

Polygonal Faulting and Seal Integrity in the Bonaparte Basin, Australia*

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Abstract

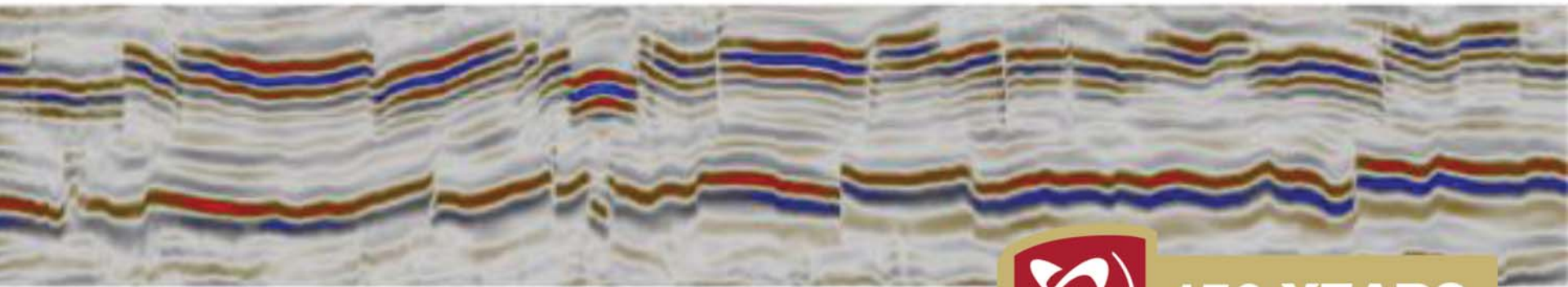
Polygonal fault systems are observed in over 100 sedimentary basins worldwide where they are confined to fine-grained strata. These widespread non-tectonic layer-bound normal fault systems therefore have the potential to impact on seal integrity for CO₂ storage and petroleum reservoirs. 3D seismic reflection and well data have been used to characterise a layer-bound polygonal fault system and gas chimneys in the Bathurst Island Group regional seal, Petrel Sub-basin, offshore NW Australia as part of Geoscience Australia's offshore CO₂ assessment program. Segmented fault arrays extend through the entire faulted interval, which contains at least 10 tiers of polygonal faults each spanning c. ~4 Myrs of sediment deposition. Polygonal fault densities and intersections reach a maximum at 1000–1100 ms TWT and in some cases extend into the Sandpiper Sandstone reservoir at >1200–1300 ms TWT. Down-dip displacement profiles are symmetrical and increase progressively across tier boundaries towards maxima of ~25–47 ms between 600 and 1100 ms TWT. These systematic displacement variations are similar to those of tectonic faults and suggest that fault segments in different tiers develop synchronously as kinematically coherent arrays. Three-dimensional imaging of the polygonal fault system indicates that throughout the Bathurst Island Group the fault network is well connected vertically and horizontally. Polygonal faulting may locally promote gas flow through the seal to the seabed suggesting that, where faulted, the Bathurst Island Group may not be an effective seal for CO₂ storage in the study area.

Selected References

Rutqvist, J., 2012, The Geomechanics of CO₂ storage in deep sedimentary formations: Geotechnical and Geological Engineering, v. 30, p. 525-551.

Tewksbury, B.J., J.P. Hogan, S.A. Kattenhorn, C.J. Mehrrens, and E.A. Tarabees, 2014, Polygonal faults in chalk: Insights from extensive exposures of the Khoman Formation, Western Desert, Egypt: Geology, v. 42/6, p. 479-482.

Polygonal faulting and seal integrity in the Bonaparte Basin, Australia



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Acknowledgements

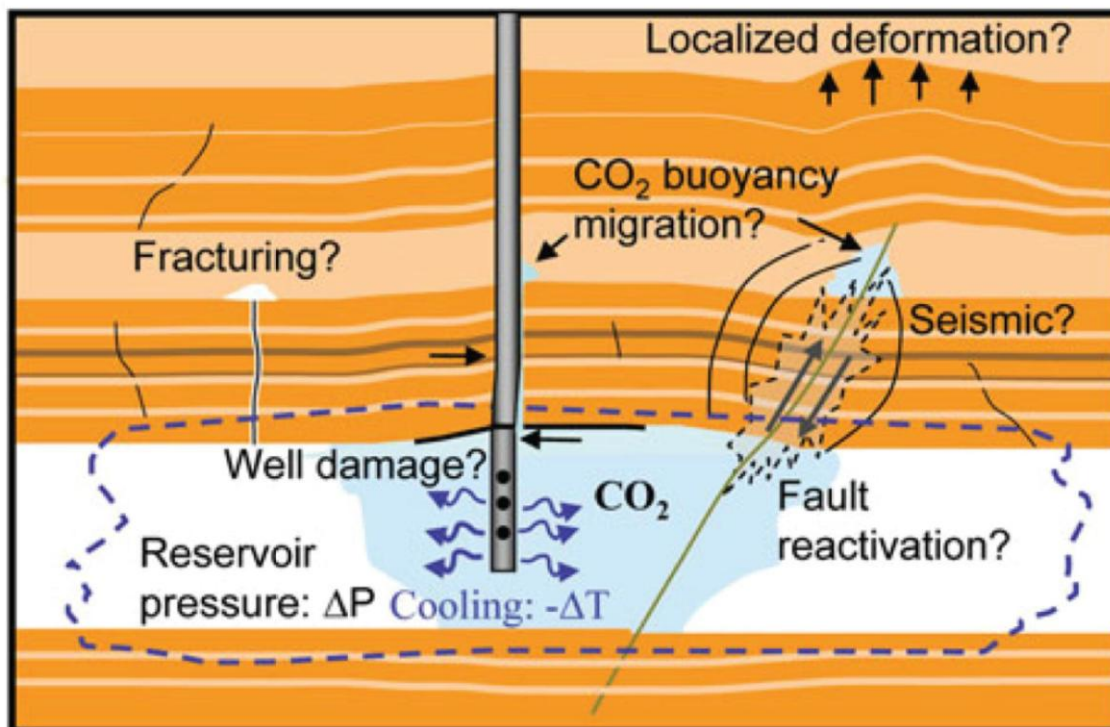
**This study was conducted as part of
Geoscience Australia's offshore CO₂ assessment program**

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and

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Rutqvist (2012)

Carbon Capture and Storage (CCS)

