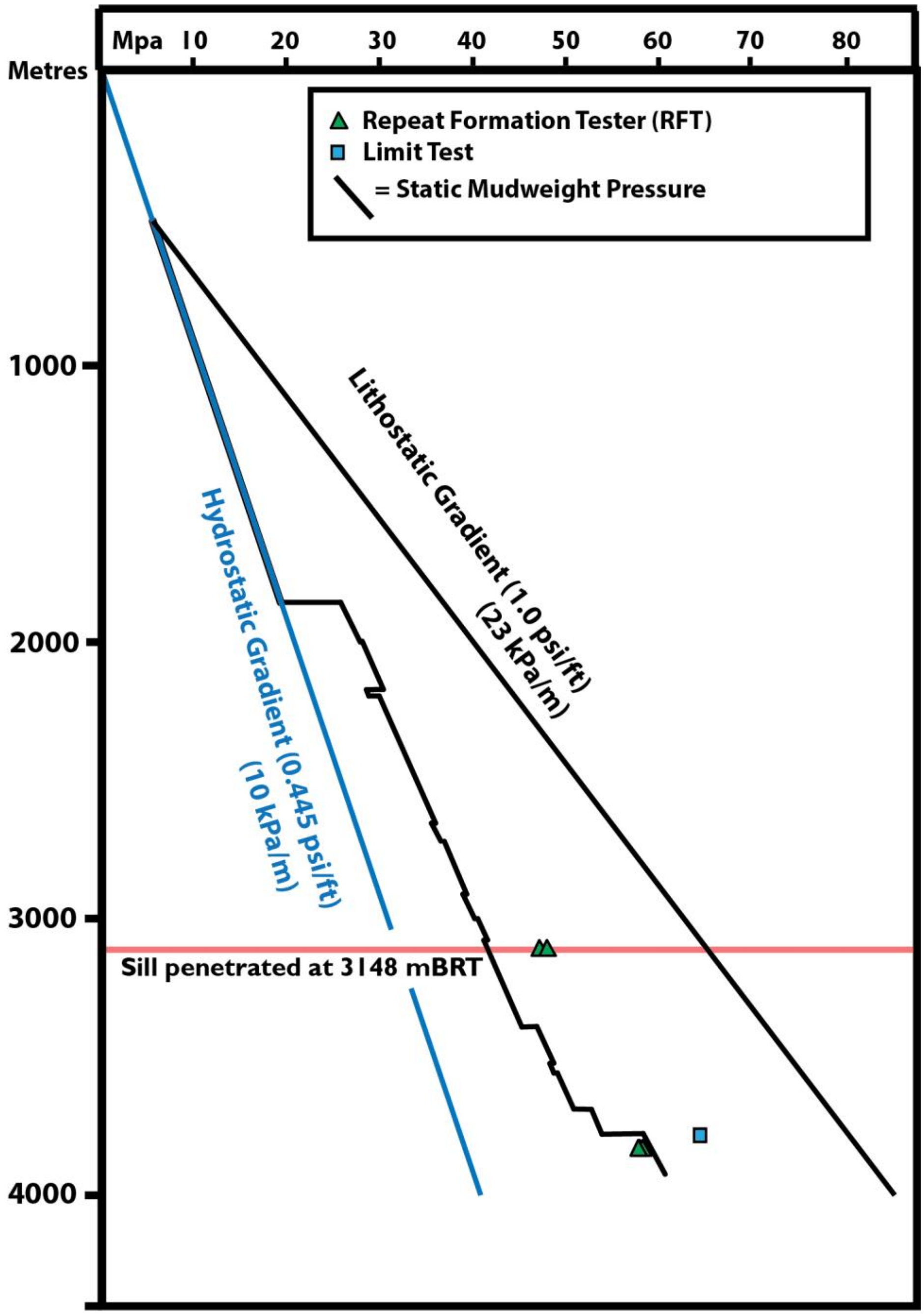


Figure 7 – Detail of a sill penetrated at 3148 mBRT. An RFT measurement taken at the sill edge recorded a pressure of 48 Mpa (6956 Psi), some 8 Mpa higher than the surrounding sequences. This pressure was equivalent to that recorded in RFT measurements at the base of the well (see main text for details). This suggests that the sill penetrated at 3150 m was in pressure communication with deeper units.



