FAULT AND TOP SEAL FAILURE: EXPLORATION RISK OR RATHER A MISSED OPPORTUNITY FOR EVALUATING HYDROCARBON PROSPECTIVITY AT PROSPECT TO SUB-BASIN SCALE?

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Introduction

The Bonaparte and Browse Basins on Australia's North West Shelf represent two adjacent, major, margin-scale compartments with vastly different rift, seal depositional, charge and reactivation histories. The Bonaparte Basin is characterised by generally thin Cretaceous seals and has been highly fault reactivated in the Neogene. As a result, intense fault seal failure throughout the basin has resulted in the formation of numerous partially to completely breached accumulations. In contrast, the adjacent Browse Basin is characterised by thick Cretaceous seals and minimal Neogene reactivation.

In this study, we have examined and integrated a range of data, including 2D and 3D seismic, basin-wide Synthetic Aperture Radar (SAR), bathymetry, water column geochemical sniffer, high-density Mark III Airborne Laser Fluorosensor (ALF), charge modelling and fluid inclusion charge history data to compare and contrast the mechanisms and effects of fault and top seal failure responses in these two contrasting basins. The study had two key goals. The first was to determine empirically where the principal zones of seal failure were located, and what was driving the failure. The second goals was to use the derived understanding to develop technical strategies to reduce exploration uncertainty associated with fault and top seal and charge in a range of basin types.

Regional Geology

The Bonaparte Basin is a low-gradient margin which, prior to plate collision in the Neogene, possessed an outer marginal plateau, similar to the Exmouth Plateau in the Carnarvon Basin. The Bonaparte compartment is about 640 km long in a strike direction and about 550 km wide ("wide" = the distance from the edge of the unextended craton to the continent-ocean boundary). Following continental break-up, the regional Early Cretaceous sealing sequence was deposited over a broad region which possessed considerable vertical relief. Some areas, such as around the Skua high (and oil field) in the south-western Bonaparte Basin, were elevated perhaps 1,000 m above the surrounding basin. As a consequence, the sealing units progressively on-lapped the highs. For example, the Cretaceous seals which overlie the Jurassic reservoir units in the Skua oil field (on the Skua high) are as much as 25-30 million years younger than those overlying the Jurassic reservoir in the Montara gas field, which is located in a (relative) structural low approximately 25 km to the south-east. The depositional processes within the Early Cretaceous in the Bonaparte Basin hence produced seals with a wide variety of ages and lithologies and rheologies. At a first-order, the generally slow subsidence throughout the Bonaparte Basin in the Early Cretaceous resulted in this sequence being generally thin (<<100 m) throughout the basin system, though in some localised areas, seal thickness is considerable.

At about 5.7 Ma BP, the progressive collision of the Australian and Eurasian Plates started to produce mild fault reactivation within the outer parts of the Bonaparte Basin. Subsequently, further convergence in the Pliocene resulted in the formation of the Timor Trough, a depocentre in which over

3,500 m of subsidence occurred in only 3-4 million years, immediately outboard of the Bonaparte Basin. In addition, smaller Neogene troughs, such as the Cartier and Nancar Troughs, began to form along the inboard (south-eastern) edge of the Timor Trough. The formation of the Timor Trough and the associated down-warping induced significant extensional flexure within the outer Bonaparte Basin, and resulted in the formation of large arrays of NE and ENE trending Pliocene faults. This extensional fault reactivation often produced faults whose displacement significantly exceeded the thickness of the regional seal, often cutting across the strike of the underlying charged traps. As a result, many of the oil accumulations which had been formed during oil generation and migration in the Late Cretaceous and Tertiary were either partially or completely breached, due to fault seal failure. In some cases, a combination of a brittle top seal facies and only relatively minor Neogene faulting appears to have been sufficient to cause complete failure of the seal. As a result of all of these processes, fault seal failure is considered the principal exploration uncertainty in the Bonaparte Basin.

This Neogene collisional event was also important in that it produced a major fluid flow event. This episode was characterised by the migration of hot (>150^{o}C), highly saline brines from (presumably) Palaeozoic evaporites at depth, through the Triassic and Jurassic reservoir units, to, or near, the seafloor.

The Browse Basin, in contrast, is a high-gradient margin compartment, which extends for about 560 km in a strike direction but is only about 350 km wide. This basin experienced rapid Early Cretaceous subsidence, and as a result, generally has very thick sealing units over most of the basin. The foreland development, which so critically affected the Bonaparte Basin, was absent from the Browse Basin, with the outer part of the basin flanked by a Jurassic ocean basin, the Argo Abyssal Plain. As a result, extensional fault reactivation is largely absent in the Browse Basin, and fault seal failure is not a prime risk. Seal thickness thins progressively to the north-east (towards the Bonaparte Basin), and to the south-east, onto the basin margin. Top seal failure is the dominant failure mechanism occurs along the basin margin as the seal becomes thinner and sandier.

Study Sub-Regions

A total of 5 study areas were investigated, which trend broadly from north to south. These were:

1. Bonaparte Basin
    - a. Eider Horst
    - b.Nancar Trough
    - c.Cartier Trough
    - d.Swan Graben
2. Browse Basin
    - a.Yampi Shelf

Each of these areas (which typically extend for at least 40 km square, and in some cases over four times that area) has a unique combination of fault reactivation history, top seal capacity and rheology, charge and subsidence history and structural setting. The key elements of each of these areas are summarised below.