Geological storage of CO₂ technically feasible

Secure CO₂ storage over geological timescales

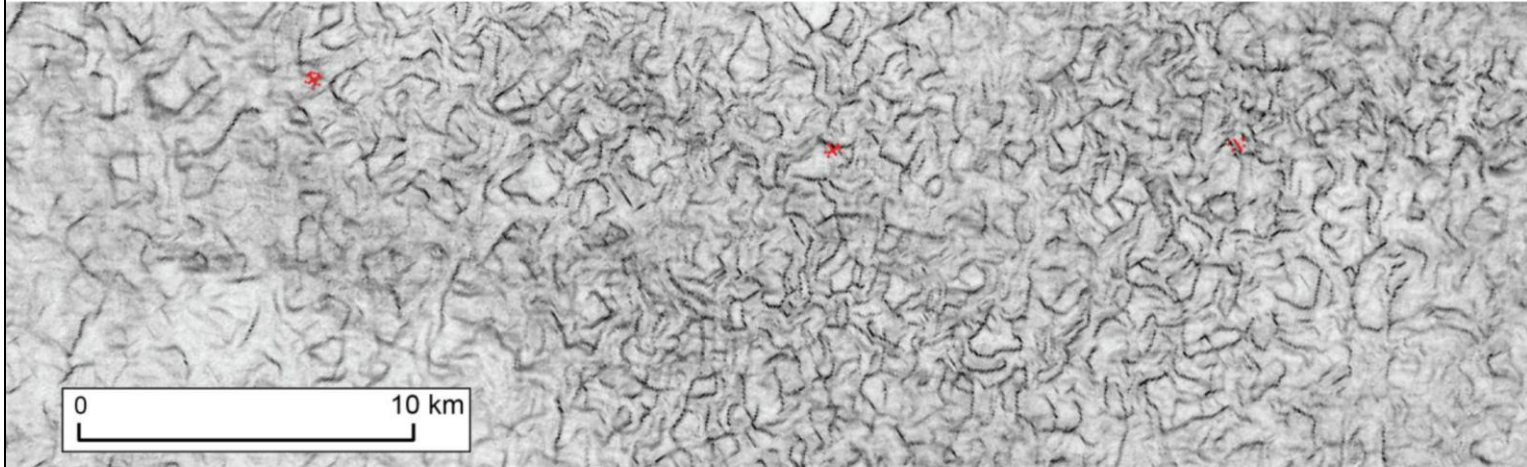
Public concern over potential earthquakes and leakage

Presenter's notes: Recent experience from CO₂ injection at a number of pilot projects, as well as a few ongoing commercial projects demonstrates that CO₂ geological storage in deep sedimentary formations is technologically feasible. However, if CCS is implemented on the scale needed to make noticeable reductions in atmospheric CO₂, a billion metric tons or more must be stored annually. For CCS to be successful the injected CO₂ needs to remain in the target reservoir over geological time scales. Seal integrity is a key risk in the storage of CO₂ with faults and wells being identified as potential high permeability pathways toward the surface. Depending on the nature of the reservoir, increased pore fluid pressures resulting from the injection (Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

of large volumes of CO₂ may result in reactivation of pre-existing weaknesses associated with faults and abandoned wells and the upward migration of super critical CO₂. To date polygonal faults have received little attention with respect to their impact on seal integrity in relation to CO₂ storage. This study focuses on an extensive array of polygonal faults within a regional seal immediately above potential CCS reservoirs.