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559 **Figure 8** – Pressure vs. Depth plot for well 219/28-2z
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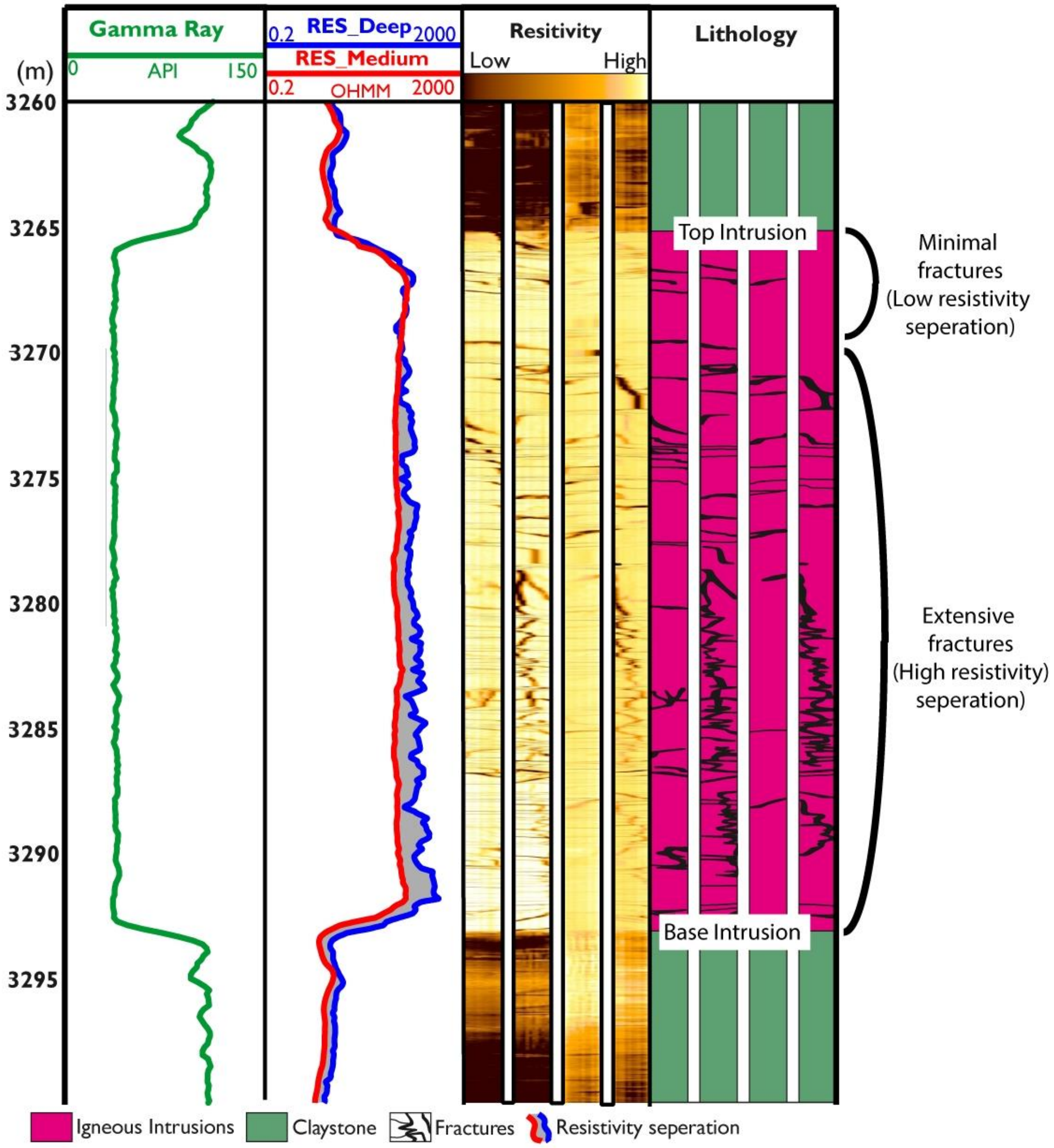

