# Impacts of igneous intrusions on source and reservoir potential in prospective sedimentary basins along the western Australian continental margin

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## Abstract

Many prospective basins in rifted continental margins, including those located along the western Australian continental margin, contain extrusive and intrusive rocks generated during rifting and particularly during continental breakup. Intrusive igneous systems in rifted margin basins are typically characterized by networks of interconnected, laterally and vertically extensive sheet complexes (e.g. sills and dykes) that transgress basin stratigraphy. The presence of igneous rocks thus represents an important geological risk in hydrocarbon exploration. Constraining the distribution, timing and intrusive mechanisms of the igneous rocks is essential to reducing exploration risk. This paper focuses on two key sources of risk associated with the intrusion of igneous rocks into prospective sedimentary basins: (1) interconnected, low-permeability sheet intrusions (e.g. sills and dykes) that can compartmentalise significant volumes of source and reservoir rock, thereby reducing migration efficiencies; and (2) igneous-related hydrothermal circulation systems that can be highly mineralising and thus detrimental to reservoir quality. It is also important to highlight that igneous rocks may also be beneficial to petroleum systems. For example, the thermal effects of igneous intrusions may in some cases be sufficient to place immature source rocks within the oil window. The impacts of igneous intrusion on the prospectivity of rift basins along the western Australian continental margin are examined, with particular focus on frontier exploration areas such as the Exmouth Plateau and Browse Basin.

**Key words:** Intrusion, compartmentalization, fluid flow, seismic, thermochronology

## Introduction

Igneous rocks are commonly generated when continents rift to form new ocean basins and are the result of decompression melting of hot asthenospheric mantle that rises passively beneath zones of stretched and thinned lithosphere (White & McKenzie, 1989). Consequently, nearly all extensional basins located along passive continental margins are associated with some degree of intrusive and extrusive activity during rifting, though the volume and distribution of magmatism generated during the rift-phase is generally minor in comparison to the voluminous, transient breakup-related magmatism that can occur if rifting culminates in rupture of the continental lithosphere (White & McKenzie, 1989; Planke et al., 2000). At so-called “magma-dominated” margins, such as the northeast Atlantic margin, transient, voluminous magmatism around the time of continental breakup can produce up to 6-7 km of melt. Even margins regarded as “magma-poor” (e.g. the west Iberian margin) may be associated with up to 3 km of igneous addition during crustal breakup (Reston, 2008).

The increasing shift in focus of conventional hydrocarbon exploration towards rifted continental margins calls for a better understanding of igneous activity, which presents an important geological risk in many frontier continental margin sedimentary basins. Hydrocarbon exploration has traditionally sought to avoid basins containing igneous rocks because of the difficulties they can pose for seismic reflection imaging and their perceived detrimental short-term and long-term impacts on petroleum systems (Rohrman, 2007). Recent years have witnessed increasing exploration activity and successes in basins containing igneous rocks intruded during rifting and/or continental breakup, such as along the northeast Atlantic margin off Ireland, the United Kingdom and Norway. This is also the case for several basins along the western Australian continental margin (Fig. 1), including the Carnarvon and Browse Basins, which contain a variety of igneous features located in close proximity to multi-TCF gas fields such as Scarborough and Icthys (Symonds et al., 1998). Prospective but relatively unexplored deep-water segments of the western Australian continental margin such as the Exmouth and Scott Plateaus are characterized by extensive breakup-related magmatism (Symonds et al., 1998; Planke et al., 2000) and igneous rocks generated during rifting are also present in less prolific petroleum provinces such as the northwest Canning Basin (Reeckmann & Mebberson, 1984) and offshore the northern Perth Basin (Gorter & Deighton, 2002). An improved understanding of the impacts of igneous activity on petroleum systems (both beneficial and detrimental) is likely to become increasingly important in reducing exploration risk and unlocking the potential of these frontier areas.

Networks of interconnected, laterally and vertically extensive igneous intrusions such as sills and dykes are a characteristic component of igneous systems in many rifted margin basins (Planke et al., 2005; Thomson & Schofield, 2008; Holford et al., 2012; Jackson, 2012; Rateau et al., 2013), including those located along the western Australian continental margin (Symonds et al., 1998; Magee et al., 2013; Fig. 2). As a result of relatively recent advances in seismic imaging and interpretation the wide range of impacts that sills and dykes pose to the elements of the petroleum system are becoming better realised. In this paper, we focus on two important but commonly underappreciated effects of igneous intrusions on reservoir and source sequences. The first is the compartmentalisation of source and reservoir units by interconnected, low-permeability sheet intrusions that transect basin stratigraphy. The second is the generation of hydrothermal circulation systems by the intrusion of igneous rocks into porous, water-saturated sedimentary rocks.

