Overpressure transmission through igneous intrusions: An unrecognized drilling hazard in volcanic affected basins?

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SUMMARY

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 basin 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 dikes that facilitate the transfer of magma over considerable vertical distances to shallow basinal depths. Here we document evidence for deep sills (depths >5 km (16,000 ft)) hosting permeable, open fracture systems that may have allowed transmission of overpressure from ultra-deep basinal (>7 km (23,000 ft)) levels. Most notably, well 214/28-1 encountered overpressured, thin (<8 m (26 ft)) and fractured gas-charged intrusions, which resulted in temporary loss of well control. While the overpressure 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 (>58 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-recognized hazard to both scientific and petroleum drilling in the vicinity of subsurface igneous complexes.

Key words: intrusions, sills, overpressure, drilling, exploration

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 (Mann and Mackenzie, 1990; Osborne and Swarbrick, 1997; Tingay et al., 2007). Encountering unexpected overpressure zones during drilling operations can pose a significant risk to both human life, the environment and a well achieving its technical objective; such zones can result in an influx of high pressure gas and/or fluid into and up the wellbore (known as a 'kick'), and in a worst-case scenario a 'blowout'. Accurate prediction of pore pressures when drilling petroleum wells fundamentally underlies safe drilling operations; the lack of adequate understanding and subsequent response to higher than expected pore pressures during drilling of the Banjar Panji-1 well in Java,

Indonesia was a contributing factor to the blowout and the flow of the 'Lusi' Mudflow, that suddenly erupted in an urban area, burying over 11,000 buildings (Tingay, 2015).

It is generally accepted that disequilibrium compaction related overpressure cannot be sustained for long periods of geological time (>20 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 globally but with a few notable exceptions. Tingay et al. (2007) demonstrated the likely vertical transfer of overpressure up normal faults within the inner shelf of the Baram Delta, Borneo. Other notable areas 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; Hoskins et al., 2015) and the Qaidam Basin, northwest China (Fan et al., 2016).

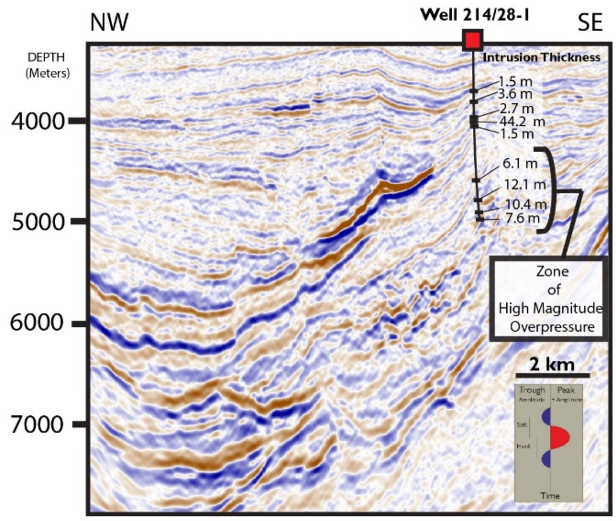

Figure 1. Seismic line through Well 214/28-1 located in the Faroe-Shetland Basin, offshore NW Scotland. The seismic line is from a 3D cube acquired 2011-2012 and reprocessed to Pre-Stack Depth Migration in 2016. The lower zone of intrusions, where overpressure was encountered (Figure 5 and 6), extend in a down-dip direction towards a depth of ~6.5 km (21,325 ft).

Here we detail the occurrence of overpressure within igneous intrusions, using a combination of subsurface datasets. We propose a new mode of overpressure transfer via interconnected networks of fractured igneous intrusions. We then discuss the ramifications of such an 'overpressure' transfer mechanism for both petroleum and scientific drilling in sedimentary basins containing extensive igneous intrusions (e.g. NW Shelf of Australia, South Atlantic Margin, Norwegian Margin, Gulf of California/Guaymas Basin), emphasizing the need to plan for the possibility of encountering significantly higher than expected pore-fluid pressures in the vicinity of igneous sheet intrusions.

WELL 214/28-1 – OVERPRESSURE

Well 214/28-1, drilled in the in 1984 within the Faroe-Shetland Baisn (UK) to a total depth of 5,124 mBRT (16,811 ft BRT) (653 m (199 ft) water depth), was designed to test Paleocene and Jurassic targets (Grove, 2013) (Figure 1). However, the well encountered substantial issues with overpressured mafic intrusions between 4,596 mBRT (15,078 ft BRT) and 5,013 mBRT (16,446 ft BRT) (Figure 2), which required the expenditure of considerable time and effort to control the overpressure and gas influx (Mark et al., 2017).

