ABSTRACT

The Sunrise gas-condensate field located in the Timor Sea is part of a planned liquefied natural gas (LNG) development. It is a broad, low-relief structure covering approximately 900 km² with two main reservoirs in the Plover Formation. While previous studies suggested that the Sunrise field was likely well connected, there still existed a downside risk of compartmentalisation because of the high degree of faulting.

New results from a multi-disciplinary investigation indicate that the Sunrise field is unusually well connected, both vertically and laterally across large distances of possibly up to 40 km. This is primarily because of the nature of the main reservoir, which is thought to be a laterally extensive shoreface facies, and the presence of conductive fault/fracture zones associated with fault reactivation in an active tectonic setting. The results of this study render unlikely the downside case of a highly compartmentalised field. Despite the relatively wide appraisal well spacing, there is confidence in these conclusions because of the consistent message obtained from the evaluation of a wide range of data.

The combination of geochemistry and the modelling of convective mixing through geological time—a method rarely used in the past—give important insights not typically available from traditional methods. This work was also used to successfully guide further data collection, which has supported the initial conclusions regarding the degree of communication across the field.

KEYWORDS

Reservoir connectivity, Sunrise gas field, compartmentalisation, convective mixing, conductive faults/fractures.

INTRODUCTION

Reservoir compartmentalisation is one of the most challenging subsurface uncertainties in the development of offshore oil and gas fields. Compartmentalisation is difficult to assess without production information and its impact on development can be severe in terms of additional capital expenditure and/or loss of reserves. This paper presents new results from an integrated, multi-disciplinary study into the potential for compartmentalisation of the Sunrise field.

Field development studies on Sunrise re-commenced in 2007. Reservoir compartmentalisation caused by faulting was recognised as a significant subsurface uncertainty having a high impact on the development concept. While previous studies (Seggie et al, 2003; Ainsworth et al, 2006) concluded that the Sunrise field was likely well connected laterally within each of six major fault blocks, a downside case of as many as 105 fault-bound compartments was deemed possible. The previous conclusions were also based on soft data, such as equilibrium in pressures. In the absence of production data and due to the low density of appraisal wells (one well per 150 km²) integration of all types of data became essential to reduce the range of uncertainty.

These studies included geochemistry, an update to the stratigraphic model, revised interpretation of faulting based on reprocessed seismic, analysis of fault and fracture network, and DST interpretation.

One powerful and innovative tool used for assessment of compartmentalisation, which has rarely been used in the past, is numerical modelling of fluid mixing over geological time. England et al (1995) investigated the use of reservoir simulators to model the time scale of mixing due to diffusion and density driven convection. They also showed how the presence and nature of barriers in an oil field could be evaluated by comparing modelled and observed variations in fluid compositions and pressures. Smalley et al (2004) have developed analytical equations to describe the rates at which pressure density, fluid contacts and composition proceed towards equilibrium.

The results of these studies helped in the placement and design of the Sunrise-3 appraisal well drilled in 2008, which further validated the conclusions regarding connectivity.

BACKGROUND

The Sunrise gas-condensate field is located in the Timor Sea, approximately 450 km northwest of Darwin, Austra-
lia (Fig. 1). The Sunrise field was discovered in 1974 by Sunrise–1 and lies approximately 16 km northeast of the earlier Troubadour discovery (Fig. 2). It covers an area of approximately 900 km² and is separated from the smaller Troubadour field, which lies to the south. It has been appraised by six wells, most recently by Sunrise–3 in 2008.

The geology and engineering context of the Sunrise field have been described in detail previously (Seggie et al, 2003; Ainsworth, 2006). Structurally the field is a complex faulted anticline, consisting primarily of a series of east–west oriented fault blocks with a maximum relief of approximately 170 m (Fig. 2).

Sunrise also has a strong lateral temperature gradient, with the reservoir temperature ranging from 110 °C to over 140 °C from west to east across the field. This is thought to be related to variation in depth to the highly-radiogenic granite basement.

**Stratigraphic setting**

The bulk of the gas resources are located in two good quality reservoirs, Units 2 and 4 (Fig. 3), contained in the Upper Plover Formation, which is an 80 m-thick section of marginal marine sandstone of Bathonian to Callovian age. Unit 2 is a laterally extensive shoreface sand, while Unit 4 is a laterally extensive early to late transgressive shoreface sand complex. Previous studies interpreted this unit as being formed in an incised valley and shoreface sand complex (Seggie et al, 2003). Units 2 and 4 are separated by the marginal marine to marine heterolithic deposits of Unit 3, which have a lower net-to-gross sand ratio and low permeability. This unit is laterally extensive across the Sunrise field.