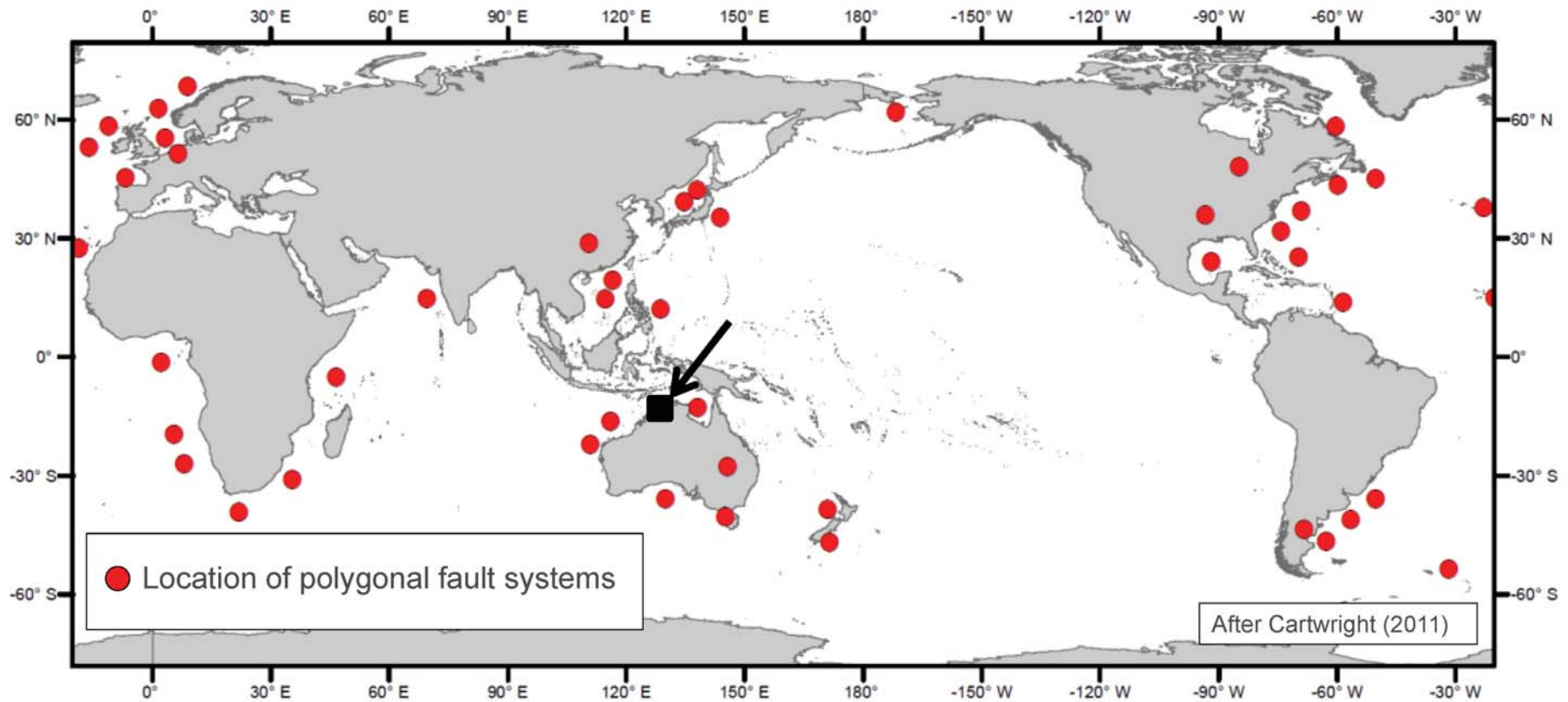
Polygonal Fault Systems

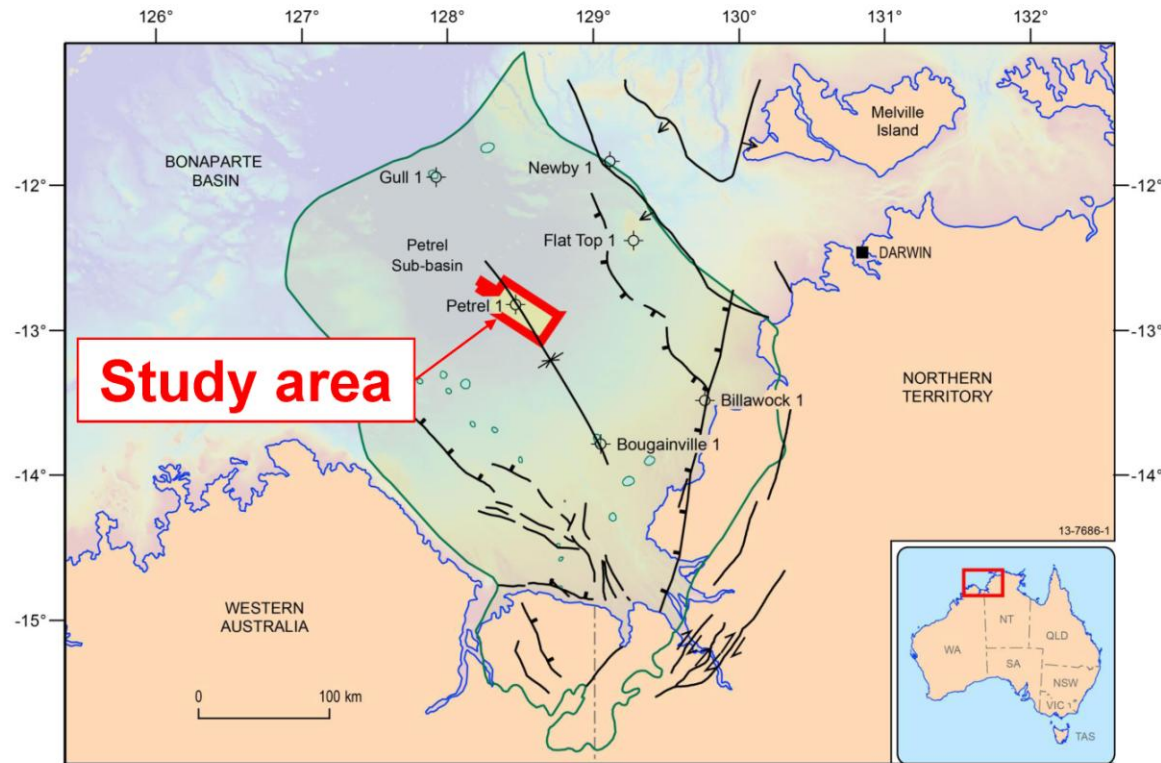


Coherency time slice
Petrel Sub-basin, NW Australia

Presenter's notes: Polygonal Fault Systems are layer-bound non-tectonic normal faults forming polygonal patterns in map view. They are believed to be formed by dewatering and/or volume contraction of hemi-pelagic sediments and cover areas of hundreds of thousands to millions of square kilometres along the majority of continental margins. The processes resulting in polygonal fault formation are not presently well known however recent outcrop studies (shown later in the presentation) indicate elevated pore fluid pressures generated during burial are a primary driving mechanism. Joint-bounded polygonal columns develop in a wide variety of materials, such as columnar joints in cooling lavas and desiccation cracks in drying mud, and range in scale from millimetres to hundreds of metres in diameter. Whereas desiccation cracks and columnar jointing are governed by dispersive laws and start at the surface and migrate down, polygonal faults nucleate at depth and migrate up and their genesis is probably linked to convective laws of fluid migration.

Global distribution





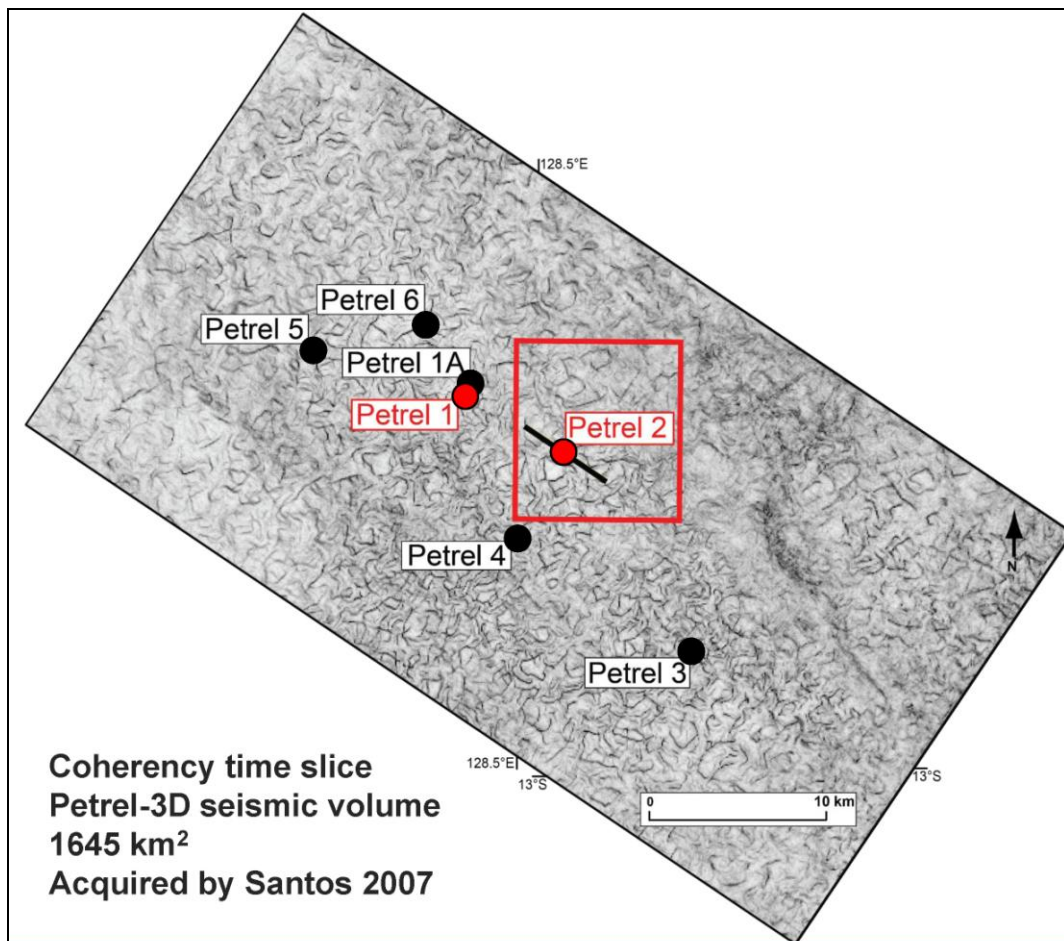
Bonaparte Basin, NW Australia

**Petrel sub-basin
highly prospective for
CO₂ storage**

**Jurassic to
Cretaceous reservoirs**

**Cretaceous Bathurst
Island Group regional
seal**

Presenter's notes: Australia's northwestern shelf has extensive oil and gas reserves, and like many CCS projects, consider hydrocarbon provinces as potential sites for CO₂ storage. The Petrel Sub-basin, part of the Bonaparte Basin on the NW Australian shelf, contains Jurassic to Cretaceous reservoirs overlain by Cretaceous seals and is considered to be a highly prospective basin for CO₂ storage. The Cretaceous Bathurst Island Group regional seal has developed an extensive polygonal fault system in this area and is the focus of this study.



Questions

How do polygonal faults form?

Do they impact on seal integrity?