Using direct (e.g. Wireline Formation Tester-WDT, Repeat Formation Tester-RFT and Modular Formation Dynamic Tester-MDT) and indirect (e.g. mud weights), pressure data indicates a consistent picture of broadly hydrostatic pressures to depth of ~3,200 m (10,498 ft) within the middle Paleocene. Below this depth, RFT and MDT data begin to indicate a departure from normal hydrostatic conditions and occurrence of overpressure, which increased gradually with small deviations (e.g. 4,100 mBRT; 13,451 ft BRT). The top of overpressure was estimated using intermediate wireline logs during drilling operations and was found at approximately 4,480 mBRT (14,698 ft BRT). This depth is consistent with regionally built shale-models in the West of Shetlands Region (Edwards et al., 2012; Tassone et al., 2014). However, on encountering a 6.1 m (20 ft) thick intrusion at a sub-seabed depth of 4,596 mBRT (15,075 ft BRT), a large magnitude overpressure was encountered associated with high pressure gas influx into the wellbore and 44% Total Gas (Methane, Ethane, Propane and Butane). 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 circulating 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) (Figure 5 and 6). On continuation of drilling, with the increased mud weight, two further intrusions where penetrated at 4,788 mBRT (15,708 ft BRT) and 4,931 mBRT (16,177 ft BRT) respectively, with no further influx of gas/fluid noted (Figure 6). However, at a depth of 5,013 mBRT (16,446 ft BRT), a 7.6 m (25 ft) thick overpressured intrusion was encountered, 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 control. After penetration of the 7.6 m (25 ft) thick intrusion, connection gas values remained at 30-45 % even at the increased levels of mud weight to the base of hole at 5,124 mBRT (16,811 ft BRT).

'OVERPRESSURE' TRANSMISSION VIA FRACTURED SILLS

Igneous intrusions within sedimentary basins often form highly interconnected complexes; Cartwright and Hansen (2006) documented this phenomenon on the Norwegian Margin, showing a complex of interconnected sill intrusions extending over 12 km (7.5 miles) vertically and 20 km (12.4 miles) horizontally. Similar, highly interconnected complexes of mafic intrusions are also observed in the FSB (Schofield et al., 2015).

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 center of the basin, 'rooting' at depths >6 km (19,685 ft) (Schofield et al., 2015; Mark et al., 2017). A continuous path can be traced from the 6.1 m (20 ft) thick overpressured intrusion penetrated by well 214/28-1 at 4,596 mBRT (15,075 ft BRT), via the interconnected intrusion to over 6 km (19,685 ft) in depth on 3D seismic data.

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.

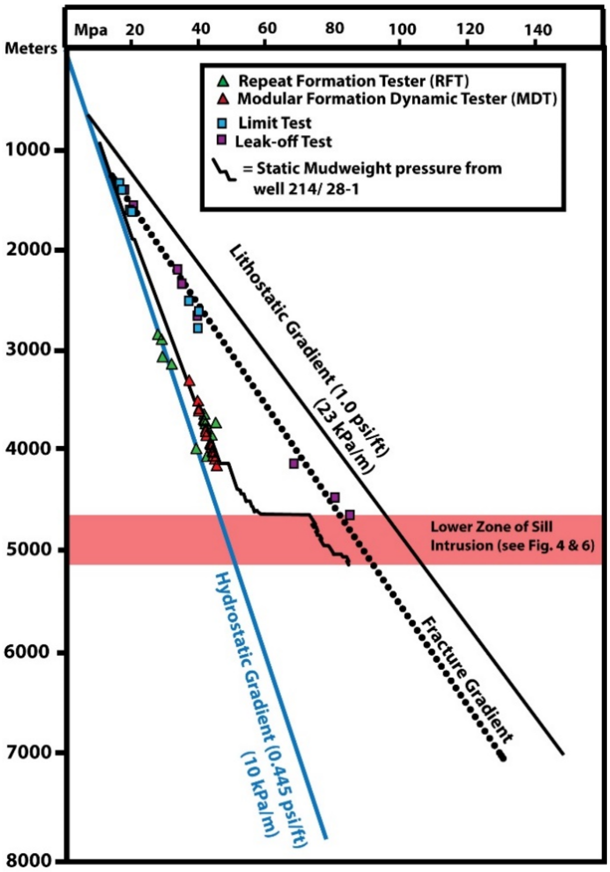

Figure 2. Pressure vs depth plot. Direct pressure data (e.g. RFT) from well 214/28-1 and well 214/27-1 (located 10 km away, that penetrated same stratigraphic succession).

A common concept used to explain the presence of overpressure within reservoir sand units is that of the centroid (Traugott and Heppard, 1994; Swarbrick and Osborne, 1998), where lateral pressure transfer 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 the 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 (~3000 ft) vertically. 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 the point of origin (Figure 3). 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 fluid drainage.

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 PETROLEUM AND SCIENTIFIC (E.G. IODP) EXPLORATION IN VOLCANICALLY-INFLUENCED BASINS?

Accurate prediction of subsurface fluid pressures is a critical element of all drilling, underpinning the design of safe wells (Board, 2012). 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 likely 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.