**Tectonic setting and structural geology**

The Sunrise field is located at the northern extremity of the Northern Bonaparte Basin, Australian North West Shelf (NWS), immediately south of the Timor Trench, which is a 3,000 m-deep, neotectonic bathymetric depression (Figs 1 and 4). It is a zone of extensive faulting and tectonic activity.

Sunrise faults are best mapped using seismic attributes (e.g. dip, semblance; Fig. 5) extracted at the Aptain age (NKA) seismic reflector, which is a primary seismic event horizon just above the reservoir (Fig. 6). These maps show the extensive faulting throughout the field (Fig. 5) with a throw resolution of approximately 15–20 m.

Thickness variations across faults in the interval between the reservoir and basement and normal fault offsets of the Jurassic reflectors document earlier faulting events most likely related to Permian and Jurassic rifting. The dominant underlying structural architecture observed throughout the basin consists of reactivated east–West–striking, tilted normal fault blocks (Fig. 7) formed during Jurassic extension. Subsequently, the Northern Bonaparte Basin has experienced widespread fault reactivation as a consequence of Neogene to present oblique, northeast–southwest convergence between the Eurasian and Australian plates.

Londono and Lorenzo (2004) described the Timor Trench as a collisional, subduction-style system with a fore-bulge in the Australian Plate. In this setting, fault reactivation formed predominantly normal faults evident on seismic data, which are interpreted as the flexural response to collision across the Australian Plate (Fig. 6). Some of these faults are clearly rooted in deeper Permian–Jurassic faults and extend into the Neogene sequences with the main faults reaching seabed. These faults can be mapped using the offsets in the shallower Base Pleistocene (BPLEI) reflector (Fig. 6). It approximates a late Miocene to Pliocene/Pleistocene age unconformity and has been broadly dated biostratigraphically to a period between 12–0.6 Ma (Figs 6 and 7).

**Fluids, geochemistry and charge history**

The condensate gas ratio (CGR) varies across the Sunrise field from 30 BBL/MMSCF to approximately 55 BBL/MMSCF.

The source rocks are coals and carbonaceous fluvio-deltaic shales in the Lower Plover formation. Gas isotopic analyses indicates that local charge and direct vertical and/or short range lateral migration is sufficient to explain the gas found in the Sunrise field. There is a subtle variation in source across the field. The Sunset–1/Sunset West–1 area, Sunrise–2/Sunrise–3 Unit 2 area, and Sunrise–3 Unit 4 were all charged by slightly different hydrocarbons.

The gas in the Sunrise field is likely to be very young geologically. Firstly, charge is modelled to be occurring at the present day and is thought to be presently leaking at a spill point located at the bounding fault on the northwest side of the field. Secondly, while the trap started forming approximately 12 million years ago at the earliest, the final trap resembling the field finished forming only around less than one million years ago at the latest.

**PRIOR ASSESSMENT OF COMPARTMENTALISATION**

The early assessment of high connectivity in Sunrise was based largely on:
Unusual reservoir connectivity revealed by data integration at the Sunrise field

Figure 2. Sunrise top structure and height above free water level.

Figure 3. Sequence stratigraphic framework for the Sunrise field. MFS is maximum flooding surface and SB is sequence boundary.
Figure 4. Tectonic elements map.
Unusual reservoir connectivity revealed by data integration at the Sunrise field

Figure 5. NKA semblance map. Dark lines are faults and the interpreted fault centreline.

Figure 6. Seismic section. Line of section is shown in Figure 5.
The apparent pressure equilibrium in the gas column across the field (Fig. 8); and,
- Geochemistry of the gases and condensates indicating close similarity laterally between Sunset–1 and Sunset West–1 and vertically across the intervening Unit 3 at Sunset–1 and Sunrise–2 (Fig. 9).

Despite the assessment of good connectivity, a significant uncertainty in the degree of compartmentalisation still remained. Equilibrium in pressures indicates connectivity only in geological time, not production time. Similarity in hydrocarbon geochemistry could be due to common source rocks rather than a reflection of connectivity.

