The Impact of Igneous Intrusions and Extrusions on Hydrocarbon Prospectivity in Extensional Settings: A 3D Seismic Perspective*

Christopher A-L. Jackson[1]

Search and Discovery Article #41168 (2013)**
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Please refer to two related articles by the author and co-workers, entitled "Interaction between Faults and Igneous Intrusions in Sedimentary Basins: Insights from 3D Seismic Reflection Data," Search and Discovery Article #41114 (2013) and "Seismic Expression and Petroleum System Implications of Igneous Intrusions in Sedimentary Basins: Examples from Offshore Australia," Search and Discovery Article #10483 (2013).

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Abstract

The emplacement of shallow-level igneous intrusions in sedimentary basins may impact significantly on the development of petroleum systems. For example, the circulation of related hydrothermal fluids, which may reduce the porosity and permeability of host rock reservoirs, and associated host rock deformation may result in the formation of "forced fold" traps. Understanding the geometry and evolution of sub-volcanic intrusive networks in volcanogenic basins is thus of interest to the petroleum industry. Whilst field-based studies permit a detailed investigation of magma properties and localised host rock relationships, outcrops are often too small to fully characterise the three-dimensional geometry and size of large igneous complexes. Furthermore, ancient volcanic edifices, and their relation to the sub-volcanic "plumbing system," are typically obscured at outcrop due to post-emplacement erosion or caldera collapse. In contrast, seismic reflection data, although typically limited in terms of their vertical resolution, can provide spectacular images of the intrusive and extrusive components of igneous networks.

In this study we use 2D and 3D seismic reflection and borehole data from the offshore Bight Basin (southern Australia) and Exmouth sub-basin (northwestern Australia) to illustrate the seismic expression and range of geometries associated with sill-dominated, intrusive igneous networks connected to submarine volcanoes and vents. Three main types of sill are documented: (i) tabular sills; (ii) saucer-shaped sills; and (iii) transgressive sills. Seismic-data resolution restricts a detailed analysis of sill volume, but our analysis indicates that the sills are up to 150 m thick, 16 km wide and 208 km² in map-view area. In both basins, forced folds, which may represent hydrocarbon traps, are developed above a range of sills. In the Bight Basin, the fold amplitudes are consistently less than the thickness of the underlying intrusions. We interpret that this discrepancy reflects fluidisation and ductile flow of coal or carbonaceous claystones during sill emplacement at relatively shallow depths. In both study areas the sill-dominated networks are overlain by large (13 km wide by 800 m high), sub-circular mounds, the majority of which

occur above the tips of sills; these mounds are interpreted as extrusive volcanic vents, adjacent to which pinch-out traps, which are related to stratigraphic onlap, may be developed

From an applied perspective, the sill-dominated networks, although areally quite extensive, are not anticipated to impact the vertical migration of hydrocarbons, due to the presence of pervasive normal fault networks that may allow shallow-level reservoirs to access deeply buried source rocks. Although the sills may locally impact the reservoir quality of the host rock successions, forced folding, which is associated with sill emplacement in the shallow subsurface, can result in the formation of viable hydrocarbon traps.

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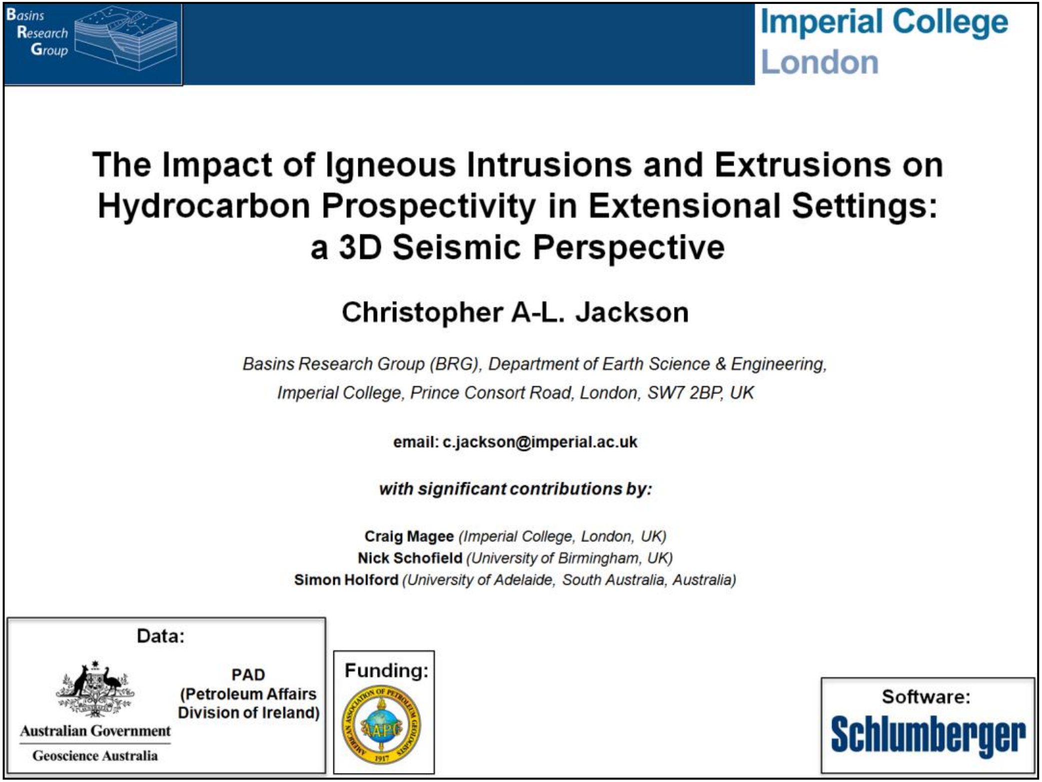

Basins Research Group

Imperial College London

The Impact of Igneous Intrusions and Extrusions on Hydrocarbon Prospectivity in Extensional Settings: a 3D Seismic Perspective

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Data:

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Geoscience Australia

PAD
(Petroleum Affairs Division of Ireland)

Funding:

American Association of Petroleum Geologists 1917 AAPG

Software:

Schlumberger

Presenter's notes: Igneous systems can affect the petroleum prospectivity of sedimentary basins.

The aim of this presentation is not to focus on the hydrocarbon prospectivity of the case study basins that are discussed; although this will be mentioned; a key aim here is to simply illustrate some of the key issues that need to be considered when exploring for and producing hydrocarbons from petroliferous sedimentary basins.

- From an academic point-of-view, the circum-Australian basins are an excellent natural laboratory to understand igneous geology in it's broadest sense due to the availability of goo-quality, publically-available seismic and borehole data

My previous experience with igneous geology…Part 1

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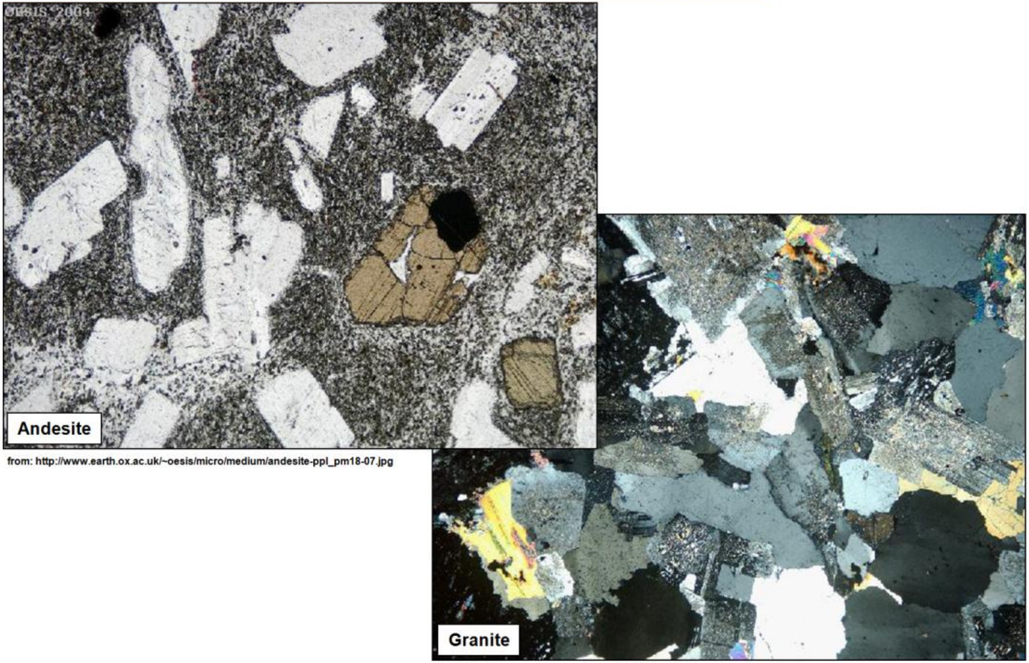

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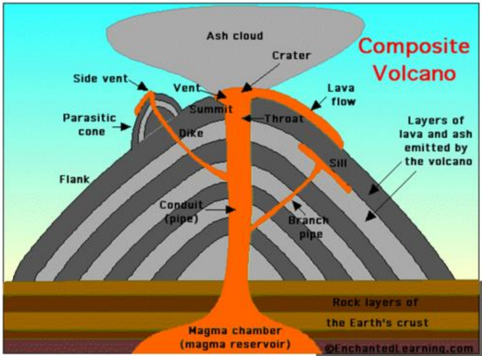
My previous experience with igneous geology…Part 2



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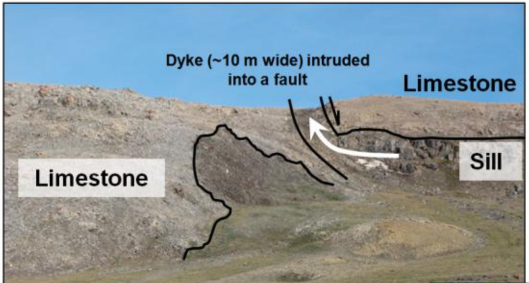
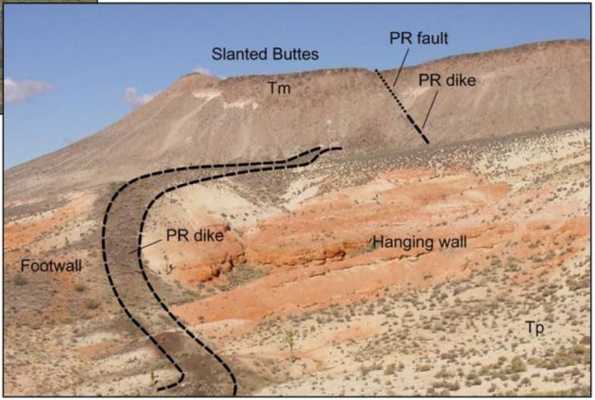
My previous experience with igneous geology…Part 3



Franklin Sills (Canada) – modified from Bédard et al. (2012)

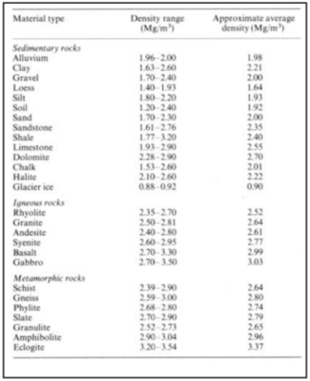
Paiute Ridge dykes (Nevada, USA) Valentine & Krogh (2006)



Presenter's notes: Field examples of dykes intruded into faults. Note the poor exposure and limited three-dimensional understanding afforded by outcrops. Note that the dykes exploit faults and may be fed by (white arrow shows magma flow direction in top-left image) or feed into sill.