## Compartmentalisation of basin stratigraphy by igneous intrusions

Recent investigations of subsurface intrusive complexes using 2D and 3D seismic datasets, mostly from rift basins along the northeast Atlantic margin (e.g. Bell & Butcher, 2002; Smallwood & Maresh, 2002; Thomson & Hutton, 2004; Planke et al., 2005; Cartwright & Hansen, 2006; Thomson & Schofield, 2008), have provided important new insights into the nature and mechanisms of magma storage and transport in sedimentary basins. Such studies have identified the true, three-dimensional geometries of subsurface igneous intrusions, repeatedly identifying concave-upwards, 'saucer-shaped' sills with radially or bilaterally symmetrical forms that possess flat or gently concave inner saucers connected to flat outer rims by steeply inclined, transgressive sheets. Detailed seismic interpretations of these sills using both horizon mapping and opacity volume rendering methods have shown that it is possible to resolve small-scale, lobate features on the surfaces of intrusions that essentially provide kinematic indicators for the directions in which sills have propagated (Cartwright & Huuse, 2005). Features such as lobate branching patterns (Thomson & Hutton, 2004) imply that magma is transported in sills through a network of magma tubes that consistently indicate upwards and outwards flow directions (Thomson & Schofield, 2008). Such findings have been supported by field studies of saucer-shaped intrusions (Schofield et al. 2010). Furthermore, detailed studies of major sill complexes located offshore Norway have shown that saucer-shaped and inclined sheet-like sills are often interconnected by junctions that occur systematically in the lowest parts of the overlying sills (Cartwright & Hansen, 2006). These observations confirm that shallower sills in intrusive complexes are fed by deeper sills, and that sill complexes can act as through-going magmatic plumbing systems capable of transporting melts over vertical and lateral distances of >10 km from mid-lower crustal levels to near-surface depths (Cartwright & Hansen, 2006). Such sill complexes are capable of transecting multiple layers of basin stratigraphy. This dynamic view of magmatic plumbing systems differs somewhat from the traditional views that magmatic systems are typically vertically stacked, and essentially comprise a large magma chamber overlain by a series of vertical dykes, feeding an overlying volcano (e.g. Gudmundsson, 1990).

The recognition of complex, interconnected networks of sills and dykes that cover large lateral and vertical distances in petroliferous sedimentary basins has several important ramifications for assessing prospectivity. The propensity for such intrusions to exploit and intrude along particular stratigraphic horizons (e.g. ductile and/or overpressured shales; Thomson, 2007) or pre-existing structural discontinuities (e.g. faults; Magee et al., 2013) can result in the compartmentalization of significant volumes of source or reservoir rock if the bounding igneous intrusions do not possess appreciable secondary permeability. Such secondary permeability can, for example, be imparted by cooling joints or tectonic fracturing (Rateau et al., 2013). Some examples of compartmentalisation of basin stratigraphy in seismic data from the North West Shelf and at outcrop scale in east Greenland are shown in Figures 2 and 3, respectively. The creation of isolated compartments of sediments sealed by low-permeability igneous intrusions would clearly impact migration pathways and the efficiency of hydrocarbon migration both out of source rock intervals and into potential reservoir horizons, whilst the permeability of sedimentary rocks adjacent to intrusions is likely to be degraded as a result of contact metamorphism. The concept of reservoir and source compartmentalization by igneous intrusions is illustrated in a series of hypothetical play scenarios shown in Figure 4. In addition, if subsurface intrusion is accompanied by the rapid burial of sediments by coeval lava eruptions this may result in significant undercompaction due to the intrusive network acting as a rigid framework. Depending on the sealing capacity of the intrusions, differential lateral pressures may develop within reservoir bodies bound by intrusive sheets. Such ‘pressure cages’ may pose a significant hazard during drilling of sub-basaltic plays.

The extent to which igneous intrusions can create barriers to subsurface fluid migration is dictated by their bulk permeability. Whilst most igneous intrusions will have negligible primary porosity, fractures generated during thermal cooling shortly after emplacement or subsequently during brittle tectonic deformation can provide some secondary porosity and permeability, thereby providing pathways for fluid migration through otherwise impermeable barriers (Rateau et al., 2013). Indeed, the Los Cavos oil field in the northern Neuquén Basin, Argentina, is reservoired in naturally fractured andesitic sills (fracture porosity = 1 to 8%) emplaced in Upper Jurassic shale source rocks (Witte et al., 2012). Though vesicles are present in these sills, they are poorly connected and do not contribute to the high reservoir connectivity and permeability which is provided by cavity zones and weakly cemented large fractures that formed during cooling-related contraction and a number of subsequent deformation events (Witte et al., 2012).

The presence of host-rock ‘bridge structures’ may provide alternative pathways for fluid migration in otherwise laterally continuous, impermeable intrusions. Bridge structures are commonly recognized in field exposures of sills, and have recently been documented for the first time in the subsurface using high quality 3D seismic data from the Faroe-Shetland Basin (Schofield et al., 2012). These structures form when separate magma lobes begin to propagate as a series of offset but overlapping en echelon bodies. Depending on the degree of diagenetic alteration, the bridges of host rock between the developing magma lobes may enable the migration of fluids through zones of compartmentalized stratigraphy, in an analogous manner to relay ramps that provide migration pathways through faults that would otherwise act as seals (e.g. Figure 5 in Schofield et al., 2012).