There is also evidence against good connectivity including:
- A circa 30 psi variation in aquifer pressures across the field (Fig. 8);
- Dissimilarity in the fluid chemistry at Sunrise–2 compared to the Sunset–1 and Sunset West–1 wells (Fig. 9); and,
- Fault seal analysis suggesting a high risk of compartmentalisation based on the observation that relatively thin sands separated by shale-prone intervals are offset by faults with throws greater than the sand thickness. Each of these observations is discussed below.

RE-EVALUATION OF COMPartMENTALISATION

Compartmentalisation risk was re-evaluated in two phases, as explained below.

Phase I

The first phase used existing pressure, PVT, and geochemical data and was carried out by examining equilibrium in pressures, fluid contacts, density and composition as outlined by Smalley et al (2004). This approach helped guide later more detailed analysis, which in turn helped justify the Sunrise–3 vertical interference test.

EQUILIBRIUM AND ASSESSMENT OF RESERVOIR CONNECTIVITY

Smalley et al (2004) studied the time for pressures, fluid contacts, density and composition to achieve equilibrium in a connected reservoir. The study was carried out by having two sides (Sides A and B) of a reservoir initialised at different conditions, such as pressures or compositions (Fig. 10). The time for equilibration to occur throughout the
Unusual reservoir connectivity revealed by data integration at the Sunrise field

**Figure 8.** Sunrise formation pressures.

**Figure 9.** Cross plot of ethane and propane $\delta^{13}$C isotopes.
reservoir was then calculated analytically. It was found that:

- Pressures equilibrated the fastest. Aquifer pressures equilibrated in < 0.1 years, or over twice as fast as gas pressures because of the higher compressibility of gas. Heavy oil took over 100 times longer to equilibrate because of its higher viscosity;
- Contacts were the next quickest. A gas-water-contact equilibrated in about 1,000 years, or ten thousand times more slowly than pressures because equilibration entails the actual movement of volumes of gas and water over some distance whereas pressure does not;
- Density equilibrium occurs when any elevation in a reservoir has the same fluid density. A difference, or disequilibrium, in density will be driven by a difference in temperature or composition such as from a variation in source rocks. This difference will induce convection in a connected reservoir and will eliminate the disequilibrium through time. Density equilibrium in the gas case took between 10,000 and 100,000 years, or a hundred thousand to a million times longer than pressure equilibrium. Density takes much longer than pressures or contacts to equilibrate because it requires mass movement possibly over long distances;
- Compositional equilibrium by diffusion takes the longest—almost ten million times longer than pressure. This is because each component must equilibrate by the very slow process of diffusion.

Examining the equilibration between different components is a powerful approach for assessing reservoir connectivity, particularly at Sunrise where the field is up to 60 km across and the gas is likely to be very young geologically.

**SUNRISE AQUIFER PRESSURES AND GAS-WATER CONTACT**

As noted above, the offsetting aquifer pressures have been interpreted to be an indicator of compartmentalisation; however, Seggie et al (2003) postulated that the offsets in Sunrise aquifer pressure (Fig. 8) could be due to a dynamic aquifer with a tilted gas-water contact instead of compartmentalisation. This re-evaluation supports the conclusion of Seggie et al (2003).

Firstly, aquifer pressure at a given elevation decreases systematically from the northeast to the southwest across the field corresponding to flow in this direction. The changes in pressure are not random or erratic as might be expected if they were due to compartmentalisation.

Secondly, regional aquifer pressure data show a consistent trend over 400 km from Evans Shoals to Laminaria (including the Sunrise field, Fig. 1). This trend indicates a regional trend of groundwater flowing from the northeast to the southwest. It is postulated that the source is a topographically-driven flow of meteoric water from the highlands of Papua New Guinea. This regional flow direction around Sunrise is supported by the observations of Otto et al (2001).

The strongest evidence for a dynamic aquifer is that the gas is in pressure equilibrium while the aquifer is not. As noted above, the lower compressibility of water versus gas should result in an aquifer reaching pressure equilibrium about twice as fast as a gas column (Fig. 10). Hence, under static conditions and with equal reservoir properties, water cannot be out of equilibrium while the gas is in equilibrium. The presence of a dynamic aquifer

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**Figure 10.** Time required for equilibration between two 1 km² reservoirs (modified from Smalley et al, 2004).
is the most plausible explanation of these observations. This is further supported by the observation that in the Sunrise field the sand quality and net-to-gross ratio in the aquifer is generally as good as or better than that in the gas column. In conclusion, the analysis indicates that the offsetting aquifer pressures are not an indicator of compartmentalisation in the gas sands.