Figure 9 - Wireline and FMI log through a 27 m thick igneous intrusion located within the Faroe-Shetland Basin (213/27-2). Clear fractures can be observed within the intrusion on the FMI log. We interpret the sub-vertical fractures, which extend >30° around the circumference of the hole, to be primary cooling fractures and not drilling induced, as no sub-vertical fractures are seen in the weaker shales horizons above and below the intrusion, and no change in mud weight occurred while drilling from the shale through to the intrusion. Note the increased separation of the Deep and Medium Resistivity wireline measurements within the heavily fractured area of the intrusion (from 3270 m down), and how this separation is greatly reduced within the zone of minimal fracturing towards the top of the intrusion and within the claystone sequence.

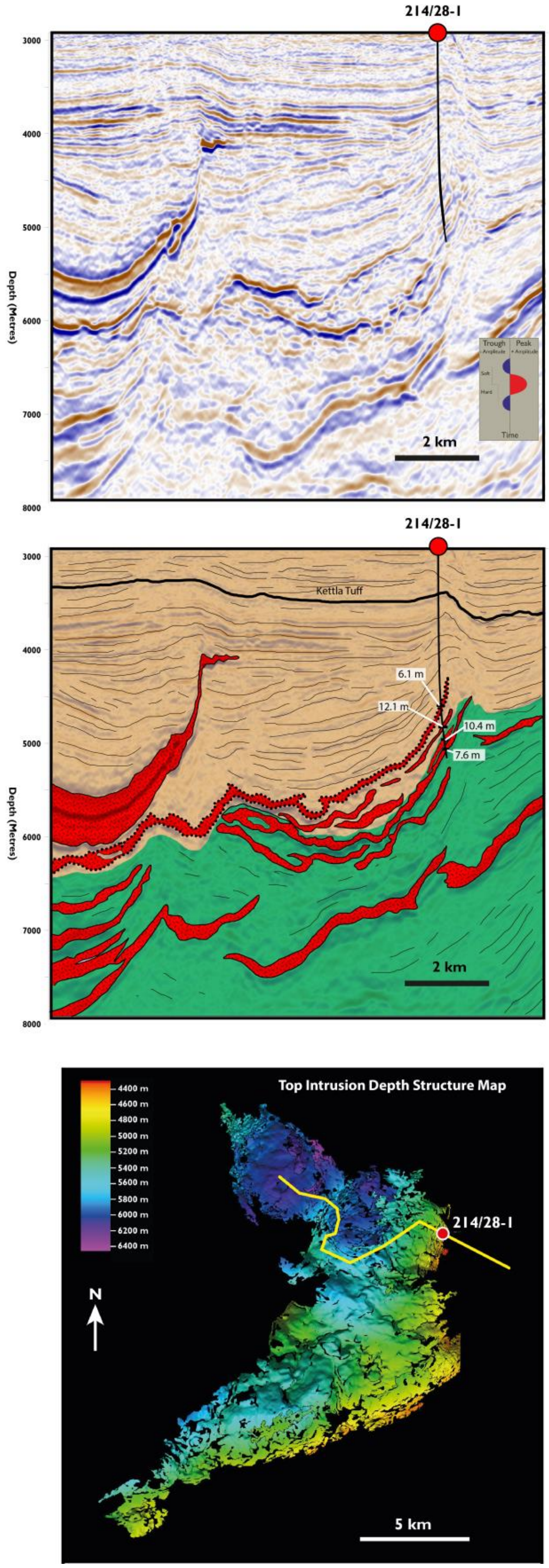

Figure. 10 – Seismic Line through the 6.1 m thick intrusion penetrated by 214/28-1, highlighting the continuous path that that can be traced vertically and horizontally through the intrusive body from point of intersection at 4,596 mBRT to a larger intrusive complex at depths >6 km.