## Hydrothermal circulation systems generated by igneous intrusions

Much of the existing research on the thermal effects of intrusive activity in petroliferous basins has focused on the direct interactions between igneous intrusions and source rock facies in an attempt to predict their impact on maturation or overmaturation (Schutter, 2003). In general, the direct thermal (i.e. contact metamorphic) effects of intrusive bodies on source rocks appears to be minimal (Rohrman, 2007) and most estimates of the thermal aureole size range from 0.5 to 5 times the thickness of the associated, individual intrusion (Duddy et al., 1994; Schutter, 2003; Fig. 4). The thermal effects of igneous intrusions appear to be most profound when the occurrence of intrusions is dense (Rohrman, 2007); i.e. when multiple, thick intrusive sills (i.e. >100 m thick) are emplaced into organic-rich sediments simultaneously (Aarnes et al., 2011), or when previous intrusive activity has already raised the background geothermal gradient as may be the case in the Taranaki Basin of New Zealand (Schutter, 2003).

Importantly, attempts to replicate levels of maturation around intrusive rocks using conductive cooling models alone have commonly produced underestimates relative to observed data (Rohrman, 2007). This observation implies that heating by convective and/or advective processes may also have a significant affect on source rock maturation (Barker et al., 1998; Rohrman, 2007). Hydrothermal systems capable of transporting heat both vertically and laterally can result from the boiling and expulsion of pore-waters and the release of magmatic fluids following igneous intrusion into porous sedimentary rocks (Einsele, 1988). Such systems can be distinguished from conductive heating effects using palaeotemperature information provided by techniques such as apatite fission track analysis (AFTA) or vitrinite reflectance (VR). Conductive heating of sedimentary rocks around an intrusion is typically manifested in VR data by significant fluctuations in maturity or palaeotemperature over narrow depth intervals around the intrusion (Fig. 5), with widths of the thermal aureole typically 0.5 to 5 times that of the intrusion (e.g. Duddy et al., 1994; Holford et al., 2010). In contrast, hydrothermal circulation systems associated with intrusions can result in observable thermal signatures at distances of up to 10's of km from the intrusion as a result of the lateral flow of heated fluids through an aquifer (Duddy et al., 1994). Such systems are characterized by bell-shaped or dogleg geothermal gradients or palaeotemperature profiles, with different forms depending on the duration of fluid flow (Duddy et al., 1994, 1998; Fig. 5).

Recognition of hydrothermal circulation systems triggered by igneous intrusions is important when assessing prospectivity because hydrothermal fluids can be highly mineralizing and thus degrade the quality of potential reservoirs through the temperature-controlled cementation of minerals such as quartz. Parnell (2010) presents fluid inclusion data from several magmatically influenced basins along the northeast Atlantic margin, including the Faroe-Shetland Basin. These data contain evidence for high temperature (>200°C) and short lived (<0.1 to 1 Myr) hot fluid pulses, which are attributed to hydrothermal activity triggered by sill intrusions, that have precipitated quartz cements within potential reservoir sandstones.

### *Case Study: The Canning Basin*

A classic example of a hydrothermal circulation system induced by igneous intrusion along the western Australian continental margin was documented by Reeckmann & Mebberson (1984) using data from the North West Canning Basin. Here, a number of large mafic sills were emplaced into Permian-Carboniferous sediments during the early Permian (Reeckmann & Mebberson, 1984; Duddy et al., 1994). These intrusions caused forced folding of the overlying strata (c.f. Hansen & Cartwright, 2006) resulting in closed domal structures. One such structure was tested by the Perindi 1 well, which intersected a 156 m thick doleritic intrusion (Reeckmann & Mebberson, 1984). VR values from Permian and Devonian sediments adjacent to the intrusion are consistently between 1 and 1.3% over a vertical distance ~550 m above and ~300 m below the dolerite, implying little palaeotemperature variation over a ~1 km depth range (Duddy et al., 1994; Fig. 6). This pattern of high palaeotemperatures is attributed to the circulation of fluids in adjacent porous sandstones, as triggered by the igneous intrusion (Reeckmann & Mebberson, 1984). Evidence from AFTA and VR data suggests that the temperature of the hydrothermal fluids was likely >160°C, around 100°C higher than the temperature throughout the sedimentary section prior to the intrusion (Duddy et al., 1994). These elevated temperatures may have placed potential source rocks of the regionally immature Permian-age Poole Formation into the oil window for the duration of the heating event, potentially explaining a number of oil shows encountered within Poole Formation limestones and the uppermost sandstone within the Permian-age Grant Formation (Reeckmann & Mebberson, 1984).