Seismic expression of igneous intrusions

- Seismic velocity and density vary mainly as a function of rock properties and depth
- Seismic reflections occur at the boundaries between rock layers that have different rock properties (acoustic impedance)



Material type	Density range (Mg/m^3)	Approximate average density (Mg/m^3)
Sedimentary rocks		
Alluvium	1.96–2.00	1.98
Clay	1.63–2.60	2.21
Gravel	1.70–2.40	2.00
Loess	1.40–1.93	1.64
Silt	1.80–2.20	1.93
Soil	1.20–2.40	1.92
Sand	1.70–2.30	2.00
Sandstone	1.61–2.76	2.35
Shale	1.77–3.20	2.40
Limestone	1.93–2.90	2.55
Dolomite	2.28–2.90	2.70
Chalk	1.53–2.60	2.01
Halite	2.10–2.60	2.22
Glacier ice	0.88–0.92	0.90
Igneous rocks		
Rhyolite	2.35–2.70	2.52
Granite	2.50–2.81	2.64
Andesite	2.40–2.80	2.61
Syenite	2.60–2.95	2.77
Basalt	2.70–3.30	2.99
Gabbro	2.70–3.50	3.03
Metamorphic rocks		
Schist	2.39–2.90	2.64
Gneiss	2.59–3.00	2.80
Phylite	2.68–2.80	2.74
Slate	2.70–2.90	2.79
Granulite	2.52–2.73	2.65
Amphibolite	2.90–3.04	2.96
Eclogite	3.20–3.54	3.37

source: http://onlinephys.com/labpressure4.html

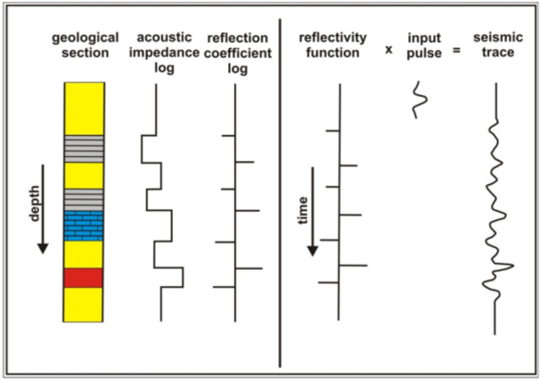


image courtesy of Gavin Elliott

Seismic expression of intrusions

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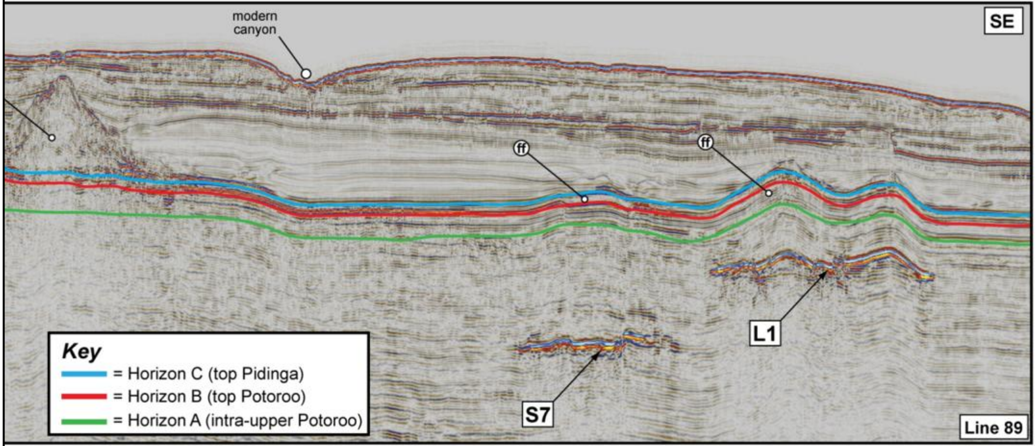

- Igneous intrusions acoustically hard and fast
- Intrusion either strata concordant (sills and laccoliths) or discordant (saucer-shaped sills)
- Intrusions overlain by extrusive igneous bodies
- Intrusions associated with folds

Presenter's notes: Igneous features in the Bight Basin are typical of intrusions observed elsewhere; they are expressed as very high-amplitude anomalies, which are typically discordant to concordant with encasing strata and are underlain by velocity pull-ups that attest to their acoustically-fast properties. Intrusive igneous features in the Bight Basin are overlain by a field of genetically-related extrusive igneous features, including large features interpreted as volcanoes and smaller features interpreted as hydrothermal vents. Intrusive igneous features are also associated with folding of overlying strata; we shall return to the genesis and importance of these folds later in the presentation.

Petroleum system implications

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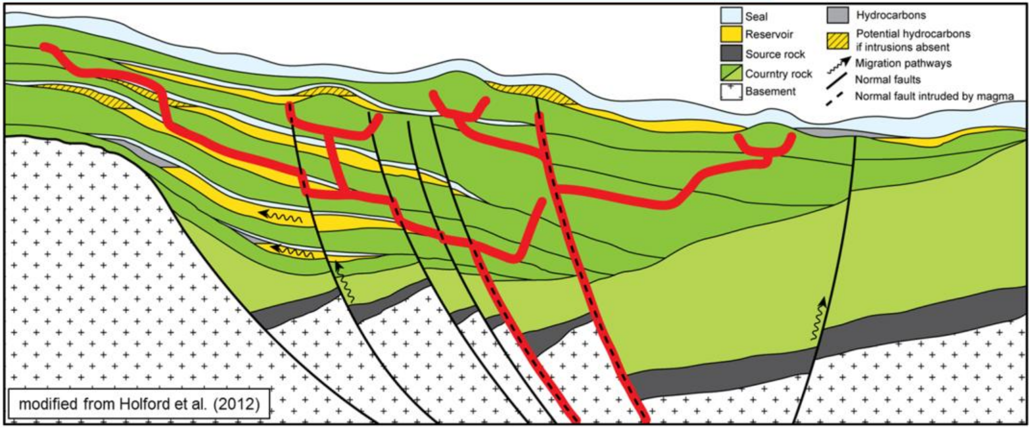


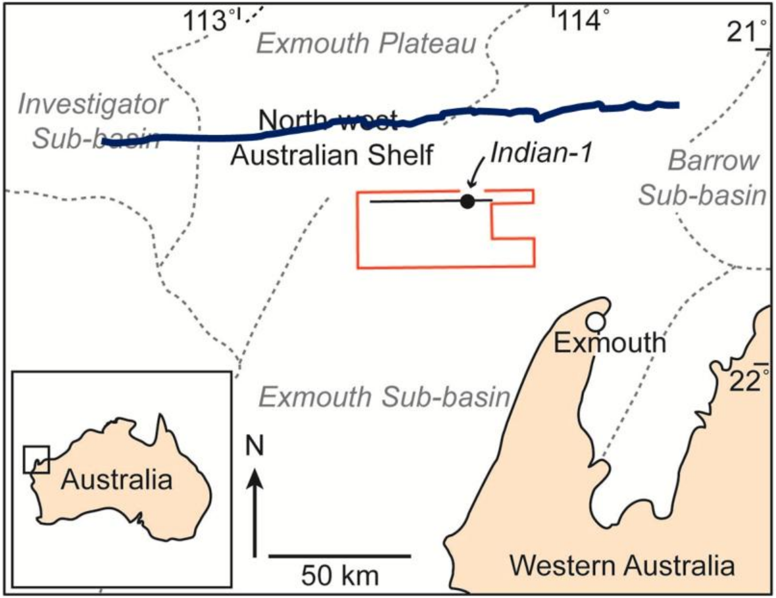
modified from Holford et al. (2012)

- Many basins associated with the intrusion and extrusion of igneous bodies
- What impact might these features have on petroleum system?
- How are igneous bodies expressed on seismic reflection data?
- Is seismic reflection data a valid tool?