Data

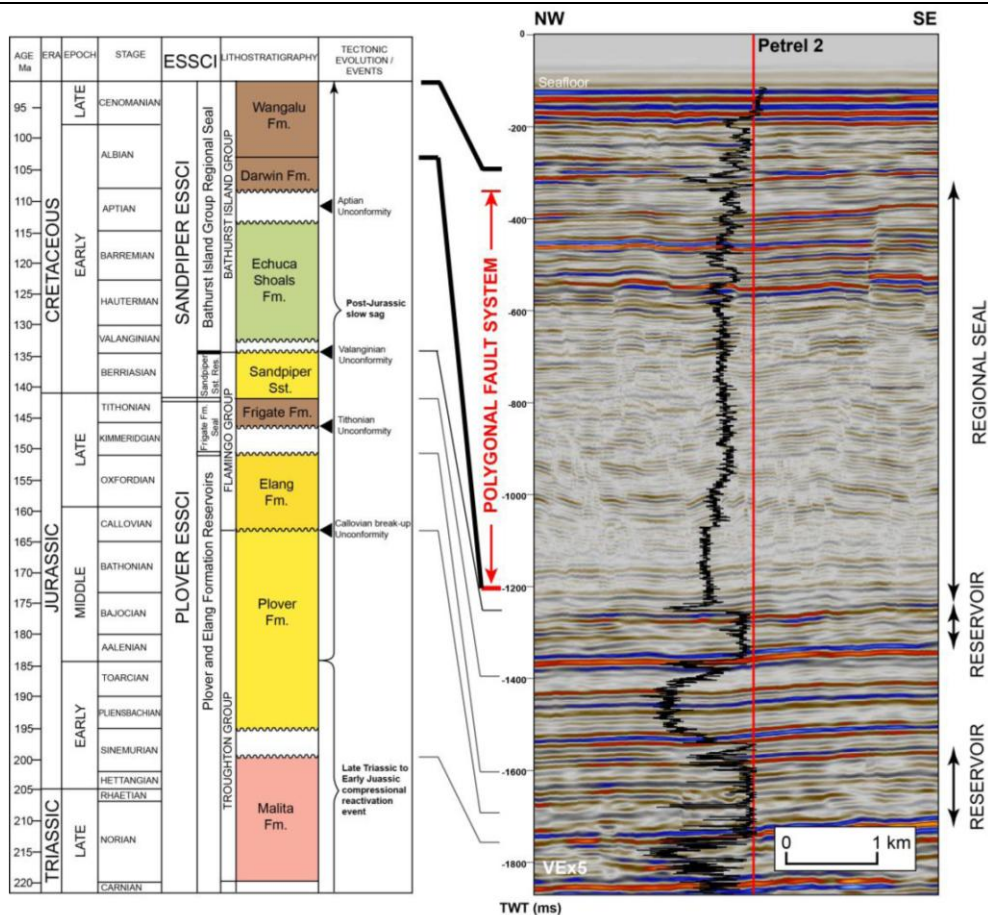
Industry standard 3D seismic reflection data

4 ms vertical resolution < 2 s TWT

Exploration well data

Outcrop analogues

Presenter's notes: Industry standard 3D seismic reflection volume acquired by Santos in 2007 has a typical vertical resolution of 4 ms in the top two seconds. To complement the Petrel 3D seismic volume, seven hydrocarbon exploration wells drilled between 1969 and 1996 provide information on sediment composition, velocity, and fluid pressures within and beneath the regional seal.



Regional Seal Bathurst Island Group

700 m thick micaceous
mudstone deposited in low
energy environment

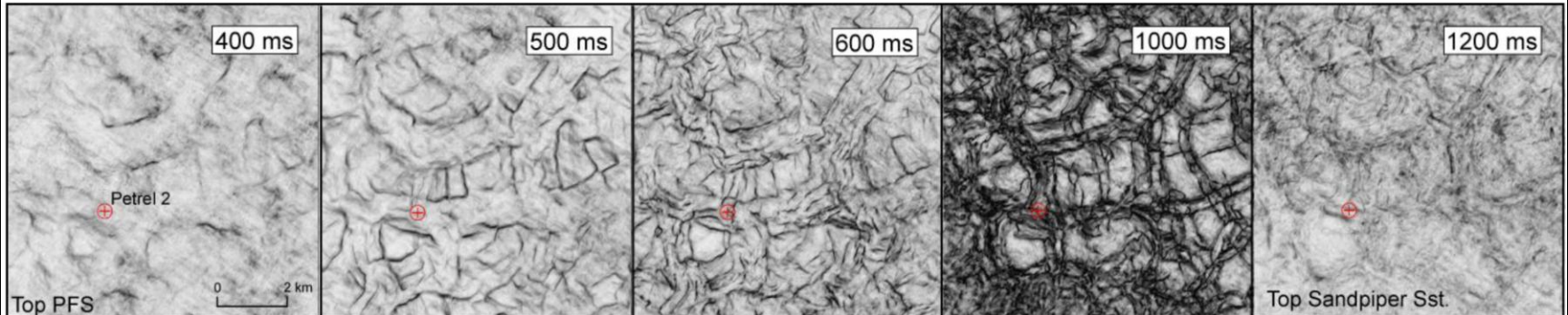
Sedimentation rate < 20 m/Ma

Extensively faulted by low
displacement normal faults

Presenter's notes: The Bathurst Island Group in the Petrel sub-basin is predominantly composed of micaceous mudstone with variable amounts of glauconitic siltstone, sandstone, marl, carbonate and claystone and overlies several prospective sandstone reservoirs (environmentally sustainable sites for CO₂ injection). In the study area, the Bathurst Island Group is approximately 700 m thick and developed over a 40 Myr interval in low energy environment with sedimentation rates ≤ 20 m/Ma. Seismic reflection data shows that the generally low reflectivity typical of shales is extensively faulted by low displacement normal faults though the majority of the Bathurst Island Group.

Polygonal Fault System geometry

Coherency time slices



10 strata bound tiers ~70m thick

Fault lengths <1.5 km

Normal displacements < 50 ms (m)