DENSITY EQUILIBRIUM

Despite the lateral variations in CGR across the field, the fluid density is interpreted as constant across the field based on:

a. theoretical densities derived from compositions, pressures and temperatures;
b. densities measured from the RFT pressures; and,
c. densities from PVT lab analyses (Fig. 11).

Densities from RFT pressures have the highest degree of uncertainty given the limitation in the number of high quality pressures points at some wells such as Sunrise-2. The theoretical densities were calculated at each well by correlations using PVT data, reservoir temperature and pressure measured at that well.

The constant density observed between the wells is an indication of density, or gravitational, equilibrium across the Sunrise field. The density equilibrium between Sunset West–1, Sunset–1, Sunrise–2, and Loxton Shoals–1 is a much stronger indication of a well connected system than pressures because it takes 10,000–100,000 times longer for density to equilibrate than pressure (Fig. 10). Without good, direct permeable communication it would be difficult to have density equilibrium across approximately 40 km of the field given its short period of existence.

GEOCHEMISTRY AND COMPOSITIONAL EQUILIBRIUM

A re-examination of the geochemistry provides valuable new insight into compartmentalisation. The high degree of fluid similarity both vertically and over large lateral distances, such as the 8 km between the Sunset–1 and Sunset West–1 wells (Seggie et al, 2003), indicates unusually efficient mixing (Fig. 9). In interpreting reservoir geochemistry data a basic principle is that differences are more significant than similarities. This is because similarities may simply reflect uniform type and maturity of kitchens; however, it is rare for fluids to show the high degree of compositional and carbon isotope similarity observed at Sunset–1 and Sunset West–1.

Furthermore, the similarities between the hydrocarbons at Sunset–1 and Sunset West–1 and vertically between the two Plover units extend to the inorganic gases; the concentration of helium, nitrogen and carbon dioxide, all of which have very different genetic origins to the hydrocarbons, are also closely similar (Fig. 12). This makes it very unlikely that the similarity in composition arises from anything other than efficient mixing.

Loxton Shoals–1 gas has a very similar composition to that at Sunrise–2, implying the fluids have mixed over a distance of more than 14 km. This conclusion cannot be as firm as that of mixing between Sunset–1/Sunset West–1 because it is based only on gas composition (no isotope data are available for Loxton Shoals); however, it implies efficient mixing over large distances in a completely separate part of the field from Sunset–1/Sunset West–1.

The efficient mixing of fluids in the Sunrise field is all the more remarkable in the context of the large areal extent of the field and the recent and ongoing charge. Analysis indicates that diffusion could not explain the mixing; it would take approximately 25 million years for diffusion to equilibrate gases between Sunset–1 and Sunset West–1, which is much longer in duration than the age of the field.

In summary, this first-phase re-evaluation clearly inferred a well connected model vertically and laterally across large areas of Sunrise. The next step was to carry out a more detailed assessment of compartmentalisation in light of this new insight.

Phase 2

The more detailed analysis evaluated sedimentology, convective mixing over geological time, structural interpretation and analysis of well tests. Recently obtained PreSTM and some PreSDM reprocessed seismic data were also evaluated.

SEDIMENTOLOGY

As part of the study, a review was conducted of the sedimentological and sequence stratigraphic framework for the Greater Sunrise area. The basic philosophy was to review and update the previous understanding by:

a. building on previous knowledge;
b. incorporating recent updates to corporate, local and regional sequence stratigraphic frameworks (Fig. 3); and,
c. incorporating new sedimentological insights and understandings from regional analysis.

Insights from the study indicated that Unit 4 is more likely to be a laterally extensive early to late transgressive shoreface sand complex rather than the low stand incised valley and shoreface complex as previously interpreted by Seggie et al (2003). As such, the Unit 4 sands are expected to be much more laterally extensive than earlier thought.