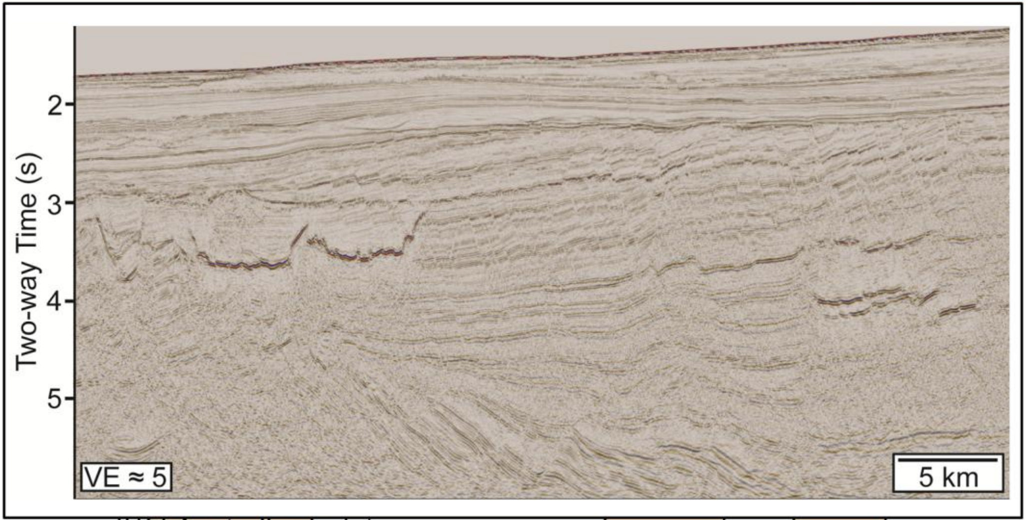
Presenter’s notes: This figure highlights the impact that igneous systems can have on petroleum system development in sedimentary basins. This figure principally highlights compartmentalisation of basin by vertically- and laterally-extensive intrusions; furthermore, in the upper part of the basin, the impact of intrusions on trap development is highlighted.

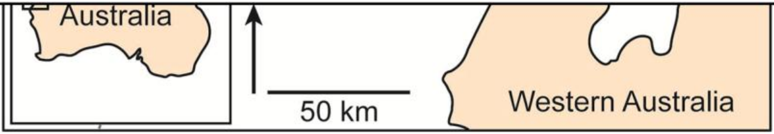
A secondary aim of this presentation, which was noted in another presentation, is how seismic reflection data, in particular high-quality, three-dimensional data, can help us understand igneous processes in a more general sense.

Exmouth Sub-basin (NW Australia)



Exmouth Sub-basin (NW Australia)





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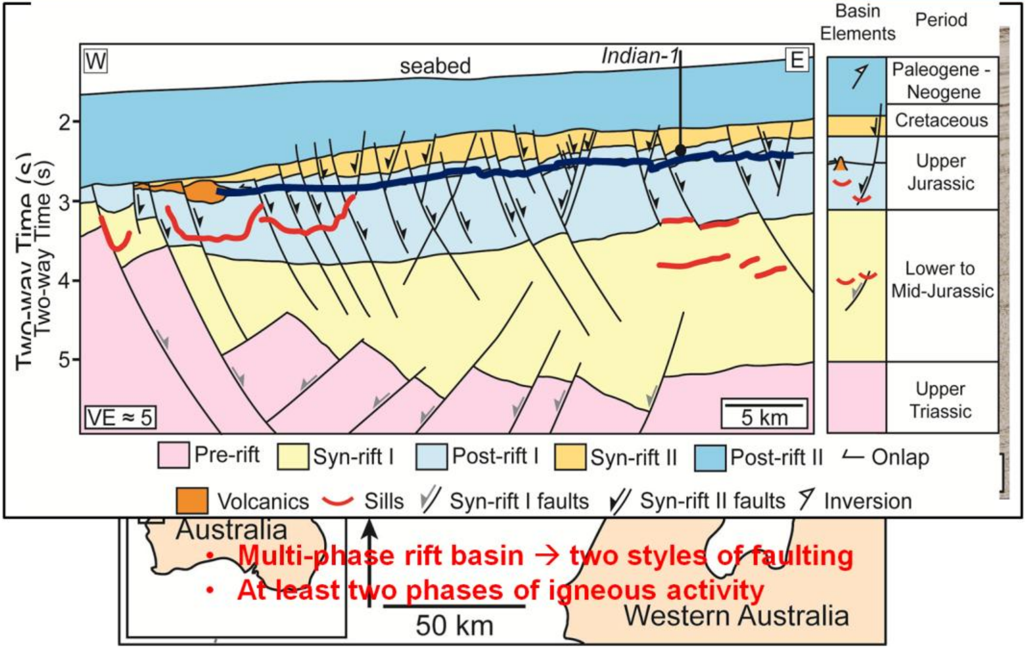
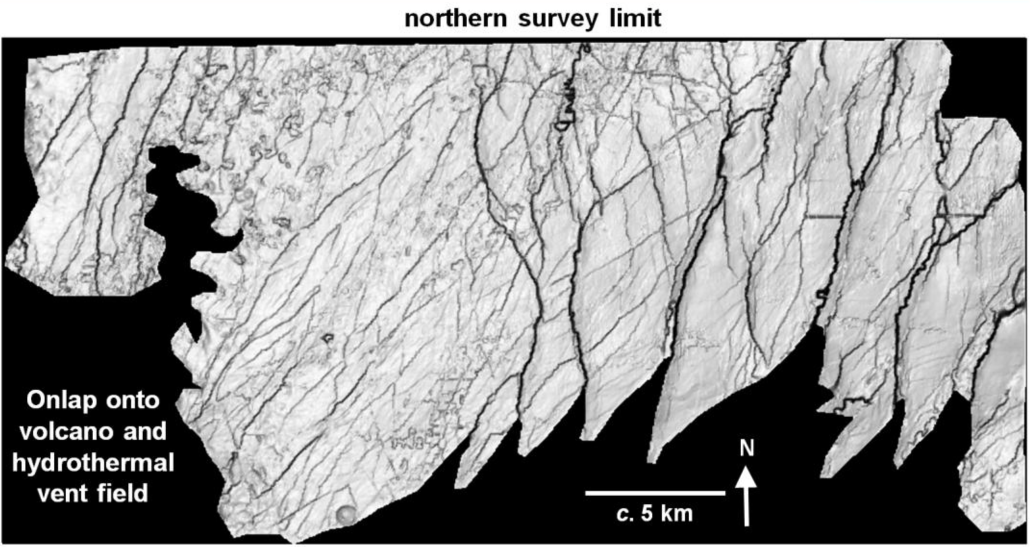


- Multi-phase rift basin → two styles of faulting
- At least two phases of igneous activity

Structural framework



- Large NNE-SSW-striking normal faults extend into Lower Jurassic
- Small NE-SW-to-NW-SE-striking faults restricted to Upper Jurassic and Lower Cretaceous

Seismic expression of igneous bodies

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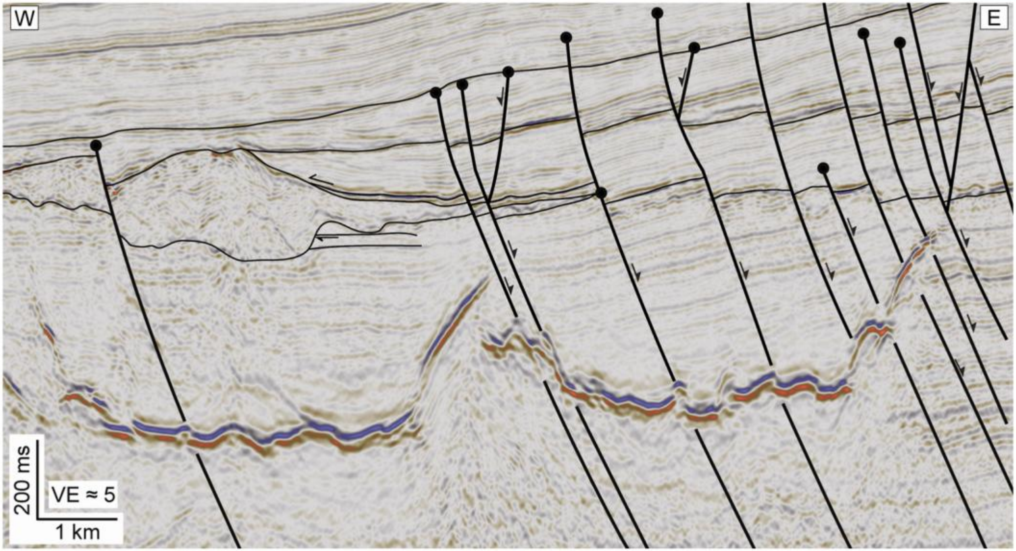
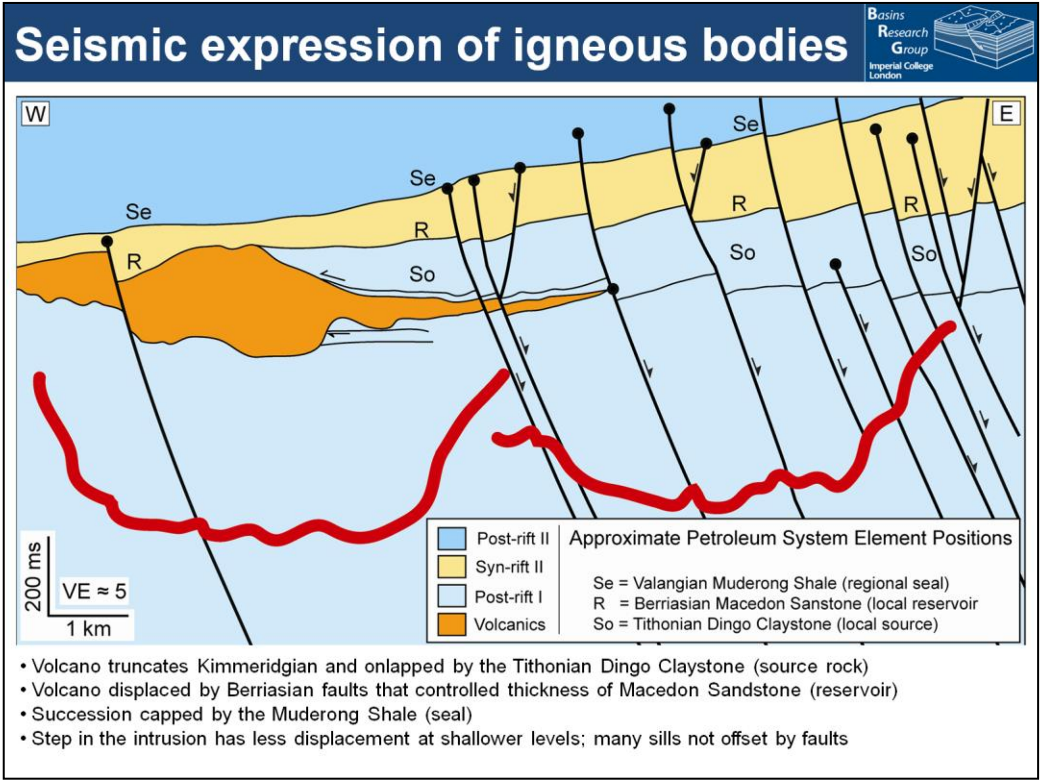