Petroleum exploration wells are designed to be able to deal with (within a given tolerance) excess pore pressures. Scientific drilling, such as IODP expeditions utilizing the JOIDES Resolution Drillship, are drilled riserless, with no BOP and primarily using seawater as the drilling fluid, meaning no primary (other than seawater) or secondary barrier exists to contain a potentially overpressured zone of fluids. The risk of encountering subsurface overpressure on IODP expeditions drilling is usually minimized 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 sheet intrusions connected to a deeper pressure regime, especially in deeper targets (>1,000 m (~3000 ft) 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, which sills are known to preferentially intrude (Schofield et al., 2012). The maximum overpressure that can be supported by a rock unit can be expressed in terms of the fracture gradient of the host rock, beyond which hydraulic fracturing and capillary leakage will take place and any overpressure can be assumed to dissipate. Following this scenario, a well being drilled in a geological sequence containing interconnected sill complexes, may have only planned to drill to a depth of e.g. 4,000 mBRT (13,123 ft BRT). 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.

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

RECOMMENDATION FOR BOTH SCIENTIFIC (E.G. IODP) AND PETROLEUM 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 (Schofield et al., 2015; Mark et al., 2017). 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 10s of meters, and at deep basin levels, e.g. 3-4 km (9842-13,123 ft), vertical resolution can drop to 40-80 m (131-262 ft) range (Schofield et al., 2015). 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 6.1 m (20 ft) and 7.6 m (25 ft) thick respectively.

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 such tools are in a fledging stage of development (Constable et al., 2016). Additionally, 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 meters (10's of feet) are potentially capable of pressure transmission (Schofield et al., 2015; Mark et al., 2017).

CONCLUSIONS

We have detailed the occurrence of overpressure within intrusions and propose a new pathway 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 drilling for oil and gas in the vicinity of interconnected transgressive igneous intrusive complexes in basins worldwide that contain substantial intrusive igneous complexes (e.g. NW Shelf of Australia, South Atlantic Margin, Norwegian Margin, Gulf of California/Guaymas Basin)

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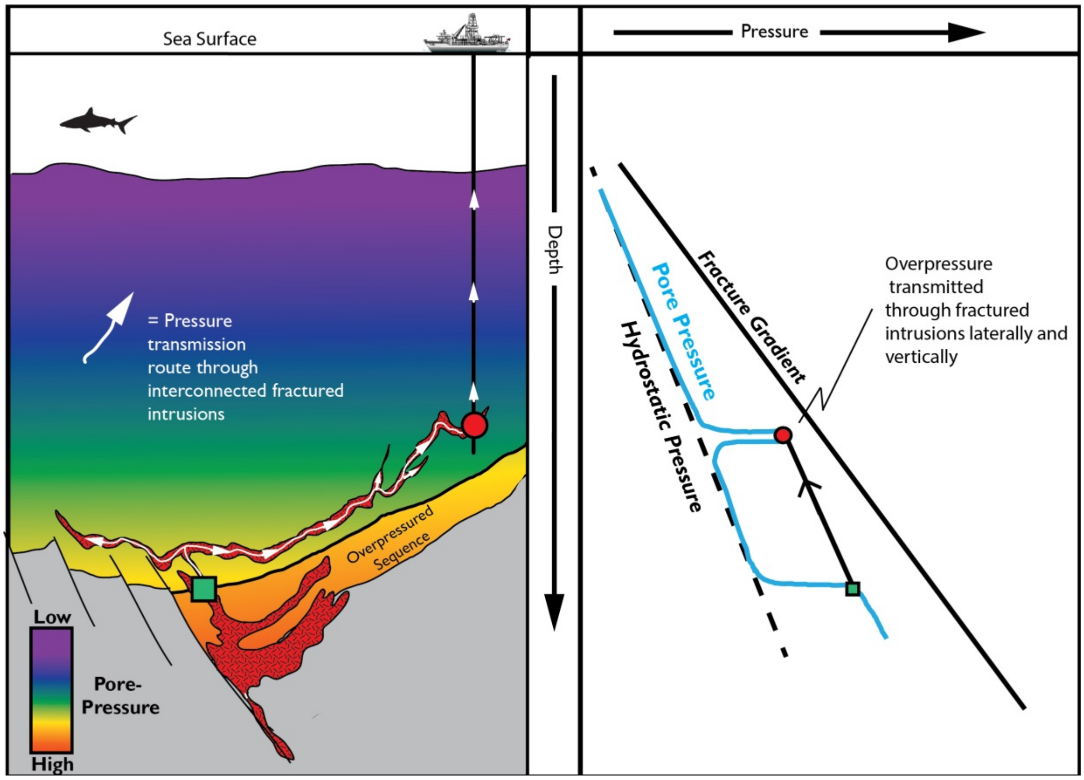

Figure 3. Conceptual diagram showing the principle of pressure transmission through a fractured igneous intrusive complex. Such a process can lead to overpressure being transferred laterally (and vertically) through a basin 10s of km away from its point of origin.