Eider Horst

The Eider Horst contains numerous traps which GOI (Grains with Oil Inclusions) analysis has shown previously contained significant oil columns. Moreover, 2D seismic data reveal the presence of extensive high velocity, carbonate cemented, Hydrocarbon-Related Diagenetic Zones (HRDZs) within the Eocene Grebe Sandstone overlying the palaeo-accumulations. The Cretaceous sealing units in this area are typically thin and are composed of a brittle, radiolarite lithology. Neogene fault reactivation is significant, with many of the faults extending at, or near to, present day seafloor. A considerable amount of water column sniffer data was acquired over the region, but no hydrocarbon anomalies were detected. Similarly, no SAR slicks were detected in the region, suggesting the neither oil nor gas is seeping from the Eider Horst at the present day. Given that this area has low fault seal integrity, these observations suggest collectively that the area is no longer receiving significant hydrocarbon charge, either because the source is spent or because migration barriers are now present. Further exploration in this region would appear to be highly unlikely to succeed. The Eider Horst appears to be a "dead" petroleum system.

Nancar Trough

The Nancar Trough is a Neogene depocentre which fluid inclusion data indicate contains one breached oil accumulation, with little evidence for oil accumulation in other traps in trough. The trough is highly fault reactivated, with the majority of the faults reaching seafloor. Moreover, the Neogene faults cut through the centre of the depocentre, rather than just extending along its margins. Both SAR and ALF data from the area demonstrate that the Nancar Trough is leaking hydrocarbons prolifically, a proposal supported by the presence of numerous gas chimneys on seismic data. Pockmarks and mud volcanoes are also common on the seafloor. The Nancar Trough is clearly a very dynamic and active petroleum system, and yet generally there is a scarcity of either accumulations or palaeo-accumulations. It seems most likely that the source rock system in the trough has been invigorated (or reinvigorate) by the very Neogene subsidence/deposition and reactivation which has produced the intense reactivation faulting in the region. The most plausible interpretation is that the Nancar Trough is characterised by a combination of strong present day hydrocarbon migration and poor fault seal integrity, which produces a very leaky system. The Nancar Trough is now a dynamic petroleum system, but one which appears to have little prospectivity because of low fault seal integrity.

Cartier Trough

The Cartier Trough is a Neogene depocentre which is effectively an unfaulted sag. Neogene faulting is restricted to the margin of the trough, where large displacement, and numerous Neogene faults are present. Fluid inclusion data show that the previously oil-bearing Oliver structure, on the eastern margin of the basin, has been almost completely gas-flushed. This gas-flushing has probably taken place in the last 3 million years or less, as a result of increased sediment load and source rock maturity in the centre of the sag. SAR data over the Cartier Trough show that oil seepage is restricted exclusively to the margin of trough. In particular, slicks are clustered up-dip from the Oliver accumulations, with their distribution appearing to be localised to where large displacement Neogene fault cut the seafloor. Mud volcanoes are also present in this area. The Cartier Trough probably represents an active petroleum system where Pliocene gas generation has flushed previously oil-charged accumulations; prospectivity for oil probably exists up-dip from the Oliver trend.

Swan Graben

The southern Swan Graben contains a range of oil accumulations, from a commercial oil field (Skua), which has been partially breached, to largely breached traps (Swift) to completely breached accumulations (East Swan, Eclipse). An enormous amount of data is available in the region, including SAR, ALF, sniffer and fluid inclusion data. In addition, HRDZs, which delineate the exact extent of leaky fault segments, have been mapped in detail using 3D seismic data. The seismic mapping clearly reveals that the over commercial accumulations, leaky fault segments extend for a maximum of 1,500 m, whereas over breached accumulations, leaky faults were invariably over 3,000 m long. SAR, localised sniffer and strong ALF fluors were found around the partially breached Skua Field and the very leaky Swift structure. In contrast, around the breached fields, no SAR or "wet" sniffer anomalies were found – strong ALF anomalies were, however, present. These observations probably relate to the fact that detecting anomalies by SAR or sniffer (which are strongly volume dependant tools) requires significant volumes of hydrocarbons to have leaked (which a charged trap does), whereas insufficient volumes of hydrocarbons are leaking from the breached traps. ALF is a high-sample rate, low volume dependency tool, and hence can detect the small volumes of hydrocarbons which leak from breached traps.

Yampi Shelf

The Yampi Shelf in the northern Browse Basin contrasts with the previous four examples as it is a region where top seal failure is critical. SAR, sniffer, ALF and 2D and 3D seismic data were used to characterise the seal capacity and seal failure style in the region, which is currently receiving an active oil and dry gas charge. Massive, natural dry gas and oil seepage was detected, though the relative abilities of sniffer, SAR, ALF and seismic data to detect, characterise and even predict this seepage were markedly different. The sniffer preferentially identified gas seepage, often in basin-ward locations, since the high relative permeability of gas favoured its early leakage, even through relatively thick seals. Gas chimneys, though obvious on seismic, contributed relatively small amounts of hydrocarbons to the seep inventory. SAR preferentially identified oil seepage, which was episodic and largely restricted to the basin-margin at the regional 'zero-edge-of-seal', reflecting the low relative permeability of oil, even through thin seals (it leaked 'late'). ALF (high sample rate, low volume dependency tool) detected low-level oil seepage from the charged trap (the Cornea field), probably because it could detect oil in the reservoir which was breaking through the top seal on the outside of gas bubbles, which were then bursting at the sea surface. The spatial distribution, concentration and relative composition of the detected seepage was controlled principally by the regional seal's thickness and capacity, rather than by the inherent composition and flux of the migrating hydrocarbons.