- Volcano truncates Kimmeridgian and onlapped by the Tithonian Dingo Claystone (source rock)
- Volcano displaced by Berriasian faults that controlled thickness of Macedon Sandstone (reservoir)
- Succession capped by the Muderong Shale (seal)
- Step in the intrusion has less displacement at shallower levels; many sills not offset by faults

Presenter's notes: This is a zoomed-in section of the area we are interested in; particularly the sill on the right. However, this seismic section serves to show the high-quality data and the dense network of faults around the intrusions, as well as providing some important time constraints. For example, this volcano truncates Kimmeridgian strata and is itself onlapped by the Tithonian Dingo Claystone, a potential source rock in the area. Its is displaced by these predominantly Berriasian faults, the movement of which coincided with the syn-rift deposition of Berriasian units, such as the local reservoir rock, the Macedon Sandstone. The succession is capped by the Muderong Shale, a regional seal. However, note that the step in the intrusion here does no correlate with the displacement of the volcano. Similarly, the sills often show no displacement across the faults, suggesting they formed during the post-rift phase. Note the saucer-shaped geometry of the sills



Seismic expression of igneous bodies

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🟦 Post-rift II
🟨 Syn-rift II
⬜ Post-rift I
🟧 Volcanics

Approximate Petroleum System Element Positions

Se = Valangian Muderong Shale (regional seal)
R = Berriasian Macedon Sanstone (local reservoir
So = Tithonian Dingo Claystone (local source)

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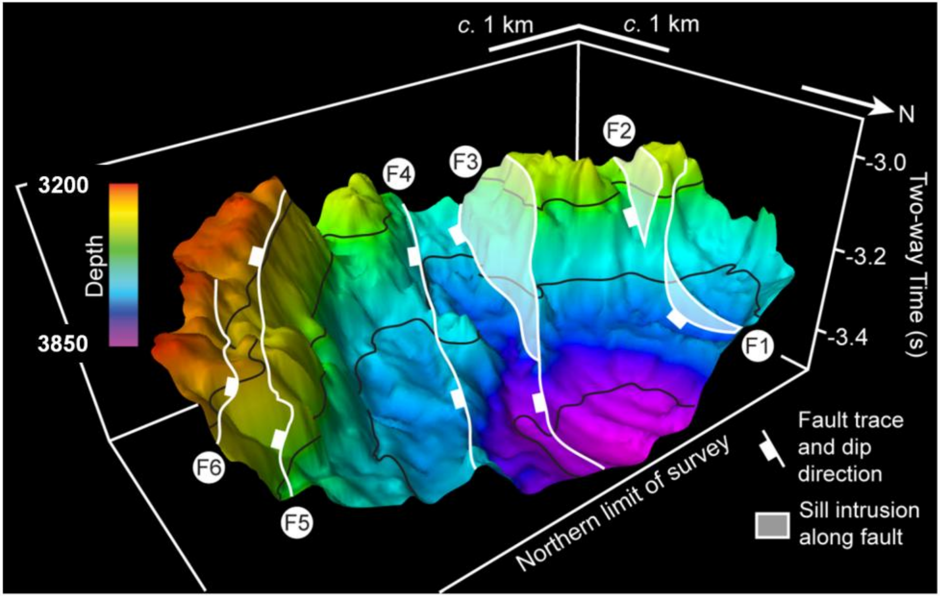
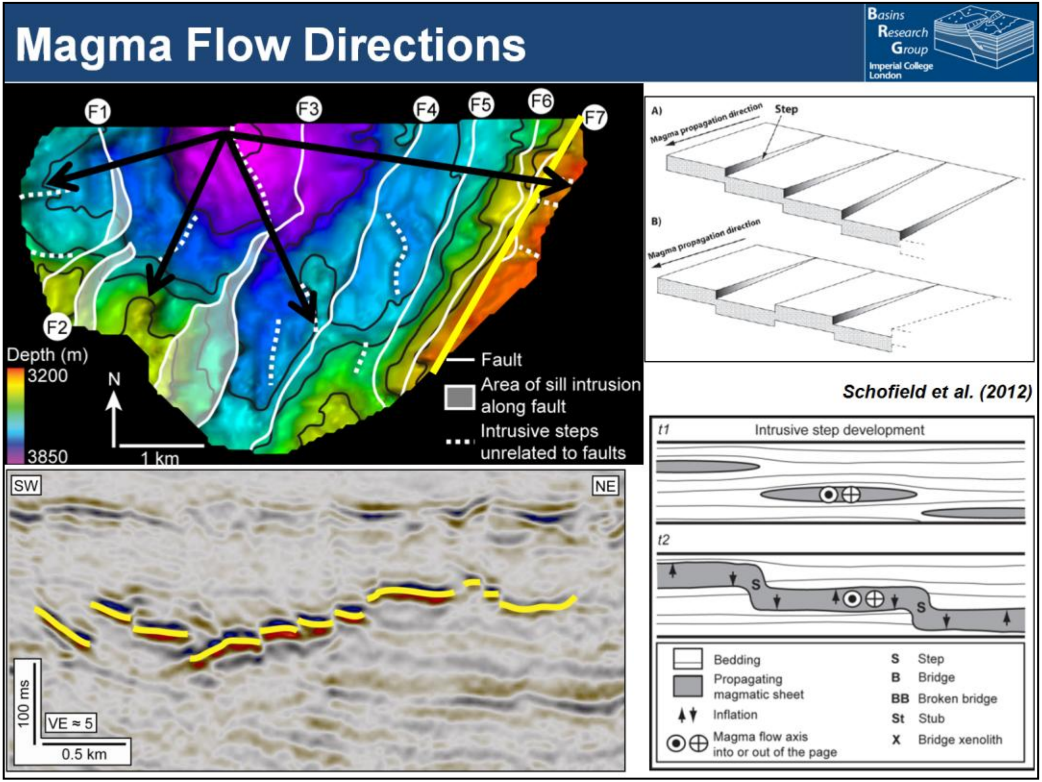
Sill Morphology



Presenter's notes: Saucer-shaped morphology commonly observed in sedimentary basins. However, the sill is cross-cut by and its overall saucer-shape is modified by normal faults. White fill along faults shows areas where inclined segments of the sill intrudes a fault for >20 m.



Magma Flow Directions

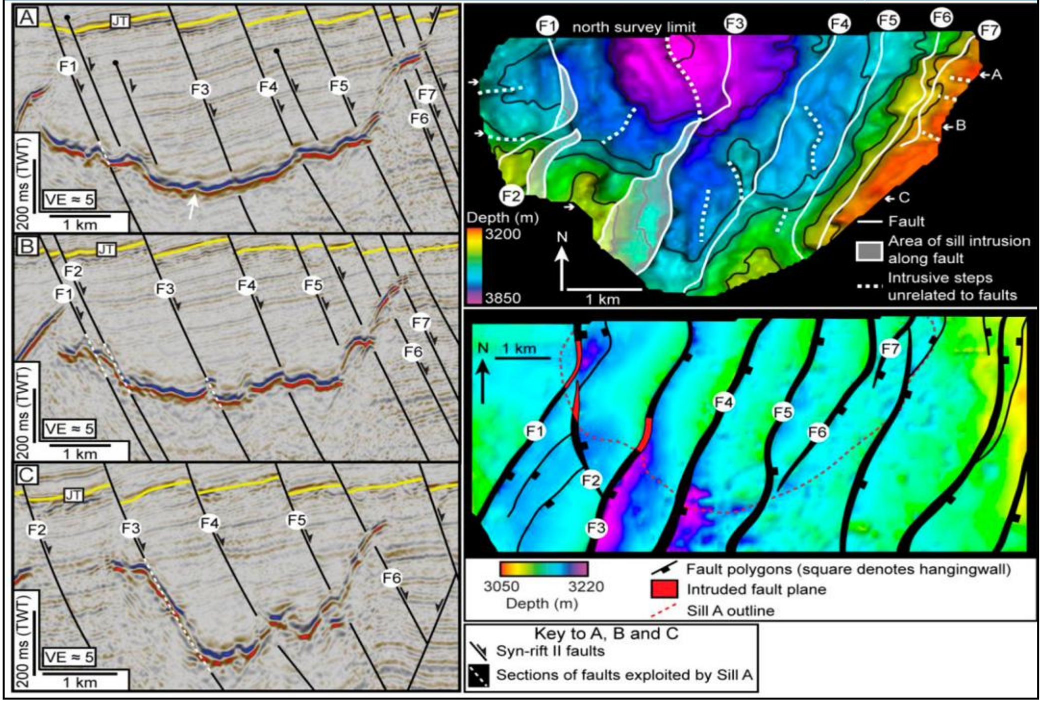
Schofield et al. (2012)

Presenter's notes: Before looking at the sill-fault interactions, it is important to determine the magma flow pattern of the sill to constrain the magma flow directions relative to the surrounding fault. Saucer-shaped sills are typically fed from a central point and magma radiates outward; field and other seismic studies have confirmed that magma initially intrudes as discrete, vertically and laterally offset segments that upon inflation coalesce to form a stepped, continuous sheet.

- Tracing the long axes of these steps can be used to determine the magma flow axis and potential source position.
- Visible flow indicators can be distinguished within this sill and typically have a stepped geometry
- For the ones in this sill, their radial nature is consistent with flow patterns observed in many other saucer-shaped sills.