The intrusion of extensive doleritic sills and laccoliths to shallow levels within porous sandstones of the Grant Formation resulted in distinct thermal effects that can be observed in wells located several kilometres away from the most proximal intrusions (Duddy et al., 1994). AFTA data from the Kambara 1 well indicate maximum palaeotemperatures of ~90-110°C during the Permian. Seismic data indicate that the nearest known Permian intrusions are located ~3 km to the northwest and southeast of this well. Interpretation of the AFTA data suggests that better aquifer zones within the Grant and Poole formations may have experienced slightly higher temperatures than less porous intervals. This observation, coupled with VR data from shales that show no pronounced increase in reflectance, seems to indicate relatively short-duration heating by fluids at some distance from the site of intrusive heating (Reeckmann & Mebberson, 1984; Duddy et al., 1994). It also implies that hydrothermal fluids are likely to exploit the same porous and permeable pathways used during the migration of hydrocarbons.

## Implications for prospectivity of the western Australian continental margin

Igneous rocks generated during the late Jurassic to early Cretaceous continental breakup between Australia and Greater India are widely distributed along the western Australian continental margin (Symonds et al., 1998) and present a key geological risk within highly prospective frontier regions such as the Exmouth Plateau and the Browse Basin. Seismic data from the Exmouth Plateau indicate the presence of large numbers of igneous intrusions within the Triassic-Jurassic succession, which includes potential source rocks (e.g. the Lower Triassic Locker Shale and Upper Triassic Mungaroo Formation) and known fluvio-deltaic sandstone reservoirs within the Upper Triassic Mungaroo Formation. Since these intrusions are generally thin (interpreted to be several tens of metres thick based on seismic data), their influence on maturation is considered to be minor (Rohrman, 2012). However, intrusions may play an important role in influencing hydrocarbon migration pathways (Rohrman, 2012), particular in regions where dense, interconnected networks of sills and dykes occur. An additional risk associated with igneous intrusion is the release of volatiles such as $CO_2$, which can lead to flushing of hydrocarbon-filled reservoirs (Holford et al., 2012). High levels of $CO_2$ (38%) and $N_2$ (27%) were recovered in repeat formation tester results from the main pay zone in Zeepaard 1 (Barber, 1988). While this has been interpreted as indicating cracking of NSO compounds from overmature source rocks following heating by proximal intrusions (Barber, 1988), $CO_2$ can also be released during magma degassing. This process is thought to be responsible for the high $CO_2$ content in a number of uneconomic gas fields in the Otway Basin (Holford et al., 2012).

Many wells in the Browse Basin have penetrated subaerial volcanics within the Plover Formation (Symonds et al., 1998) and their distribution throughout the basin poses a significant exploration risk (Jason et al., 2004). Buffon 1 encountered a 489 m thick sequence of layered basalts overlying 193 m of volcaniclastics (Symonds et al., 1998). Such layered volcanic sequences generate strong multiple reflections and lead to scattering of the seismic signal (Rohrman, 2007), making it difficult to image the sub-basaltic sequences. This constitutes one of the most significant exploration risks in the Faroe-Shetland Basin (Archer et al., 2005) because it is difficult to predict the precise thickness of the extrusive sequences and to image sub-basaltic intrusions that may impede drilling and lead to compartmentalization of source and reservoir intervals (Rateau et al., 2013). Thicker than expected volcanics and the absence of reservoir were identified as a key factors in the failure of Maginnis 1/ST2, which was drilled in 2002-2003 in the deep-water Seringapatam sub-basin beneath the eastern Scott Plateau (Jason et al., 2004). In addition to the absence of reservoir, it has been postulated that the thick volcanic sequence within the target interval may have formed a barrier to lateral migration from mature source rock intervals in adjacent grabens (Jason et al., 2004).

## Conclusions

The focus of this paper has been to demonstrate that the intrusion of igneous sills and dykes into prospective sedimentary basins can have potentially drastic impacts on petroleum systems. By understanding the magmatic history, and nature and distribution of intrusions within the basin, it is possible to assess the risks that intrusions may pose on the elements of the petroleum system; however, it is important to emphasise that the impacts of intrusions in basins with active petroleum systems are still not well understood. Key uncertainties include the factors that dictate whether igneous intrusions are likely to act as barriers or baffles to hydrocarbon migration, such as the depth of burial of the intrusions within the sedimentary section, the intensity of jointing and the thickness of the intrusive bodies (Rateau et al., 2013). Detailed studies are needed to improve knowledge of the sealing capability of intrusions within the subsurface, and in particular, to understand how migration pathways and efficiency are affected by intrusions. Despite these uncertainties, it is tentatively suggested that the impact of igneous intrusions on petroleum systems in basins modified by magmatism, particularly breakup-related magmatism, is generally underestimated.

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## Figure captions

**Figure 1:** Distribution of magmatism along the western Australian continental margin (modified after Symonds et al. (1998) and Rey et al. (2008)).