CONVECTIVE MIXING OVER GEOLOGICAL TIME

It was earlier shown that diffusion could not explain the efficient mixing of fluids over large distances at Sunrise. A more logical mixing mechanism is convection. This can be driven by the large lateral temperature gradient observed across the Sunrise field and/or differences in fluid densities caused by active charge. The convective mixing process was tested using the Permedia Corporation’s MPath software. The theoretical basis for fluid fill and mixing in reservoirs has been discussed at length, notably by England (1989), Smalley et al (2004) and Stainforth (2004).

Lateral convective mixing was tested using a series of 2-D cross sections. The first cross-section is a 13 km-long sec-
Figure 11. In situ densities at the different Sunrise appraisal wells.

Figure 12. Cross plot of helium and nitrogen.
Unusual reservoir connectivity revealed by data integration at the Sunrise field

Unusual reservoir connectivity revealed by data integration at the Sunrise field (Fig. 13). Pressure and temperature conditions were set to those of the reservoir and the model was initialised with three gases of different density distributed laterally across the reservoir (Fig. 13).

The results of this simulation are illustrated in Figure 14. The degree of mixing is shown by the difference in the maximum and minimum densities in the reservoir and is represented by the blue and red lines, respectively. After approximately one million years, the maximum and minimum densities start to converge. The system is relatively well mixed at a period of approximately 25 million years. This mixing definition is based on an arbitrary assumption that the system is well mixed when maximum and minimum densities across the model are less than 0.03 g/cc apart. As a result, this model does not explain the degree of mixing noted in the Sunrise field.

The simulation was repeated, modelling the Unit 2 reservoir as a rectangular box 12 km in length. This model dimension eliminates the rugosity effects of the first cross section and increases the efficiency of mixing; however, this model still requires 17 million years to mix, and suggests that convective mixing in a single 15 m-thick layer is not efficient enough to explain the mixing in the Sunrise field.

Since the geochemical data suggests fluids have mixed between Units 2 and 4, the next scenario tested was a sandwich box model 12 km long with Units 2 and 4 connected by conductive fractures since a stratigraphic connection is not likely (Fig. 15), given the lateral extent and the low net-to-gross nature of the intervening Unit 3 section. Initial conditions were the same as discussed above.

Vertical connectivity was created by incorporating five 40 m-wide windows of 25 mD vertical permeability spaced 3 km apart. These windows represent permeable fracture zones through the vertically impermeable Unit 3.

The simulation results indicate that mixing of gases in this sandwich model occurred both vertically and laterally in only approximately 65,000 years—almost instantaneous in geological time (Fig. 16). The maximum and minimum density curves start to converge after only 1,000 years. This mixing appears to be almost 300 times more efficient than that of the single layer, Unit 2 model. The very fast mixing rates observed in the sandwich model are largely due to vertical density differences at the fault locations (i.e., between the fluids in Units 2 and 4 at the fault locations) that drive vertical fluid transfer and enhances mixing rates. Mixing in the sandwich model is more efficient than a single box of the same dimensions.

It is assumed here that because of simplifications related to the fluid initialisation and geometry, that the exact mixing times calculated are not necessarily accurate, but that the relative differences are reliable.

As noted earlier, mixing time is sensitive to the spacing of the permeable fracture zones (Fig. 17). Increasing the fracture zone spacing to 6 km caused the mixing time to increase to approximately 1 million years. When the fracture zones are reduced to two zones at either end of the model with a spacing of 12 km, mixing takes nearly

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**Figure 13.** Cross section of Unit 2 used to examine convective mixing through geological time.
8 million years. By comparison, Unit 2 mixes in almost 17 million years with no fractures. These model runs indicate that conductive fracture zone spacing directly influences convective mixing efficiency and that the most reasonable connective window spacing ranges from a few kilometres to, at most, 6 km.

The spacing of faults with large offsets, which are easily mapped on seismic, is generally on the order of 5 km to >10 km (Fig. 5). Hence, the requirement for permeable windows to be spaced every few kilometres (maximum <6 km) suggests that minor faults that are not resolvable on seismic are providing the vertical connectivity.

Sensitivity analysis indicates that the permeability of the fault zones could be as low the milli-Darcy range and still geologically fast mixing will result. Fault zones with permeabilities of 2.5 mD and 0.25 mD enabled mixing in 100,000 and 200,000 years, respectively.