No preferred fault strike

High angle intersections

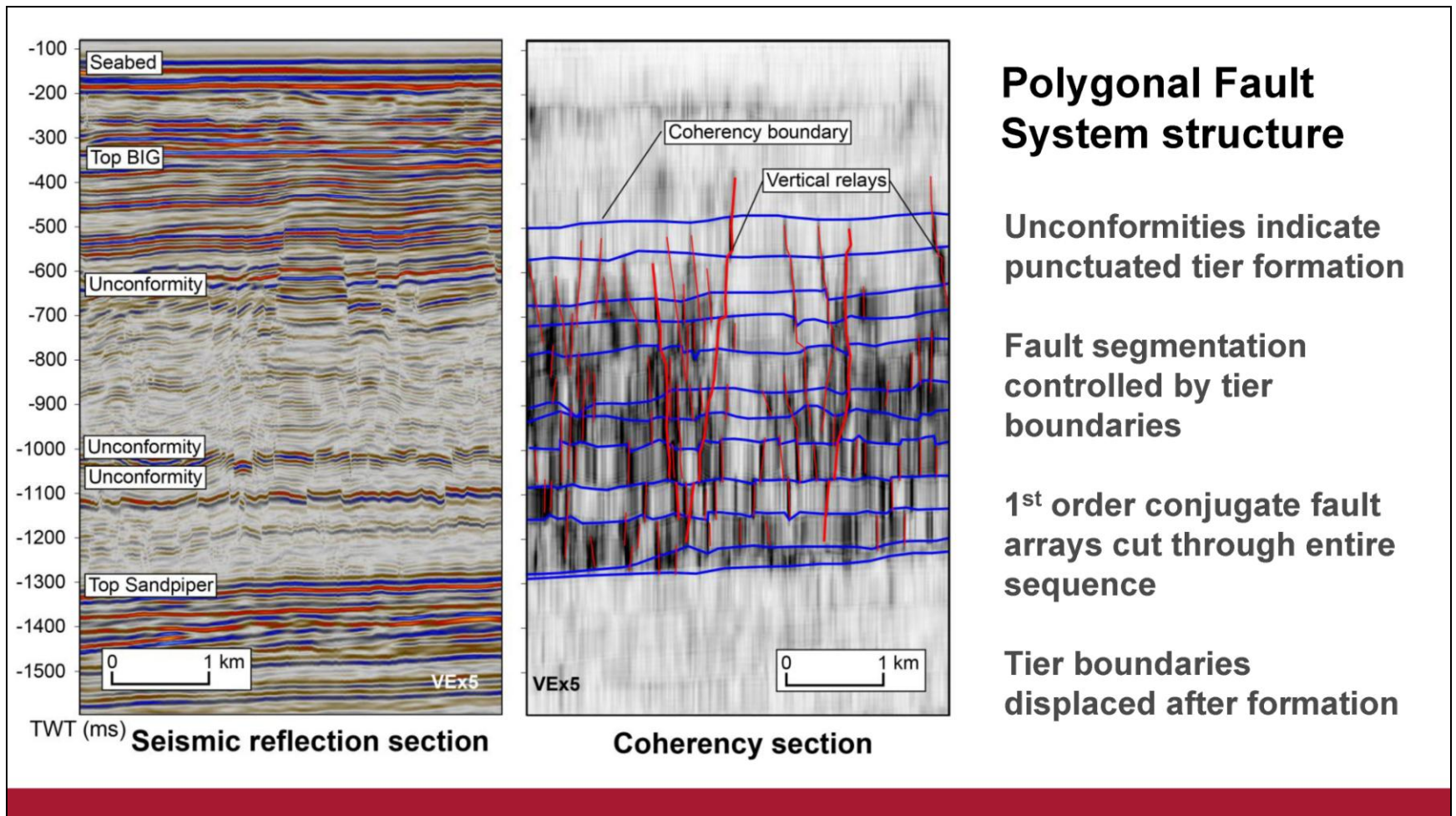
Cell dimensions 0.5 to 1.5 km

Increasing fault frequency with depth

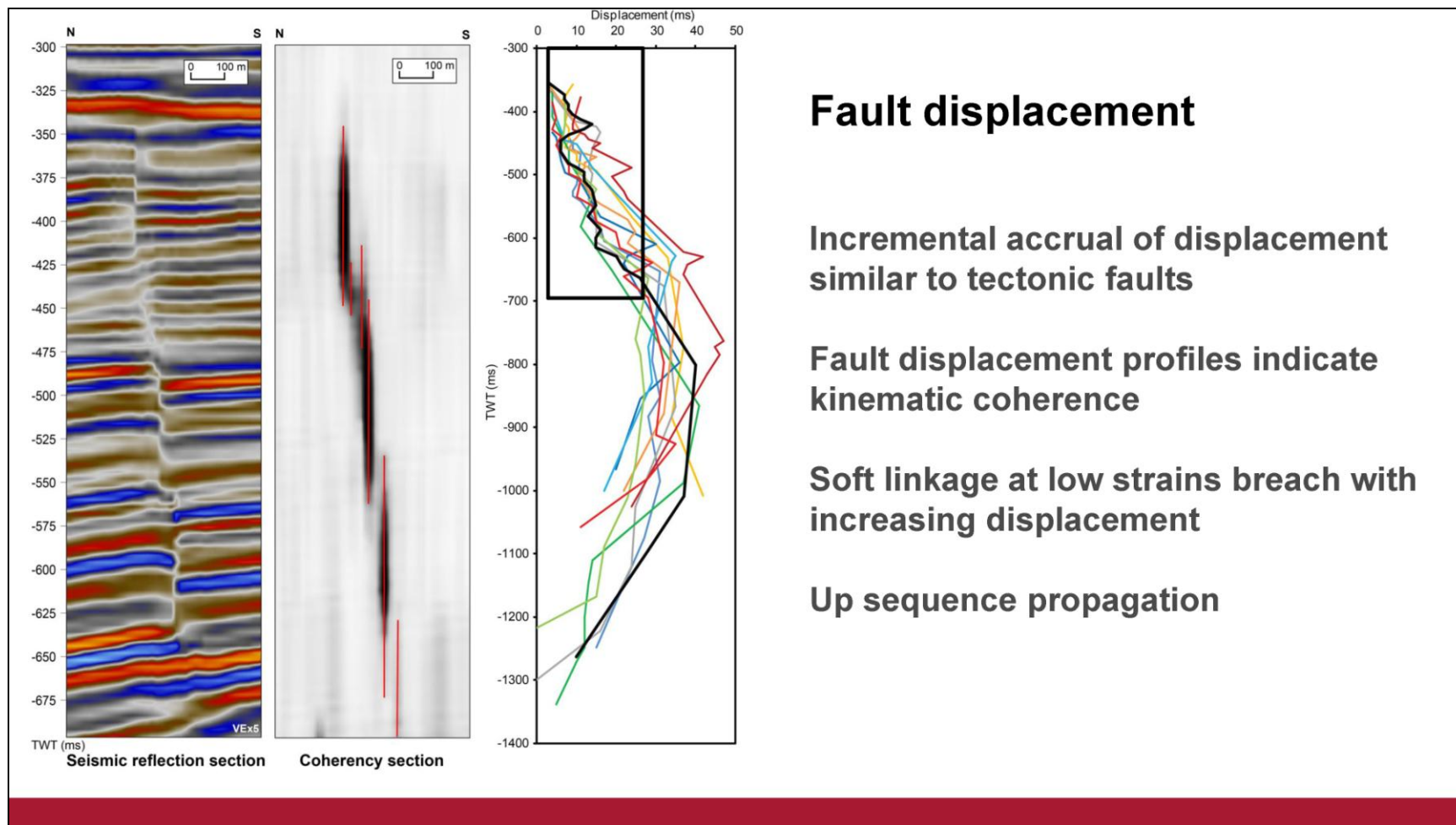
Increasing maturity with depth

No single fault cuts entire interval

Presenter's notes: The seismic attribute of coherency (or edge detection) reveals a systematic pattern of lineations, which are directly correlated to normal faults. Geometric details of the polygonal fault system (on slide). Main point: like the polygonal fault systems elsewhere fault frequency, linkage, and intersections increase with depth. In the Petrel sub-basin this is important as one prospective reservoir lies immediately beneath the seal and shows evidence of faulting.

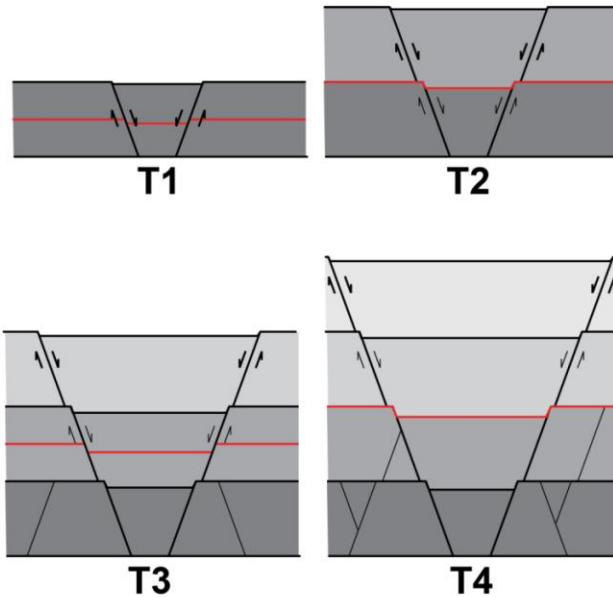


Presenter's notes: Like many other polygonal fault systems the polygonal faults in the Petrel sub-basin form in strata bound tiers. Despite limited information on lithology, reflectively suggests some variation with depth. First order structural elements of the polygonal fault system (on slide) – tiers represent mechanical stratigraphic boundaries that influence fault segmentation. 1st order segmented fault arrays generally separate relatively unfaulted polygonal cores from more intensely faulted regions between antithetic pairs.