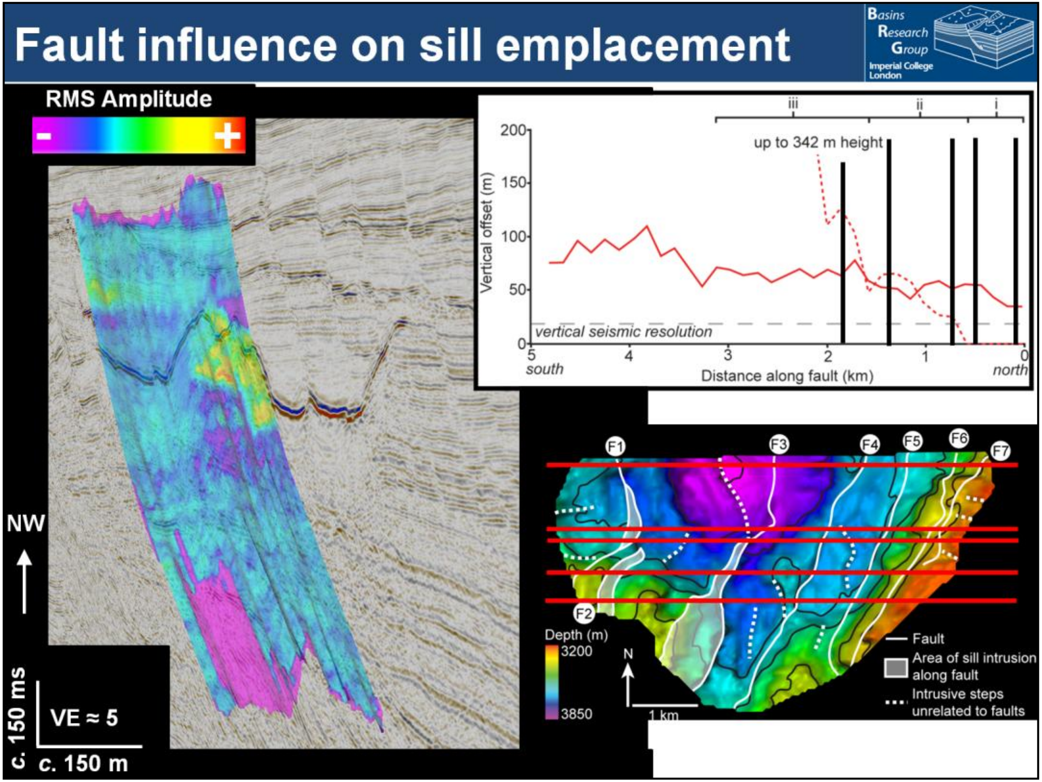
- **I am not sure that both models are needed, although I guess one shows the step orientations (upper) and one is more 'dynamic' in that it shows the progressive growth and linkage of individual lobes? → *I think they work well. I attempted to combine the two but my efforts are a bit complicated at the minute and I don't think theres time to get them right for this talk.***

Fault-Sill relationship



Presenter's notes: Throughout the sill, 3 main types of relationships between the sill and fault can be distinguished; 1/ no displacement on sill; 2/ step (20-50 m high) developed; 3/ inclined segment parallels fault. This results in a sill with a complex geometry associated with variable sill-fault interrelationships.

Fault influence on sill emplacement



Presenter's notes: RMS amplitude map of fault 3. Warm colours indicate where sill interacts with the fault. NOTE FAULT THROW INCREASE TO SOUTH. As you progress along the fault from north to south, the style of sill-fault interaction changes: starts as passing-through fault and at the junction with the intrusive step, a step is developed along the fault. This abruptly changes to a laterally restricted inclined segment.

Fault Influence on Sill Emplacement

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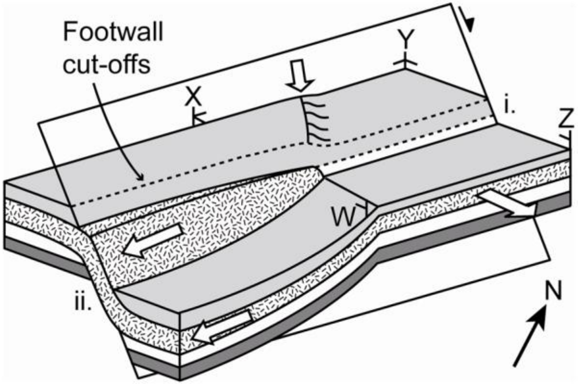
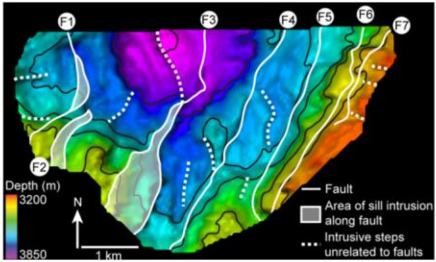




T0 – pre-intrusion stratigraphy

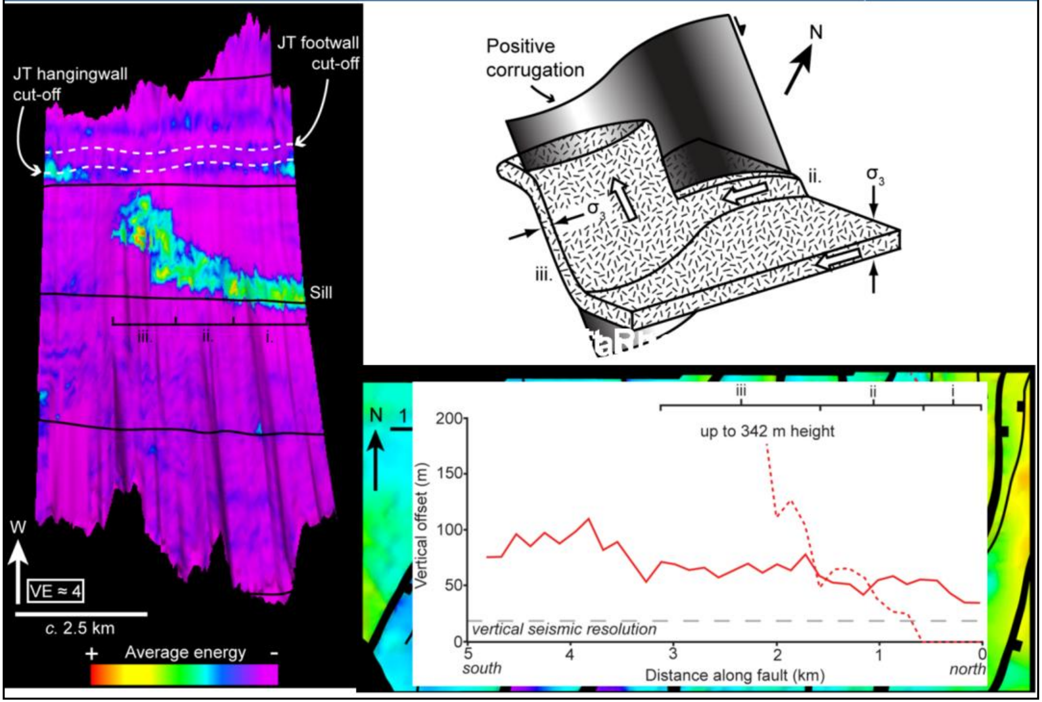
T1 – sill intrusion and step development

T2 – juxtaposition of preferentially intruded horizons across pre-existing fault

T3 – step developed along fault

Presenter's notes: Modelled pre-intrusion stratigraphy with red lines highlighting where the sill will be preferentially intruded. Where the intrusive step is observed, two different stratigraphic horizons have been intruded. As fault is approached, the lower segment passes directly through the fault, suggesting the two preferential horizons have been juxtaposed. The magma flow pattern that this suggests is consistent with the axis of the intrusive steps to the SE. Where the upper intrusive step segment interacts with the fault, the increased fault throw means the preferential horizons are not juxtaposed so some magma has to intrude fault to 'bridge' the horizons. Two possible flow mechanisms: 1/ down the fault, although this is inconsistent with the sill transgression in the hangingwall; 2/ or more likely, the magma flow is locally redirected to flow parallel to the fault.

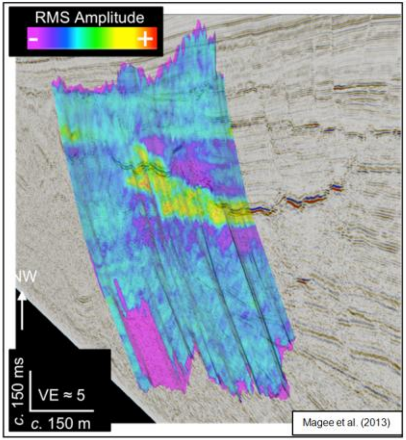
Fault Influence on Sill Emplacement



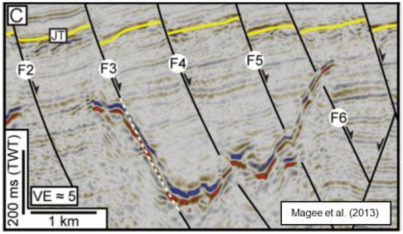
Presenter's notes: Average energy map of fault to highlight the restricted intrusion along the fault. Abrupt transition from step to intrusion along fault implies a change in magma flow from fault-strike-parallel to up the fault. Why such a rapid, localised change?

Two possibilities are considered: 1/ change in fault rock properties; although not directly detectable using seismic-imaging methods, the throw along the fault does not seem to change significantly; and 2/ fault geometry; map view of Base Tithonian horizon to highlight fault geometries shows that the inclined sill segments exploiting fault segments occur at positive fault corrugations. Intrusion often occurs orthogonal to the least compressive stress; for sills sigma 3 is typically vertical. We suggest that stress field variations associated with an irregular fault geometry locally reorients sigma 3 to be fault-perpendicular, thereby favouring magma intrusion along the fault.