**Figure 2:** Seismic line 110/12, central Exmouth Plateau. Interconnected igneous intrusions are common within the Triassic section, which contains both source rocks (e.g. the Lower Triassic Locker Shale and Upper Triassic Mungaroo Formation) and fluvio-deltaic sandstone reservoirs (Mungaroo Formation). The Eendracht 1 exploration well targeted a Triassic fault block leading to a gas discovery, whilst Investigator 1 recorded gas shows within the Mungaroo Formation (modified from Geoscience Australia, (2012)).

**Figure 3.** Seismic-scale outcrop showing a 'box-work' of sills and dykes intruding a faulted section of Jurassic-Triassic sediments on Traill Island, eastern Greenland. This outcrop provides an analogue for compartmentalization of a prospective reservoir in an extensional basin setting. Note the zones of visible contact metamorphism around the intrusions, likely resulting in a significant reduction in the volume of potential reservoir rock.

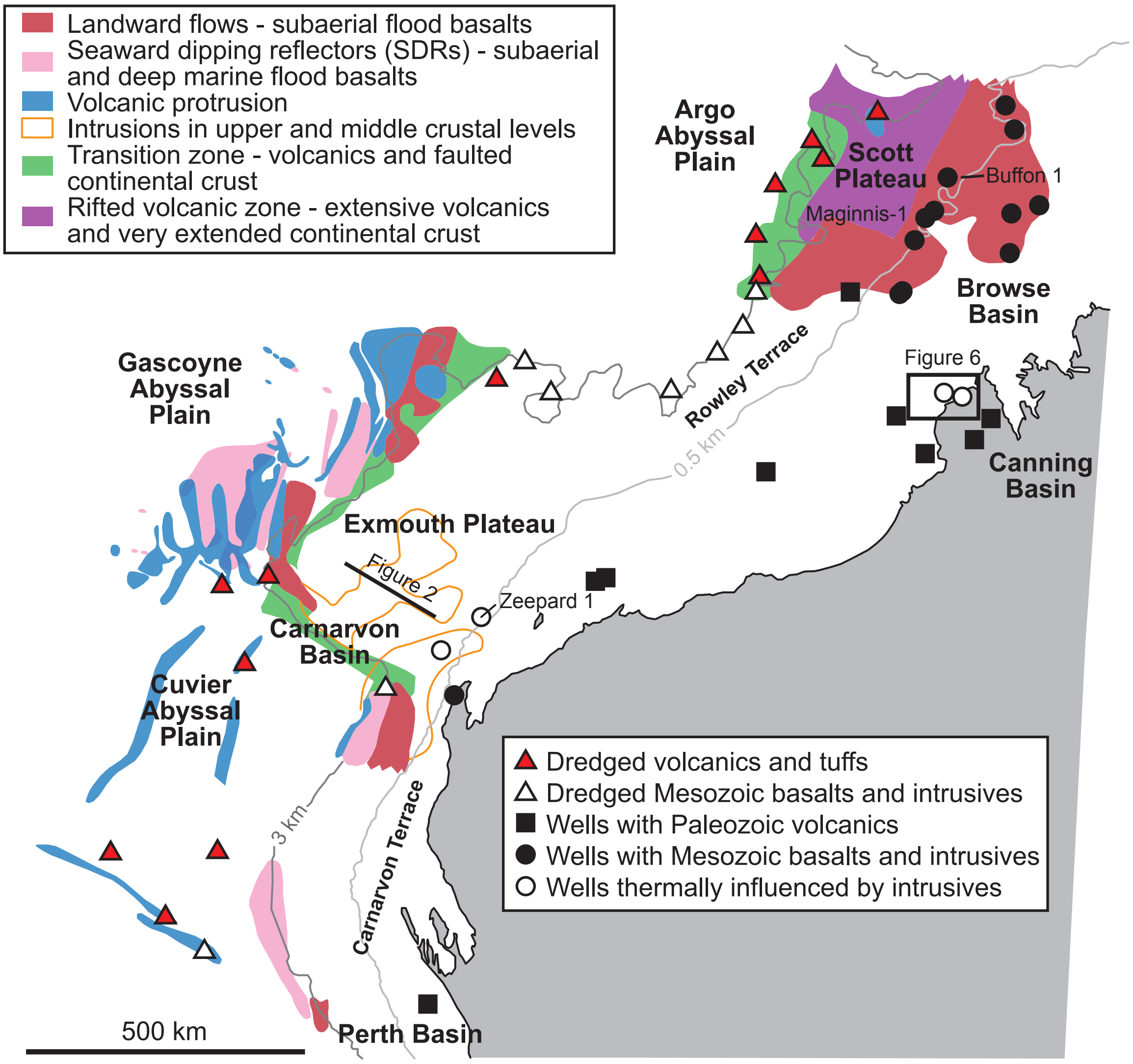
**Figure 4.** Series of conceptual play diagrams illustrating the potential impacts of igneous intrusions on compartmentalization of source and reservoir units in sedimentary basins (modified from Holford et al. (2012) and Rateau et al. (2013)).