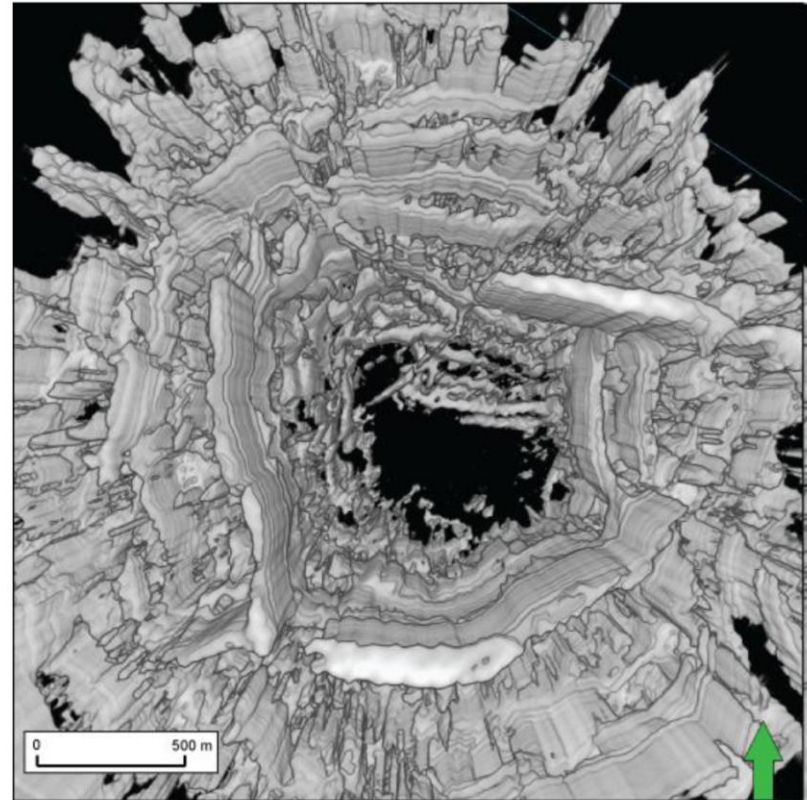


Presenter's notes: Fault displacement curves show similarity of polygonal faults to tectonic faults. The 1st order segmented fault arrays show increasing displacement with depth reaching a maximum of around 40 m (or approximately half an individual tier thickness). Relays between individual tiers breach with increasing fault displacement, which indicates up-sequence fault propagation. The coherency attribute is common used to visualise polygonal fault systems however, in this case because of the alignment of displaced reflectors the algorithm does not detect the fault. Coherency time slices therefore should be considered a minimum representation of the fault frequency in any given timeslice.

Fault system growth and connectivity



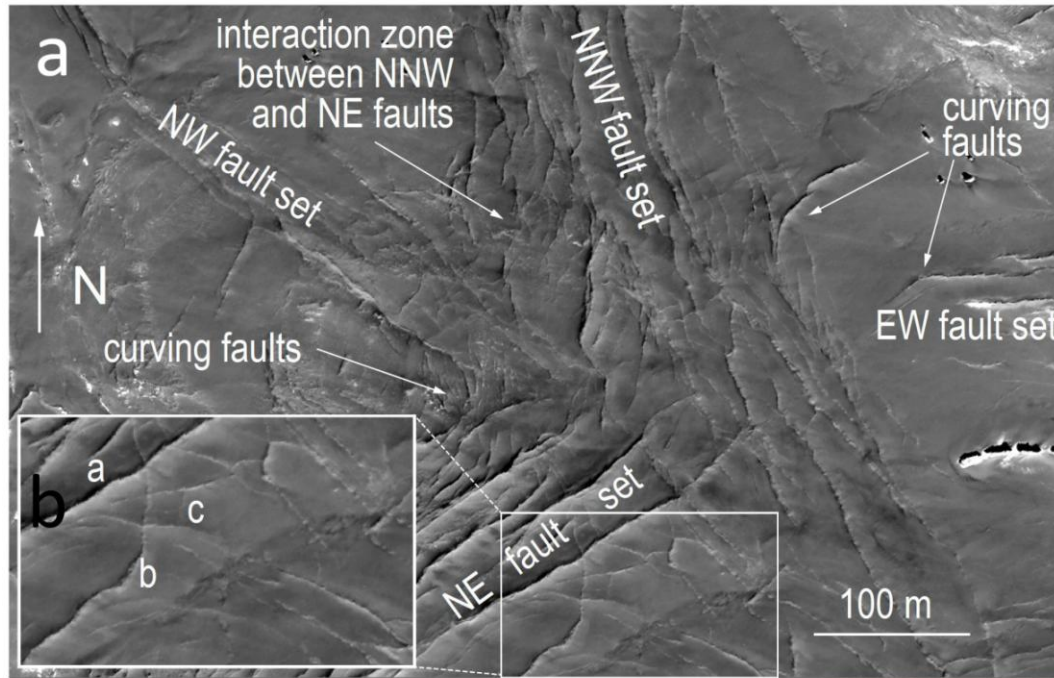
Bottom up polygonal fault growth model



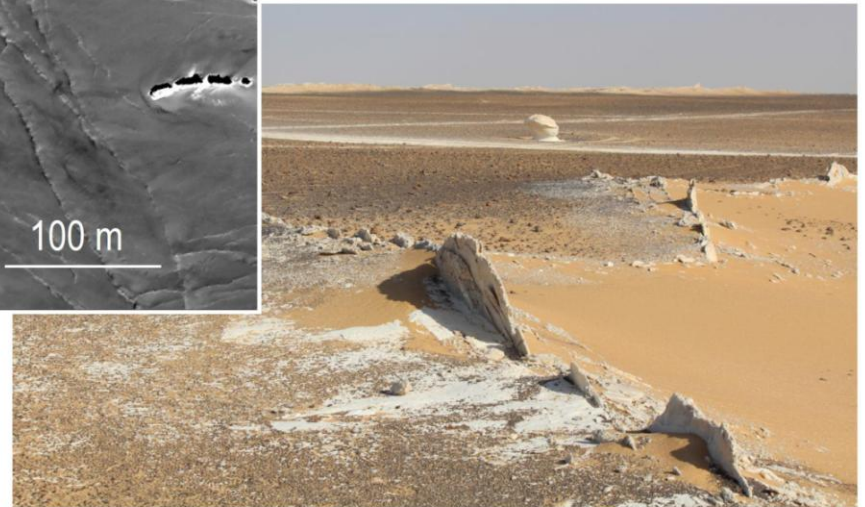
3D visualisation down through a polygonal fault cell

Presenter's notes: The geometric and fault displacement characteristics of polygonal faults in the Petrel sub-basin indicate up-sequence propagation where by the faults of the underlying layer control the fault geometry and displacement of the faults forming in subsequent layers. This is contrary to present models of polygonal fault formation, which favour a top-down mechanism. Regardless of how polygonal faults form the resulting fault network is highly connected in three dimensions. Image shows a simple volume analysis of the coherency attribute which shows, except for the top-most tier, the fault network is extensively connected in both horizontal and vertical dimensions. (Faults shown as white as opposed to black). In such a fault network, high angle fault intersections would form vertical high permeability migration pathways.