Sill-fault relationships



Magee et al. (2013)



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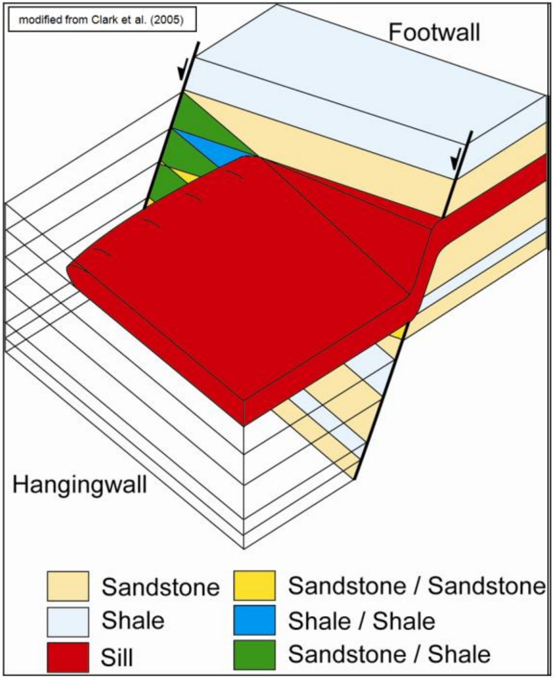

modified from Clark et al. (2005)

Presenter's notes: As I discussed in another presentation, the geometric relationship between igneous intrusions and faults in the encasing host rock is very complicated. For example, igneous bodies may preferentially intrude certain parts of faults and contribute to hydrocarbon trapping in both the footwall and hangingwall.

Petroleum system implications

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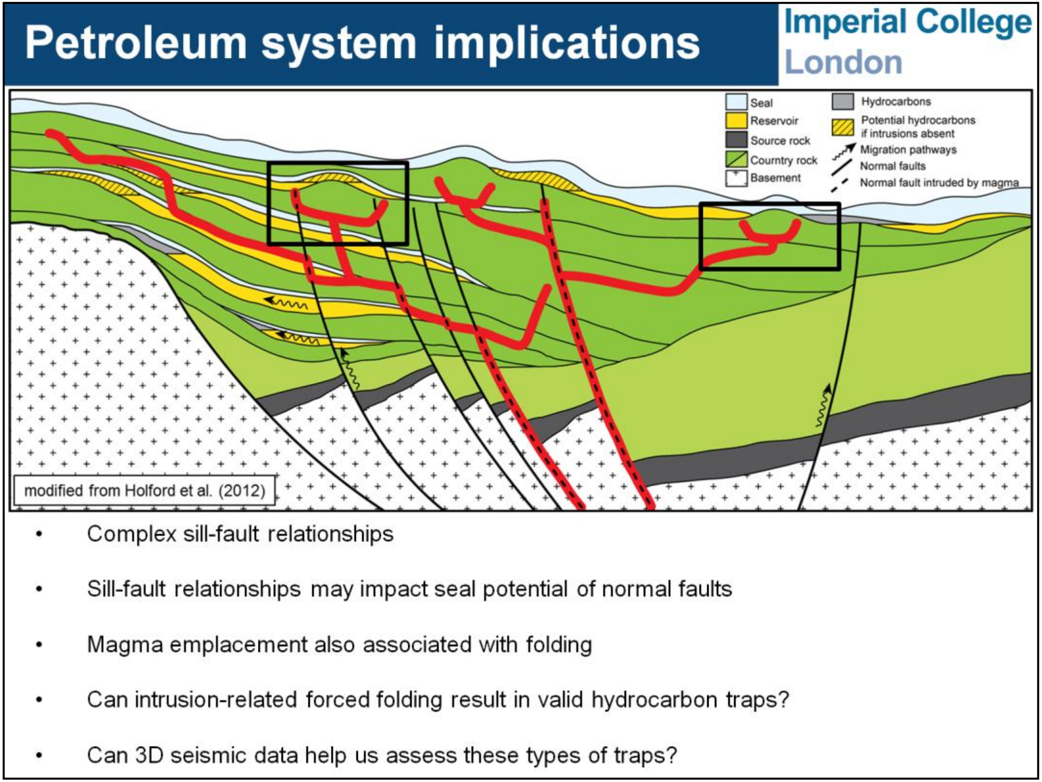


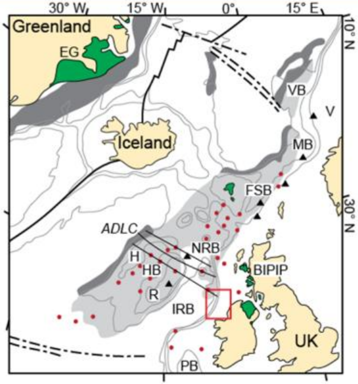
modified from Holford et al. (2012)

- Complex sill-fault relationships
- Sill-fault relationships may impact seal potential of normal faults
- Magma emplacement also associated with folding
- Can intrusion-related forced folding result in valid hydrocarbon traps?
- Can 3D seismic data help us assess these types of traps?

Presenter’s notes: This figure highlights the impact that igneous systems can have on petroleum system development in sedimentary basins. This figure principally highlights compartmentalisation of basin by vertically- and laterally-extensive intrusions; furthermore, in the upper part of the basin, the impact of intrusions on trap development is highlighted.

A secondary aim of this presentation, which was noted in another presentation, is how seismic reflection data, in particular high-quality, three-dimensional data, can help us understand igneous processes in a more general sense.

Geological Setting



Presenter's notes: Well drilled in 2001 on an oil prospect called Errigal, defined as a 70km2 4-way dip closure of uncertain origin. Well had two objectives: Upper and Lower Palaeocene deep-water sandstones.

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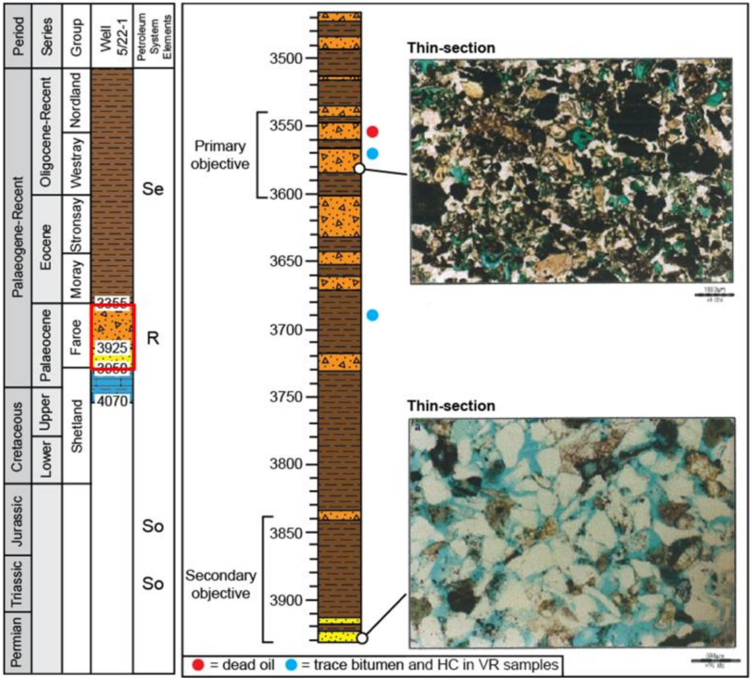

● = dead oil ● = trace bitumen and HC in VR samples

- Complex sill-fault relationships
- Sill-fault relationships may impact seal potential of normal faults
- Magma emplacement also associated with folding
- Can intrusion-related forced folding result in valid hydrocarbon traps?
- Can 3D seismic data help us assess these types of traps?

Presenter's notes: Upper Palaeocene primary objective is dominated by 1-4 m thick beds of poorly cemented, very fine-to fine-grained (with occasional medium and coarse grains), volcaniclastic sandstones with little or no reservoir quality. Sands are subangular to subrounded, well sorted, of moderate sphericity. Underlying Upper Palaeocene objective is composed of reservoir quality, quartzose sandstones that were water-wet. No sandstones in Lower Palaeocene. No HC shows (dead oil at 3558 m). Fluid inclusions indicate locally high (119 degrees) temperatures related to a short-term heating event; volcanic-related hydrothermal fluids. Minimal impact on reservoir quality due to poor inherent reservoir quality, but it does provide auxiliary evidence for volcanic activity…

Igneous intrusions and regional structure

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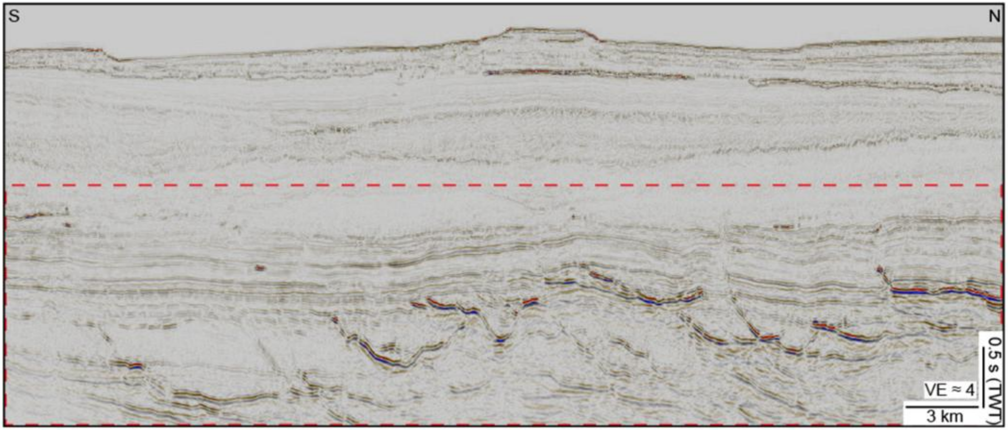
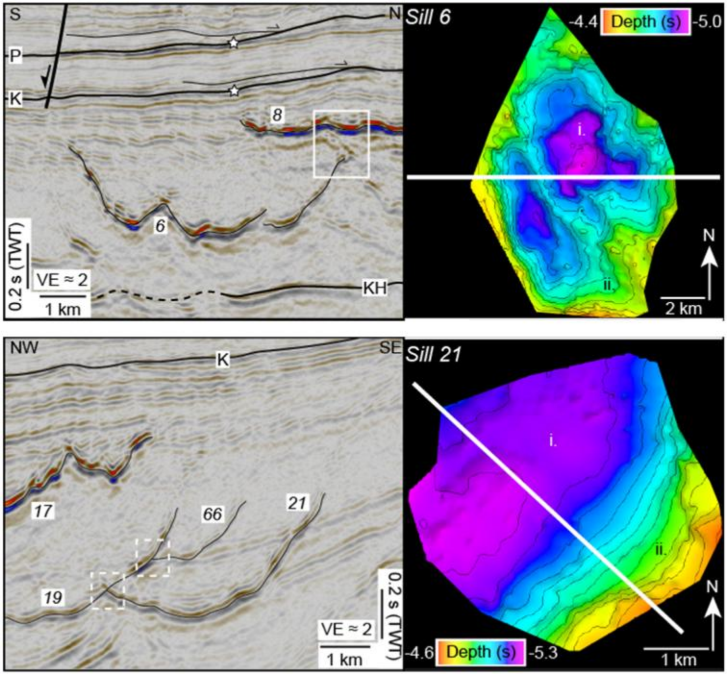
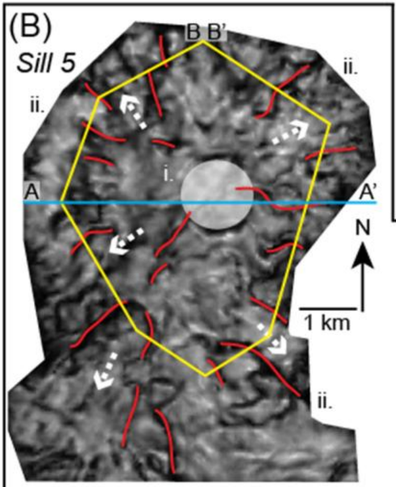