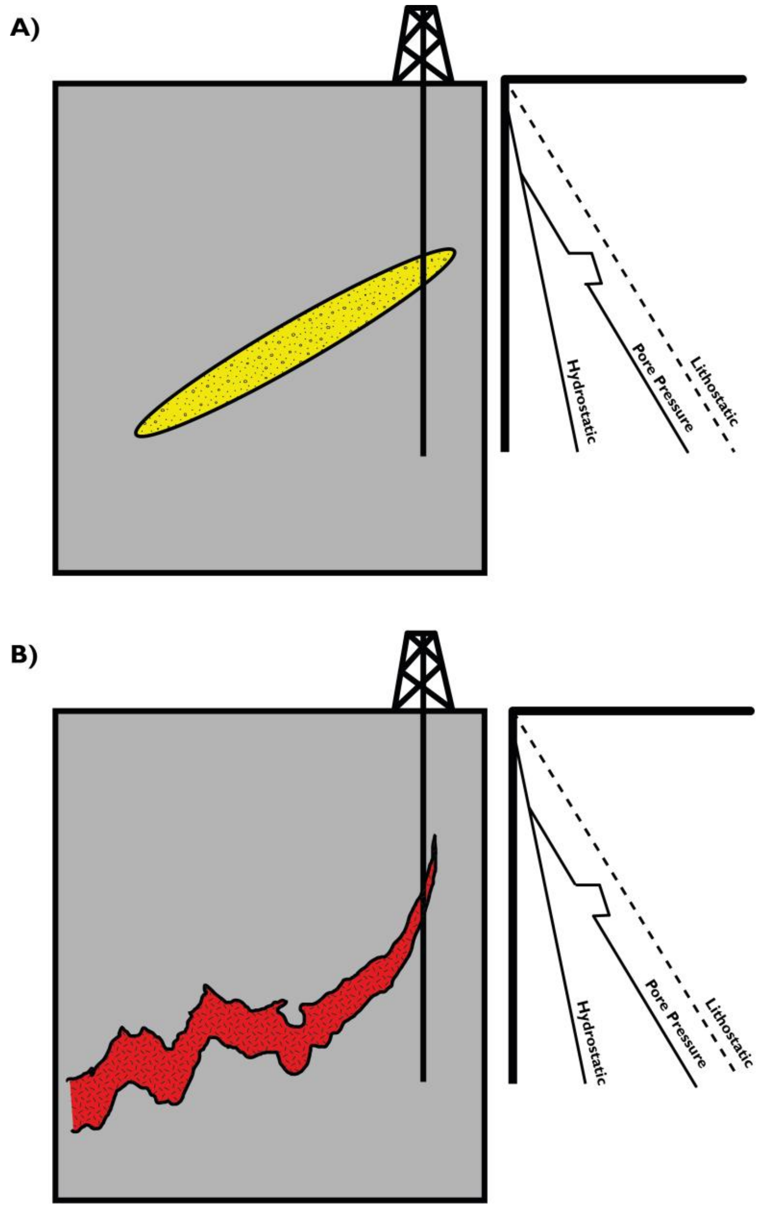

Figure 11 A) Diagram showing concept of the Centroid, which is commonly used to explain overpressure within sand bodies as a result of becoming inclined post-deposition (see Traugott and Heppard, 1994; Swarbrick and Osborne, 1998) **B)** The modified concept of lateral drainage through a fractured intrusion. It is important to note that unlike the concept of the centroid, which relies on recent tilting of the sand body to produce differential pressures, in the case of intrusions, it is their cross-cutting and tendency to intrude sub-vertically which leads to the pressure transfer and drainage, if connected at depth to more overpressured units.