The impact of placing an impermeable barrier in Unit 4, to potentially prevent or slow down the rate of convection in Unit 4, was also tested. The mixing time is observed to increase from 65,000 years to 15 million years, indicating that a continuous Unit 4 (or similar) layer is required over much of the field for effective mixing of fluids to occur. This conclusion is in line with the present sedimentological and stratigraphic interpretation of Unit 4 as a laterally-continuous shoreface unit and not a series of stratigraphically-confined incised valleys.

Geochemical differences between Sunset–1/Sunset West–1 and Sunrise–2 show that rapid mixing is not occurring over the entire Sunrise field; however, this difference does not necessarily indicate compartmentalisation. The difference can be explained by the circuitous, approximately 90 km-long pathway between the two areas: this

Figure 14. Mixing of reservoir gases in Unit 2 over time.

Figure 15. Cross section with permeable windows that represent conductive fault/fractures zones.
Unusual reservoir connectivity revealed by data integration at the Sunrise field

New reprocessed seismic data has allowed detailed interpretation and structural modelling. The field is transected by a population of complex fault zones comprising en-echelon arrays of fault segments. These segments are separated by variably deformed relay ramps, which are commonly intact at the limit of seismic resolution, thereby providing lateral flow paths. Previous reservoir models have interpreted these faults as continuous faults/barriers (e.g. Ainsworth, 2006) and were too pessimistic with regard to connectivity.

Based on evidence discussed earlier of a well connected field, it was realised that the typical fault seal scenario did not appear to fit the Sunrise data. Instead, a conductive fault model was investigated.

Two dominant mechanisms of enhancing fault permeability are envisaged. First, optimal orientation of faults/fractures with respect to principal stresses has been proposed in a few field studies to enhance fault permeability in siliciclastic reservoirs (e.g. Barr, 2007; Barr et al, 2007). This possibility was investigated.

Second, recently active faults are linked with vertical fluid flow (e.g. Wilkins and Naruk, 2008). Neogene to present day neotectonic activity in the Sunrise area occurs in the form of the development of the antiformal Sunrise closure, and extensive fault reactivation provides the distinct possibility of reactivated fault zones being associated with high permeability fracture networks that are conductive to flow, both vertically and laterally.

A conductive fault model is also supported by analogy with other fields in the northern Bonaparte Basin. Although the Jurassic reservoirs in the area have better reservoir properties than Sunrise, conductive fault models have been proposed to explain production behaviour for the Bayu Undan (Lozada et al, 2006) and Laminaria fields.

To assign flow-effective properties to faults in the Sunrise simulation models, the faults were categorised into three main classes depending on whether they are recently reactivated and their orientation relative to the principal stress orientations. Faults that offset the BPLEI horizon are considered to have a high chance of being associated with fractured, conductive damage zones (Fig. 6). Faults that are non reactivated (they cannot be mapped into the Tertiary section) but are optimally oriented for slip (mainly northeast- to east–west-striking faults) have been identified as probable candidates for being conductive, albeit of lower probability. The remaining faults are interpreted as not prone to slip and therefore most likely act as baffles. An example is shown in Figure 19 of one realisation of the fault model that incorporates all three fault types in the reservoir simulation model: reactivated (conductive), prone to slip (conductive), and neither (baffling). The properties assigned to faults in the simulator are based on an empirical fault zone thickness derived from displacement data and production well tests (see next sections).

**FAULT AND FRACTURE MODELLING**

Figure 16. Mixing of reservoir gases over time for sandwich model with 5 permeable windows.

Figure 17. Mixing time as a function of number of permeable windows.
The interpreted reactivated, conductive faults are generally evenly spaced across the field and as such should enhance lateral connectivity. The faults that have not been reactivated, while assumed not to be conductive, will nevertheless likely serve as baffles rather than complete seals because of the presence of relay ramps along their length (Fig. 18).

**RE-INTERPRETATION OF PREVIOUS WELL TESTS**

Re-evaluation of the Sunrise–2 Unit 2 well test, or drill stem test (DST), provides important insight into fault behaviour. Previous interpretation of this well test outlined a radial concentric flow model with permeability increasing away from the well. The re-interpretation of the data takes into account local structural geology and provides an alternative conclusion. A large fault approximately 300 m from the Sunrise–2 well offsets both Units 2 and 4. Conventionally, this fault would be interpreted to act as a lateral seal because both Units 2 and 4 are completely offset along the fault and even though they are locally juxtaposed elsewhere against each other (Fig. 20).