**Figure 5. A.** Schematic diagram showing a typical vitrinite reflectance profile developed in lithified, low porosity sediments by conductive heating near an intrusive sill (modified from Duddy et al. (1994)). **B.** Schematic illustration of the development of a palaeotemperature profile around an aquifer or reservoir following initiation of intrusion-related hydrothermal fluid flow at 60°C. Illustrates the change from a linear

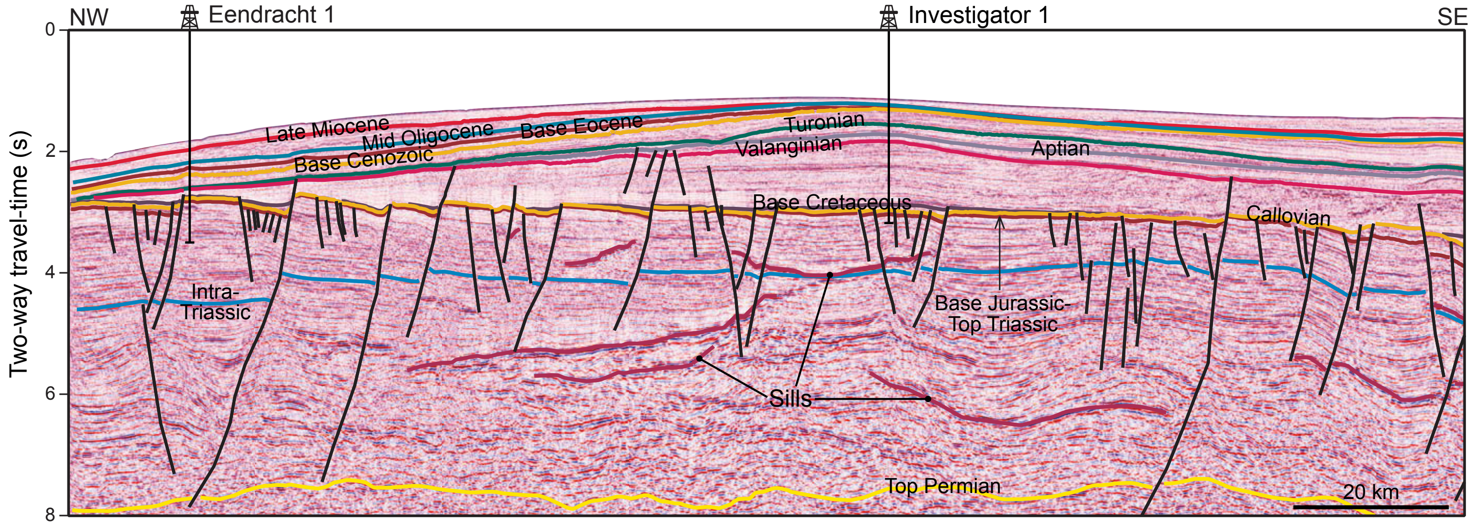
background thermal condition, through a bell-shaped transient profile, to a linear steady-state profile (modified from Duddy et al. (1998)).

**Figure 6. A.** Distribution of shallow sill intrusions in the northwest Canning Basin. See text for further discussion. **B.** VR depth plot for Perindi 1 and Tappers Inlet 1 wells, northwest Canning Basin. Note the lower, near vertical palaeogeothermal gradient associated with the dolerite sill in Perindi 1 (modified from Reeckmann & Mebberson (1984)).