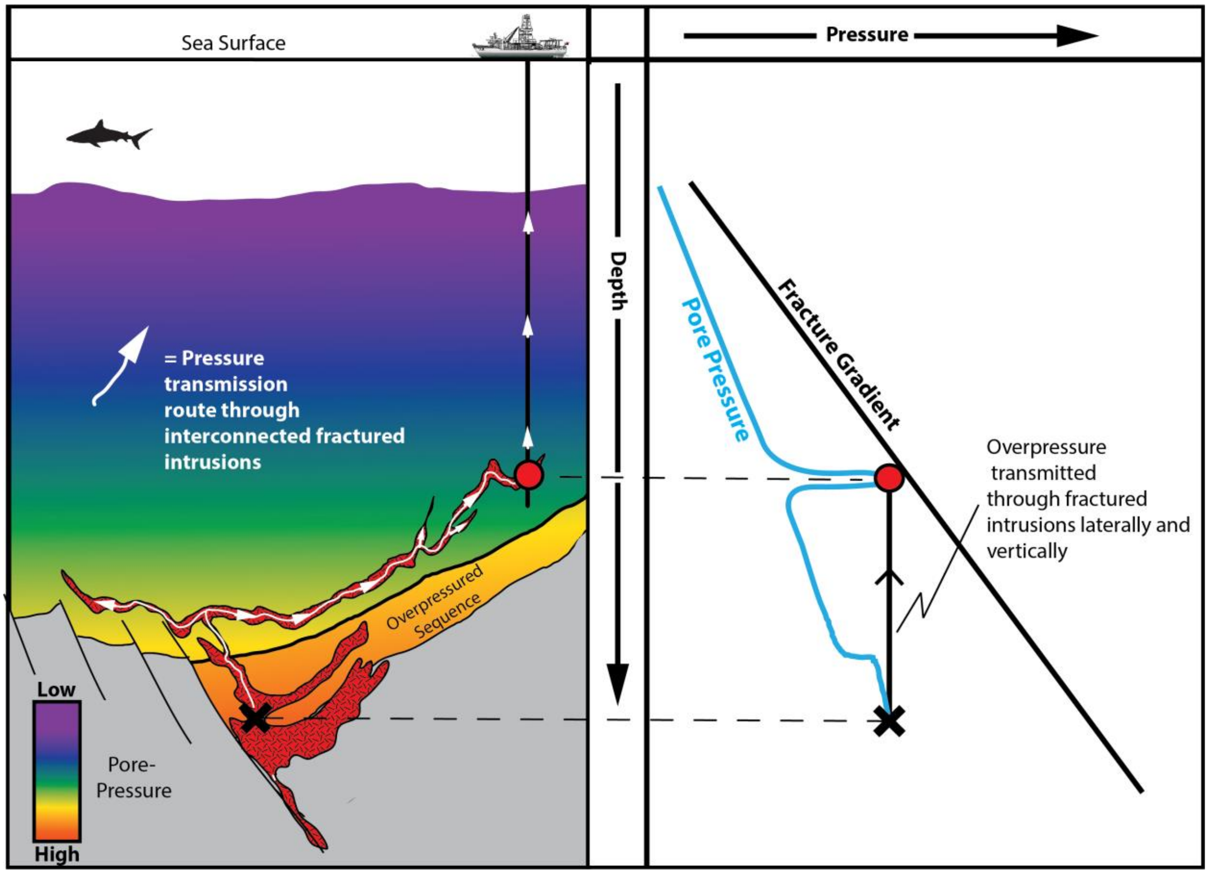

Figure 12 - Conceptual diagram showing the principle of pressure transmission through a fractured igneous intrusive complex. Such a process can lead to overpressure being transferred laterally (and vertically) through a basin 10's of km's away from its point of origin.