Seismic expression of intrusions



Magma flow directions

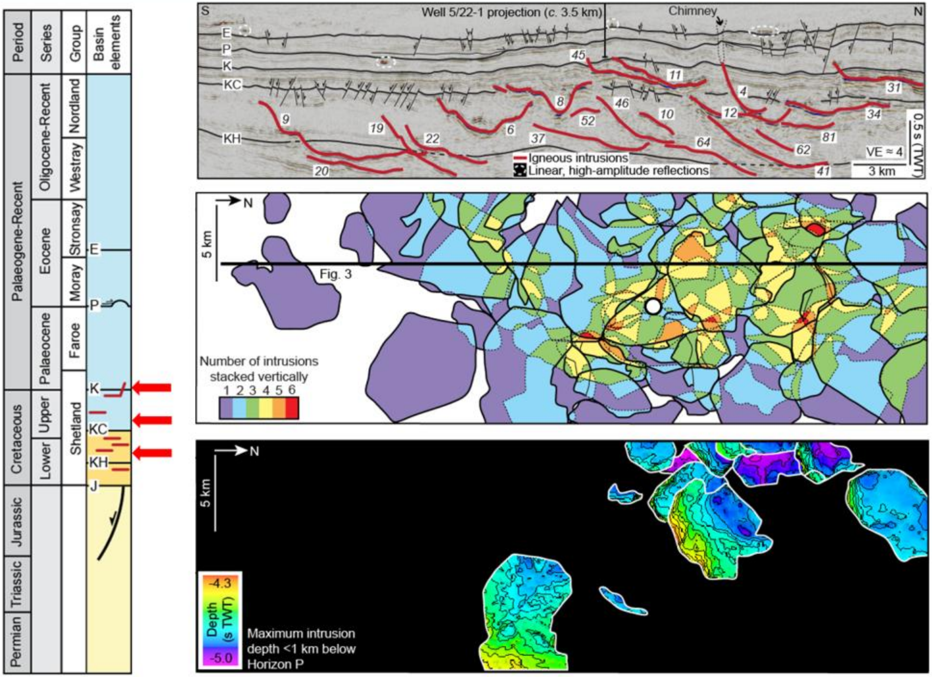


Key

- — Flow indicator long axis
- ···➔ Inferred magma flow direction
- ● Potential feeder zone
- **S** Intrusive step
- **B** Host rock bridge
- **L** Lobe-lobe contact

Amplitude: − to +

Sill stacking and density



Intra- and supra-sill structure

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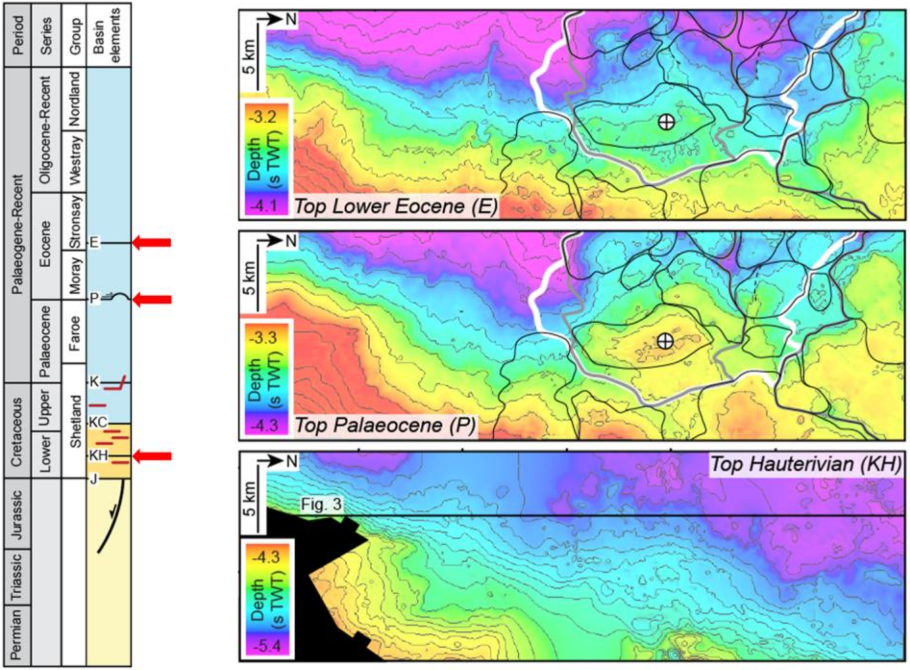
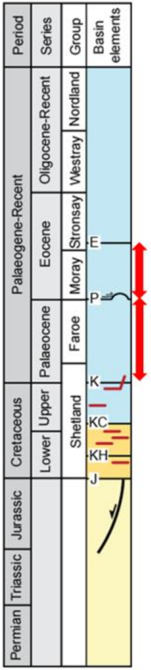
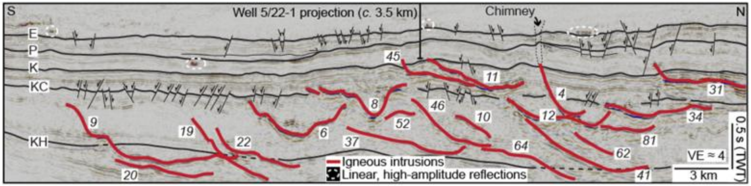
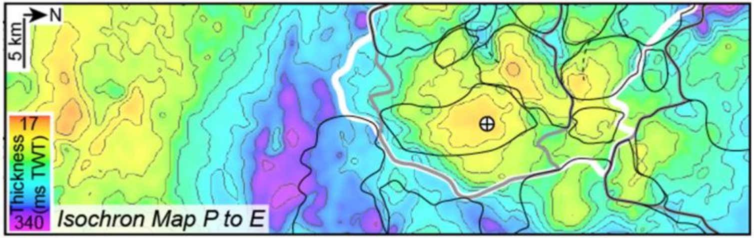