Polygonal faults in outcrop



Cretaceous Khoman Formation, Egypt
Tewksbury et al., 2014



Presenter's notes: Tewksbury et al. document the first confirmed polygon fault outcrop and show the complexity of polygonal fault intersections. The majority of faults in the left hand image would be considered sub-resolution in seismic reflection studies. These polygonal faults can be observed in high-resolution aerial photographs covering 900 km². Calcite infilling the polygonal faults is typically more resistant to weathering than the host lithology leaving exposed fault surfaces across the region.

a



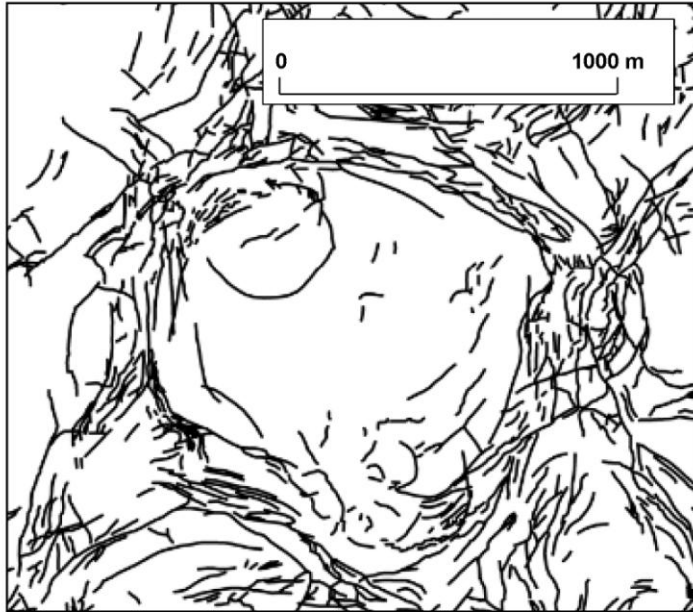
Fault permeability

Cretaceous Khoman Formation, Egypt
Tewksbury et al. (2014)

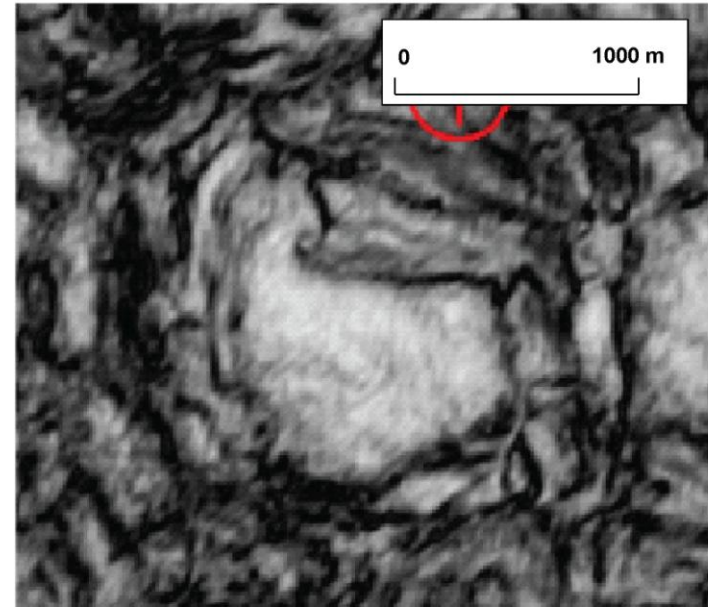


Presenter's notes: Fault surfaces (in top photograph) show repeated episodes of fluid flow and calcite growth and synchronous displacement across high angle intersections. In some cases, void space has been preserved which has allowed the growth of calcite crystals (in bottom photograph). This example highlights that mineralisation/dissolution within the fault zones may contain high permeability pathways that are stress independent.

Sub-seismic resolution faults

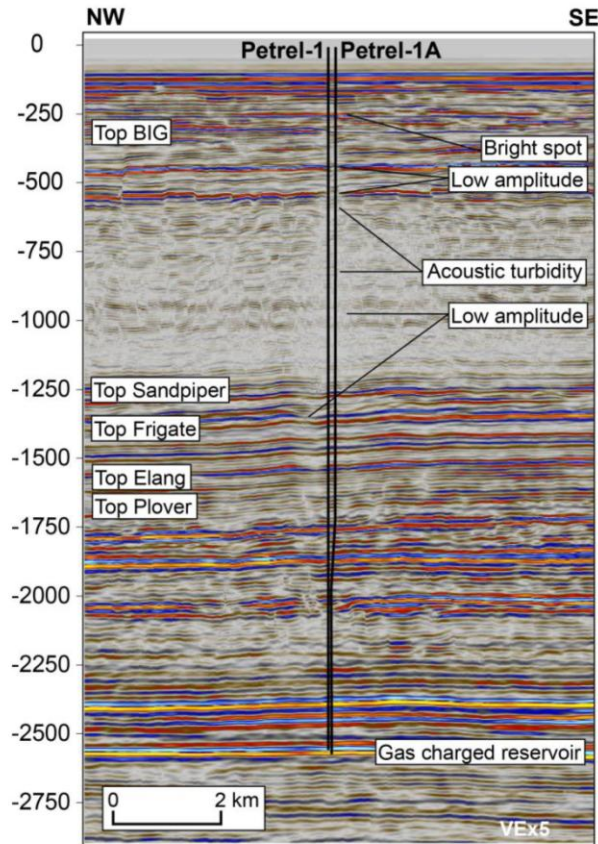


Outcrop fault map Tewksbury et al. (2014)



Coherency 1000 ms time slice

Presenter's notes: Polygonal fault cells from outcrop analogues and this study scaled to approximately the same size show the intensity of faults that could be typically associated with the polygonal fault system in the Bathurst Island Group. The majority of faults in outcrop would be sub-seismic and where many of the 'single' fault planes imaged in seismic may in fact be faults comprising multiple slip surfaces. Both these features add to the overall complexity associated with polygonal faults.