**Holford et al Figure 1**

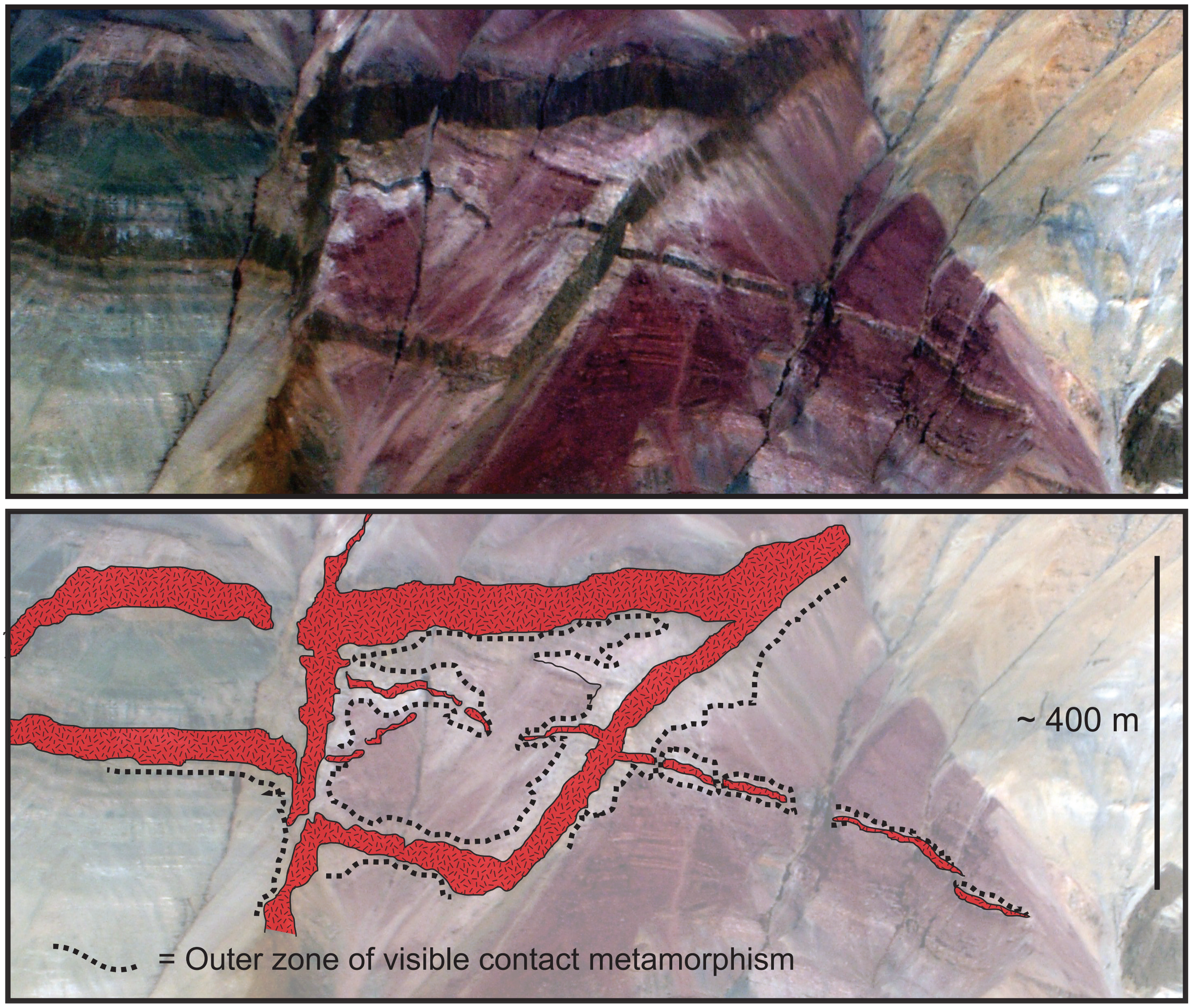


**Holford et al Figure 2**



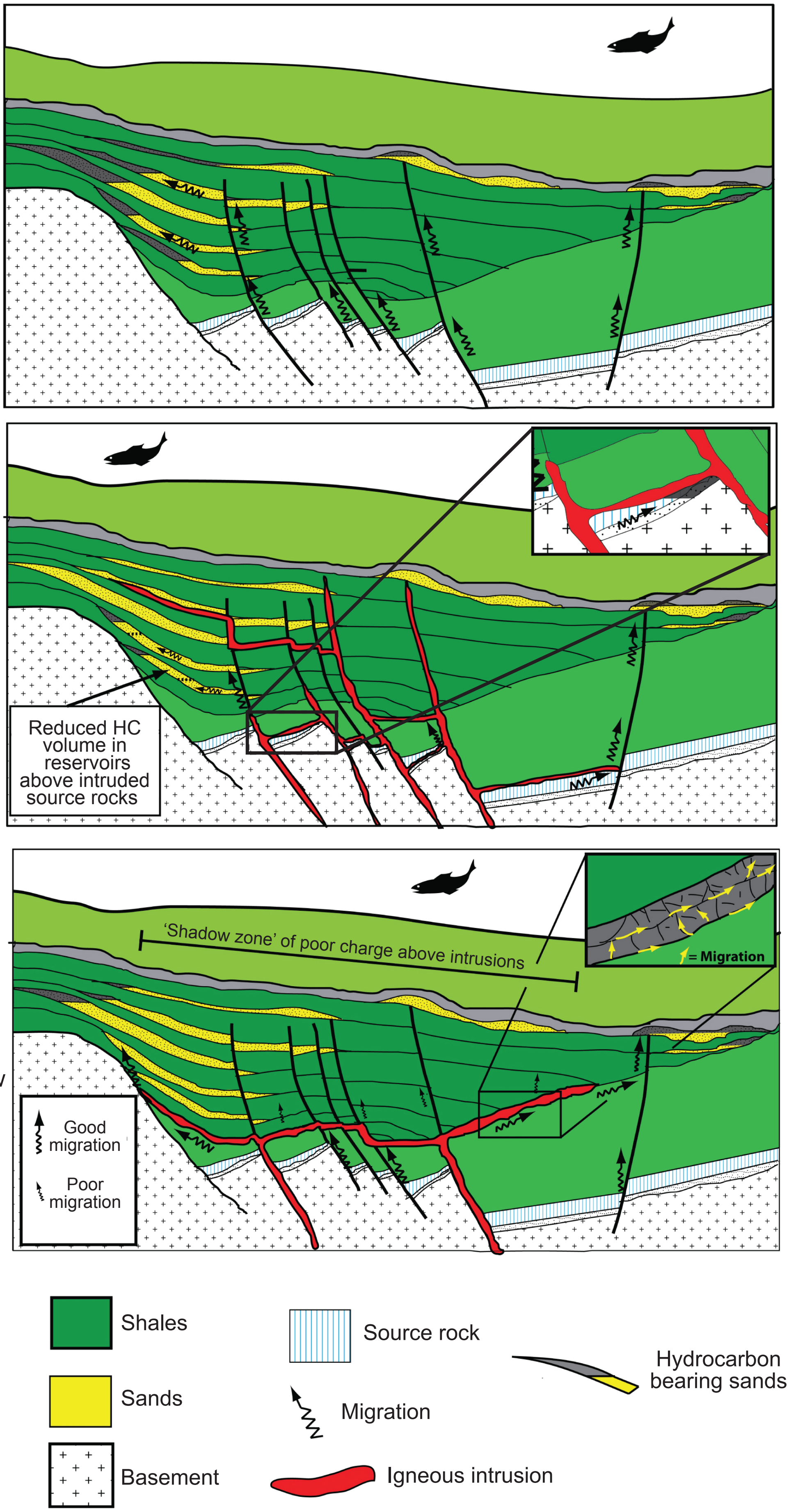
**Holford et al Figure 3**

**‘Box-Work’ igneous compartmentalisation of sedimentary strata, East Greenland**



**Holford et al Figure 4**

## End-member impacts of igneous intrusions on conventional sandstone plays

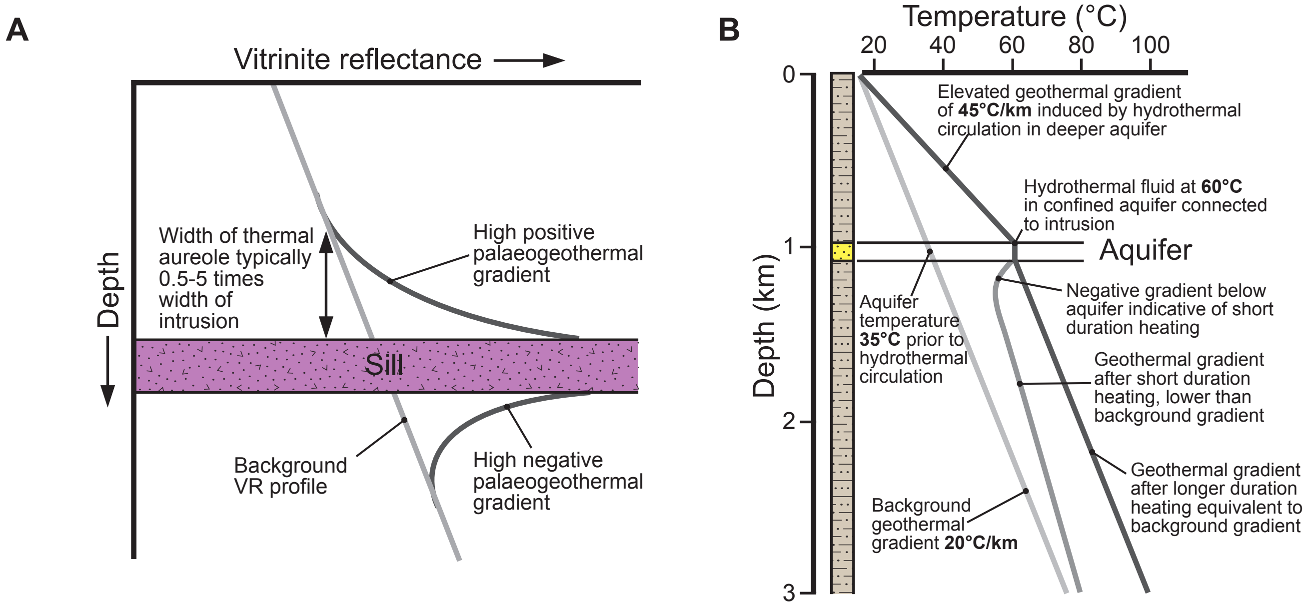


**Scenario 1**
No intrusions - petroleum systems unaffected

**Scenario 2**
Compartmentalisation of source rock intervals - hydrocarbons trapped close to source, unable to migrate to reservoirs leading to reduction in charge

**Scenario 3**
Compartmentalisation of basin fill - intrusions act as barriers and baffles to hydrocarbon migration, creating 'shadow zones' of underfilled reservoir units overlying intrusions

**Holford et al Figure 5**



**Holford et al Figure 6**