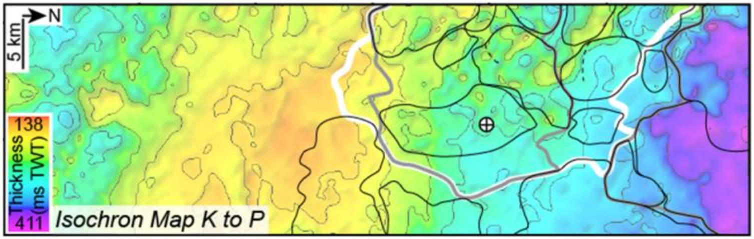
Stratal patterns and intrusion timing





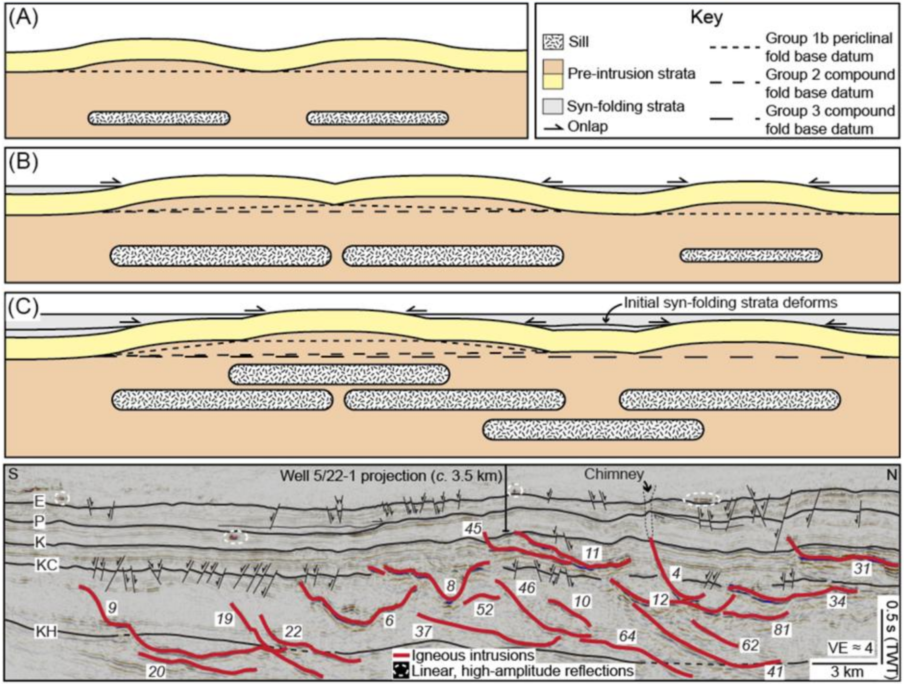


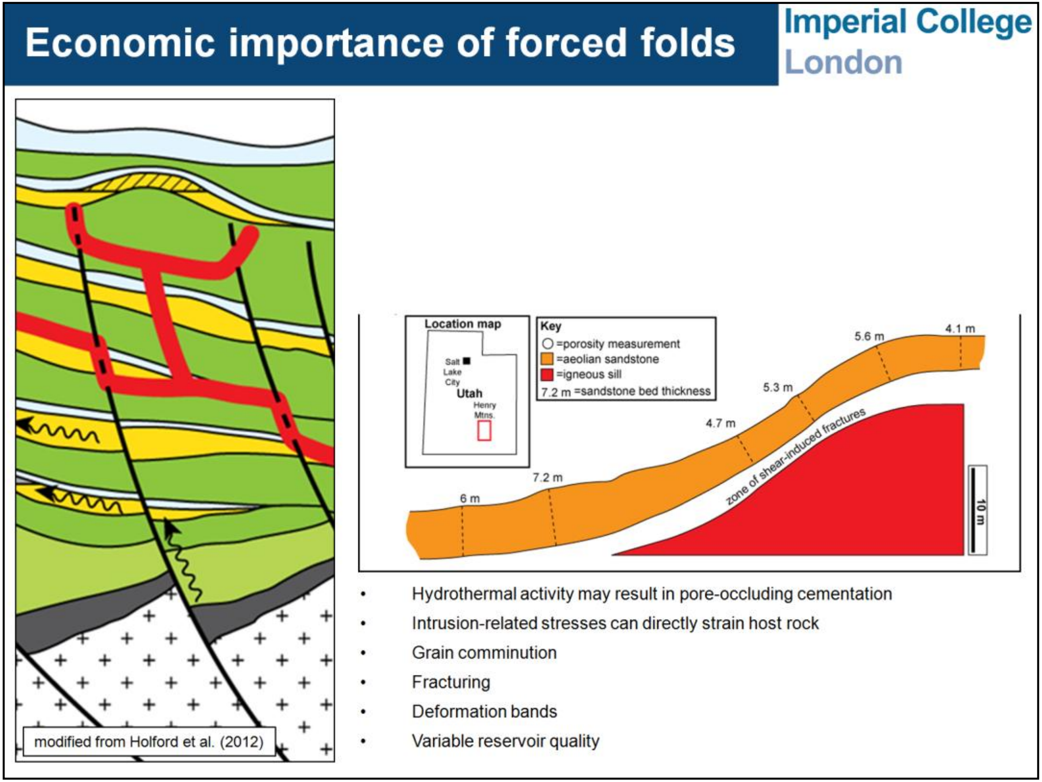
Isochron Map P to E



Isochron Map K to P

Intrusion-related forced folding





Economic importance of forced folds

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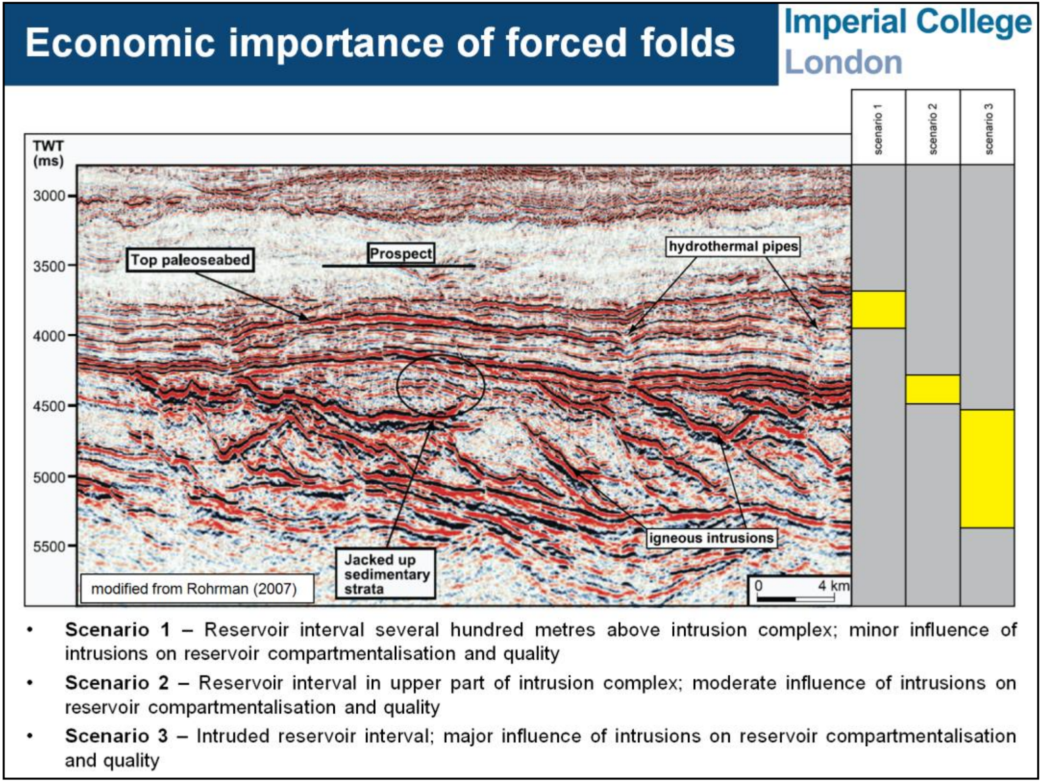
modified from Holford et al. (2012)

- Hydrothermal activity may result in pore-occluding cementation
- Intrusion-related stresses can directly strain host rock
- Grain comminution
- Fracturing
- Deformation bands
- Variable reservoir quality

Presenter's notes: Reservoir quality may not only be affected by pore-occluding cementation driven by sill-related hydrothermal activity; intrusion-related stresses may result in direct straining of the reservoir, which can result in grain comminution and direct porosity reduction, fracturing, and deformation band development (which may result in local reduction in porosity and permeability)



Economic importance of forced folds

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- **Scenario 1** – Reservoir interval several hundred metres above intrusion complex; minor influence of intrusions on reservoir compartmentalisation and quality
- **Scenario 2** – Reservoir interval in upper part of intrusion complex; moderate influence of intrusions on reservoir compartmentalisation and quality
- **Scenario 3** – Intruded reservoir interval; major influence of intrusions on reservoir compartmentalisation and quality

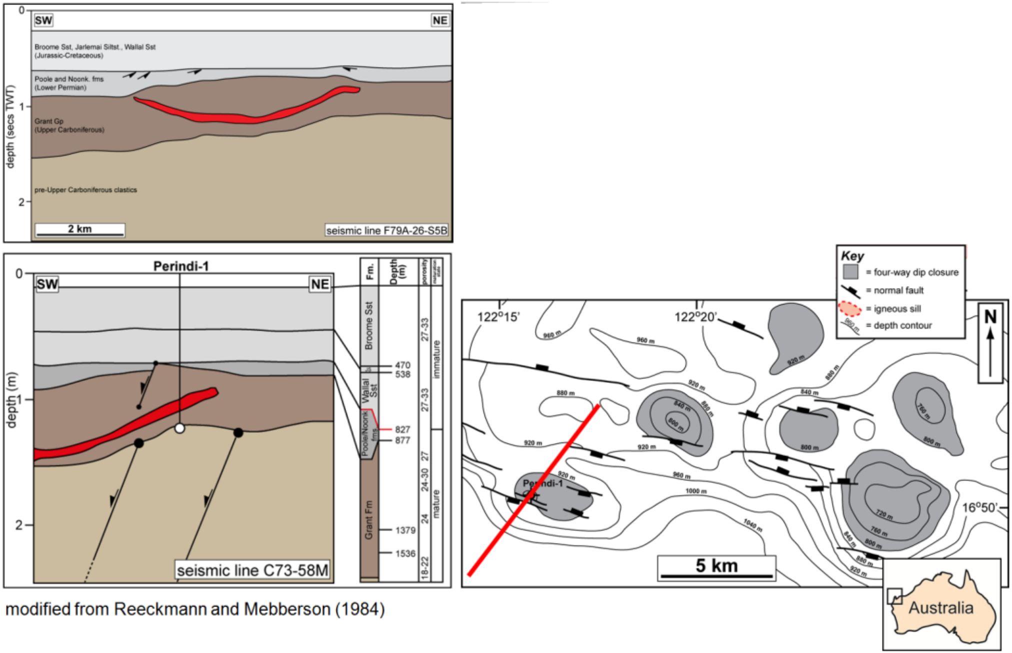
Presenter's notes: As highlighted by the conceptual model of Holford et al. (2012) (as noted earlier), the intrusion of igneous bodies can result in compartmentalisation of several elements of the petroleum system (i.e., source, reservoir, and seal).

• This example, which has been modified from Rohrman (2007) and which we speculate comes from the North Atlantic Igneous Province (NAIP), illustrates a highly intruded part of the stratigraphic interval, which underlies a low-relief, forced-fold trap

• Depending on the stratigraphic level at which the reservoir occurs, the igneous intrusions have a range of potential impacts on prospectivity as highlighted in the three scenarios above.

• Note that all three scenarios are associated with a migration risk if the source interval is located beneath the heavily-intruded interval

Economic importance of forced folds



modified from Reeckmann and Mebberson (1984)

Presenter's notes: Another example of sill-related forced folding comes from the Canning Basin on the NW Shelf of Australia in the ground-breaking paper of Reeckmann and Mebberson (1984). In this location a series of sills and dykes of suspected Permian age intruded an Upper Carboniferous, predominantly clastic succession and resulted in forced folding of overlying Permian deposits. The dome-shaped folds in the Canning Basin display amplitude of up to several hundreds of metres and are several kilometres in diameter.

- One of these folds was the target of the Perindi-1 exploration well in 1983, and this proved hydrocarbon shows in the Upper Carboniferous; failure of the well was ascribed to trap leakage due to normal faults and fractures located at the crest of the structure.

Implications and Conclusions

- Shallowly dipping igneous intrusions (sills) can be well imaged on seismic reflection data
- It is possible to constrain magma flow directions and timing of emplacement without the use of classic dating techniques (e.g., Ar-Ar, K-Ar)
- Normal faults can influence the transport of magma in the upper crust and the morphology of the sills
- The emplacement of sills can be accommodated by kilometre-scale forced folding
- Igneous intrusions can have a major impact on petroleum system development (e.g., trap development, reservoir quality, source rock maturation)
- Key areas for future research include:
  - Forced-fold trap mapping and volumetric calculations
  - Reservoir quality variations as a result of igneous emplacement
  - Sill-fault relationships and influence on seal capacity
  - Impact of igneous emplacement on source rock maturation