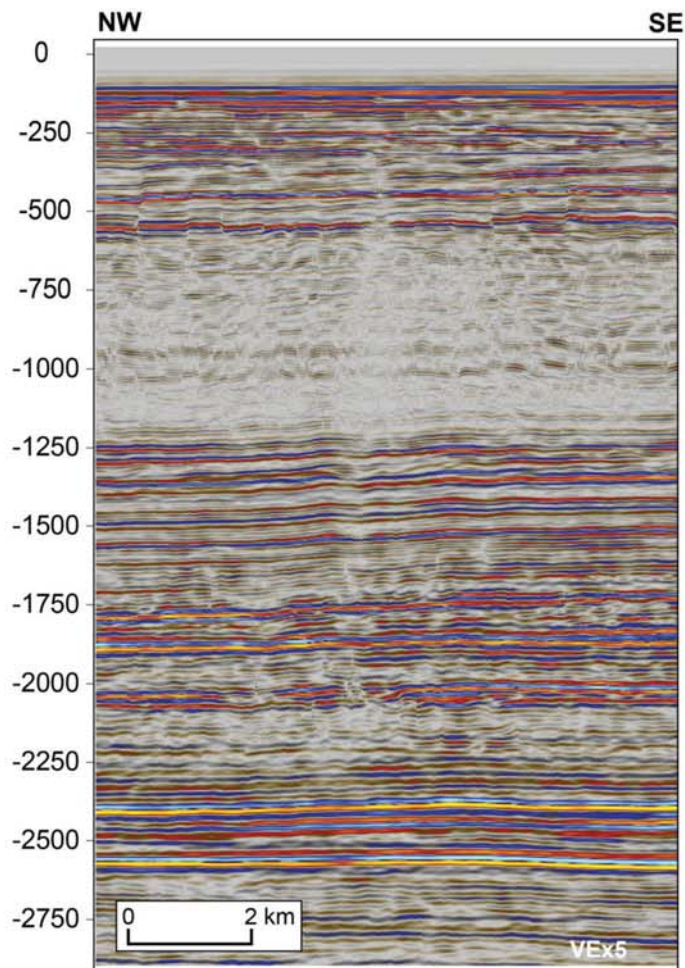
Seal Integrity

While highly complex, is the polygonal fault system impacting on seal integrity?

Petrel-1 drilled 1969 suffered uncontrolled gas leak (14 month duration)

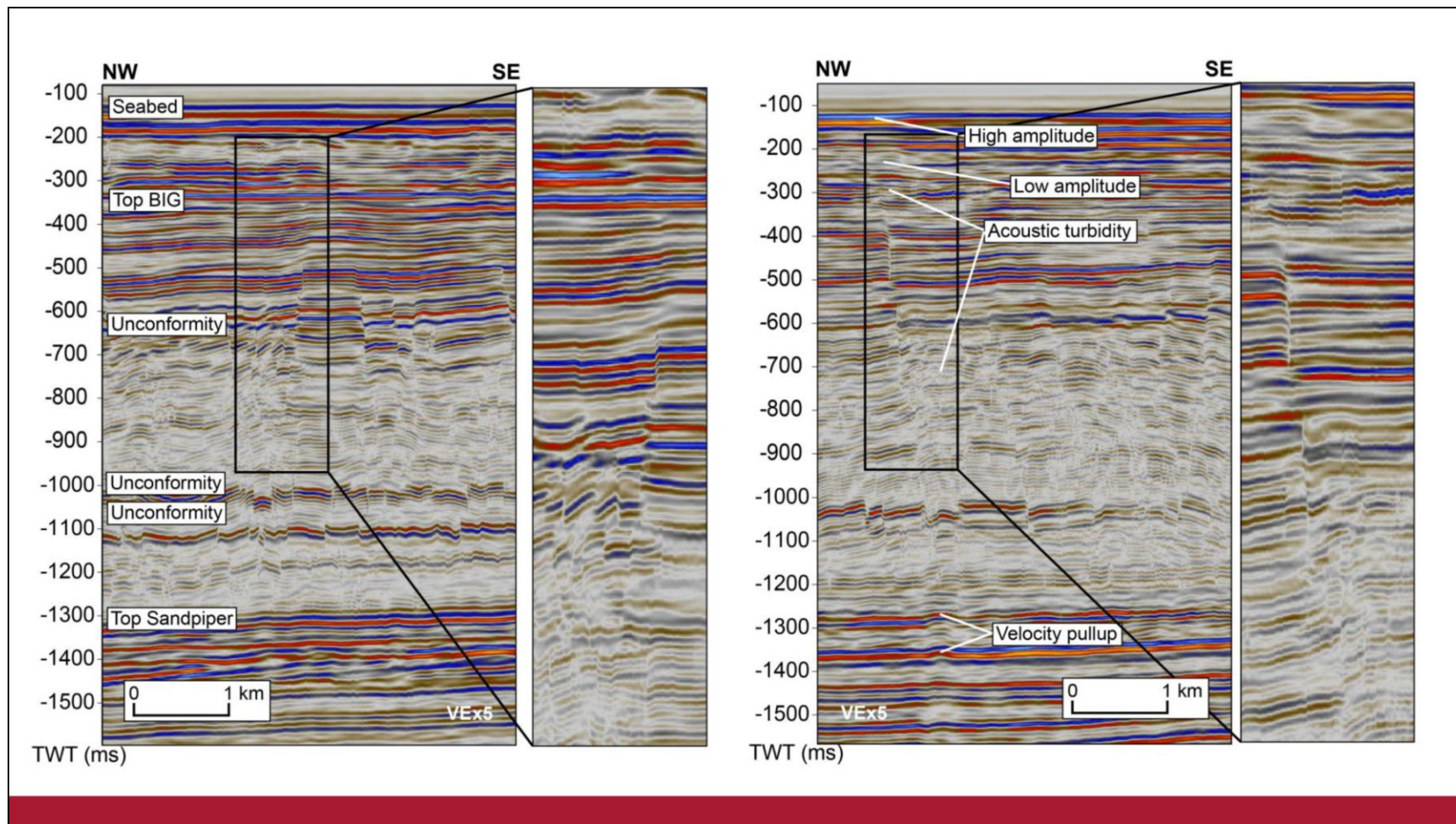
Seismic volume around Petrel-1 has the characteristic of a gas chimney

Presenter's notes: 3D Seismic reflection provides indirect evidence of hydrocarbon migration through the Bathurst Island Group seal. The Petrel-1 well drilled in 1969 penetrated a high-pressure gas reservoir at ~3980 m (2573 ms TWT) and suffered an uncontrolled gas leak at the surface that took 14 months to control. The seismic volume around the Petrel No. 1 well displays seismic attributes within the Bathurst Island Group that are widely attributed to the presence of gas chimneys in the literature (e.g., low trace-to-trace coherency, low reflection strength, highly variable dip and azimuth of amplitude and velocity anomalies). Amplitude and velocity anomalies associated with the Petrel-1 well have a radius of up to 500 m, extend vertically to at least 2000 ms TWT and may indicate an active or paleo-fluid migration pathway through the Bathurst Island Group.



Seal Integrity

Site specific analysis required to determine present condition of well



Presenter's notes: Many polygonal faults within the 3D seismic volume show two contrasting seismic attributes. The first show coherent reflectors throughout the Bathurst Island Group. The second show many features commonly associated with vertical fluid migration such as acoustic turbidity, amplitude anomalies, and velocity pull ups that define the geometry of the polygonal cells well into the reservoir intervals. The fluid pressures below the Bathurst Island Group within the study area are hydrostatic and indicate that the seal may be imperfect over geological timescales.

Summary & Conclusions

- Polygonal fault systems evolve as part of dewatering and compaction process of hemi-pelagic sediments
 - Polygonal fault frequency and connectivity increases with depth
- Polygonal faults are potential high permeability conduits through sealing formations
- Further multidisciplinary site specific analysis is required to test hypothesis that Bathurst Island Group less than efficient seal