The derivative response from both build ups in the test, indicate initially radial flow, but then exhibit a steeply increasing pressure derivative with time over a short distance from the well (Fig. 21). In a laterally continuous, homogenous reservoir, the derivative of the change in pressure with time will not increase once radial flow has been established. This steeply increasing derivative indicates a ten-fold increase in transmissivity (Kh) only 90 m from the well. This response is a reservoir effect since it is occurs in both build ups.

From this reassessment, the offsetting fault is clearly not acting as a typical seal. There is also no geological reason for a ten-fold increase in Kh, given that Unit 2 is a laterally continuous and smoothly changing shoreface facies with generally consistent reservoir properties across the field. Pressure transient analysis indicates that the best model that fits the data is one that incorporates a highly conductive fault or fracture system 90 m from the well with an extremely high Kh of $2.8 \times 10^6$ mD-m. Although the nearest seismically resolvable fault is 300 m from the

![Figure 18. 3D perspective view of NKA map with semblance (coherence) seismic attribute (grey scale) highlighting faults. Red arrows and blue arrows represent breached and intact relay ramps, respectively. Intact relay ramps provide conductive lateral flow paths.](image-url)
well, the interpreted high conductive zone that is 90 m from the well is interpreted as either a fault below seismic resolution or a fracture corridor associated with the seismically-mapped fault. This result also gives insight into the possible width of the damage zone associated with a main fault. The well test information indicating that this fault is highly conductive is consistent with the seismic interpretation that this fault is recently re-activated and provides a means of calibrating the work done to estimate fault behaviour from the fault orientation relative to the primary stress directions calculated for the field.

In summary, more detailed work has strengthened the initial interpretation that the Sunrise field is well connected vertically and laterally across the field and indicates that the connectivity is due to the laterally continuous reservoirs and the fact that faults do not appear to be sealing. The faults are likely either conductive or baffling because relay ramps providing permeable windows through them. In particular, the mixing work has indicated that there is vertical connectivity between Units 2 and 4 via small scale or sub seismic faults. A vertical interference test was designed for the Sunrise–3 appraisal well to test for vertical connectivity along small scale faults.

**SUNRISE–3 APPRAISAL WELL**

The Sunrise–3 appraisal well was spudded on 31 August 2008, approximately 6.5 km west of Sunrise–2.

**Well location planning and design**

The Sunrise–3 appraisal well was located 900 m away from a large fault that has been interpreted as a non-reactivated, non-conductive fault in an area of generally low density faulting (Fig. 22).

To test the vertical connectivity of small scale faults, Sunrise–3 was located about 470 m from an interpreted...
small scale fault. It also targeted an aquifer in Unit 4 so that a small pressure response could be measured. The Sunrise–3 well came in structurally higher than expected and Unit 4 had gas rather than water; however, the thickness of Unit 4 was low enough such that it was estimated that a pressure response from a well test in Unit 2 would likely be measured by a gauge in Unit 4. Consequently, the planned interference test proceeded.

Analysis of results

A pressure transient analysis of the Sunrise–3 well test in Unit 2 found largely radial flow and evidence that the major fault is acting like a baffle rather than a seal with a leakage factor of 0.3 (Fig. 23). A leakage factor of 0.3 implies that 30% of the fault is not sealing. This interpretation fits the fault geometry observed on seismic, which shows a series of ramps that provide conductive pathways across approximately 20–30% of the fault (Fig. 22). The pressure transient analysis shows that this major fault is not highly conductive in contrast to the fault near the Sunrise–2 well. The Sunrise–3 well test provides an important calibration point, thus supporting the view that non-reactivated faults are baffles rather than being highly conductive. No sealing boundary was detected in a radius of investigation of 2 km.

Geochemical analysis of Sunrise–3 fluids (Fig. 9) also support the above well test interpretation showing that Unit 2 at Sunrise–3 is connected to Sunrise–2 6.5 km to the east (Fig. 22), and likely to Loxton Shoals–1 approximately 21 km to the east-southeast. The conclusion of connectivity to Loxton Shoals–1 is tentative as this interpretation is based only on gas compositions; however, it also supports the new structural interpretation that non-reactivated faults act as baffles rather than seals.

The test confirmed that vertical connectivity between Units 2 and 4 exists in production time (Fig. 24a). A pressure transient analysis found that the best fit to the data was leakage through the small conductive fault zone approximately 470 m from the well, with an effective width of 20 m (Fig. 24b) and an estimated permeability of 1.3 mD.

The observations from the interference test are in line with the conclusions from the mixing study that Units 2 and 4 are vertically connected in the major fault blocks via smaller scale faults/fractures that are difficult to detect on seismic, and that the permeability of these zones can be as low as a milli-Darcy.

Interestingly, even though the interference test proved that there was production time-scale communication between Units 2 and 4, fluids recovered from the two units at Sunrise–3 were different (Figs 9 and 12). Normally, such a difference would infer no connectivity. Just like the difference in composition between Sunrise–2 and Sunset–1/ Sunset West–1, this apparent paradox is likely explained by poor mixing between Units 2 and 4 at Sunrise–3. The fluid sample in Unit 4 was taken from what is interpreted
Unusual reservoir connectivity revealed by data integration at the Sunrise field

Figure 22. Sunrise–3 and location of nearby fault that is between Sunrise–1 and Sunrise–3.

Figure 23. Pressure transient analysis of Sunrise–3 DST.
to be a smaller, more isolated sand body that overlies the main Unit 4 sand. The main Unit 4 sand was also of poorer quality at Sunrise–3. Hence, while there is communication between Units 2 and 4, it likely that it does not allow for rapid enough convective mixing for the gases to have mixed in the short life of the field. In this case, mixing is likely controlled by diffusion.

In summary, the Sunrise–3 appraisal well confirmed the conceptual model of non-reactivated faults acting as baffles rather than seals. The vertical interference test also confirmed the vertically connectivity via small scale faults/fractures between Units 2 and 4 that was indicated by the mixing work, and that vertical connectivity was in production time.

SUMMARY AND CONCLUSIONS

The analysis indicates that the Sunrise field has unusually good connectivity that is even better than earlier thought. It is likely well connected, both vertically and laterally, across most of or even the entire field. Large areas over a several-kilometre, and possibly over a larger 10+ km scale, are likely connected in production time. The interpretation of the data suggests that the case of a highly compartmentalised field is unlikely.

The good connectivity is primarily because of:

- the good quality Unit 2 and 4 reservoirs that are laterally-continuous, shoreface facies;
- the characteristically segmented Sunrise fault zones preserve relay ramps, which are expected to permit lateral fluid flow so that non conducting faults are likely baffles rather than seals; and,
- the likely presence of conductive fault/fracture networks associated with the recently active tectonic setting and fault reactivation. Some faults, based on the interpretation of well tests, appear to be conductive over production timescales.

A conceptual model of the fracture connectivity is shown in Figure 25. At a large scale, on the order of 5–10 km, major reactivated faults are conductive while major non-reactivated faults act as baffles. At the medium scale of a few kilometres, there is subtle vertical connectivity via more minor faults/fractures. This provides vertical connectivity in major fault blocks.

There is confidence in these conclusions because of a consistent message over the wide range of data that has been evaluated, including pressure, density, geochemical convective mixing, structural, seismic, stratigraphic and well test data combined with results from mixing modelling. The conductive fractures are likely to greatly facilitate the density equilibrium and the efficient mixing over large distances.

The small data set suggesting compartmentalisation can be easily explained in the context of connectivity. Offsetting aquifer pressures are due to a dynamic aquifer. The geochemical difference between Sunrise–2 and Sunset–1/ Sunset West–1 is a result of inefficient mixing caused by the large distance separating the two areas and the young life of the field. The earlier interpretation of sealing due to faulting in the thin sands does not fit.

It is likely that some gas in the better sands in the poorer-quality bounding Units (1 and 3) will be recovered by completions in Units 2 and 4 because of vertical drainage into those units via fractures.

The modelling of convective mixing through geological time—an approach hitherto rarely used in studying

![Figure 24.](image)
Unusual reservoir connectivity revealed by data integration at the Sunrise field

reservoir connectivity—gave valuable insights not typically available from traditional methods, such as vertical communication via subtle conductive fractures in major fault blocks, and that Unit 4 should be laterally continuous. It also successfully guided further data collection for appraisal such as the Sunrise–3 vertical interference test that supported the earlier conclusions from modelling.

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Unusual reservoir connectivity revealed by data integration at the Sunrise field

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