Horizontal microfractures and core discing in sandstone reservoirs, Cooper Basin, Australia

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Abstract

Core discing is common in gas wells in the Cooper Basin, central Australia. The occurrence of discing is consistent with the high in situ horizontal stresses that prevail in the basin. Thin sections in intervals of disced core reveal the occurrence of pre-existing, clay-filled, horizontal tensile microfractures in the same interval. This association implies that, although discing is a drilling-induced phenomenon in a high in situ stress environment, it utilizes pre-existing weaknesses presented by the microfractures. The development of the horizontal, tensile microfractures suggests that the basin must have been subject to a reverse fault stress state consistent with observed Tertiary thrusting. Indeed, regions exhibiting the greatest amount of Tertiary exhumation are most prone to horizontal microfracturing and associated core discing. Microfracture development is interpreted to be due to stress concentrations at grain contacts and microfractures are most prevalent in fine-to medium-grained, well-sorted sandstones. The presence of horizontal microfractures can complicate hydraulic fracture stimulations in the area. Hence an understanding of the origin of and controls on these fractures has a profound influence on strategies for well completions during field development. Together, grain size and amount of exhumation can be used as key criteria to successfully predict the occurrence of horizontal microfractures in sandstone reservoirs.

Keywords: Horizontal Fractures, Sandstone Reservoirs, Stress, Exhumation, Cooper Basin.

Introduction

Cores often split spontaneously into discs which form by cracking roughly normal to the axis of the borehole and are usually convex-concave with the convex side facing the bottom of the borehole (Kulander et al. 1990; Engelder 1995). It has long been recognised that core discing is a sign of high stresses perpendicular to the borehole axis (e.g. Obert & Stephenson 1965). Discs are often described as ‘saddle’-or ‘potato chip’-shaped with the axis of the peaks yielding the minimum horizontal stress direction (Lehnhoff et al. 1982). Based on numerical modelling, Dyke (1989) inferred that flat discs developed in vertical wells where the horizontal stresses were high and approximately equal, and the greater the relief between the peak and trough of the discs, the greater the ratio of horizontal stresses. Fundamental to these interpretations is the assumption that discing is primarily a function of the in situ stress environment.

During an active gas exploration and development campaign in the Cooper Basin, central Australia, numerous occurrences of core discing have been observed. These were originally and conventionally interpreted as a purely drilling-induced phenomenon. However, upon examining thin sections, pre-existing horizontal microfractures were found to be associated with the zones of core discing. Hence conventional models of the origin of discing and the simplistic assumption of discing being primarily associated with high in situ horizontal stresses may not be appropriate for the Cooper Basin.

Initially it was considered that these fractures might enhance permeability in the tight reservoirs of the area. However, many of the fractures are clay-filled and hence they may in fact reduce vertical permeability. Furthermore, it appears that the horizontal microfractures create a fabric that complicates hydraulic fracture completions. Hydraulic fracture treatments in certain parts of the Cooper Basin have experienced complexities ranging from pressure-dependent leak off to premature screenout. Fracture gradients vary significantly from 18–29 Kpa/m (0.8–1.3 psi/ft). The varying success of fracture treatments has been interpreted to be a reflection of the high in situ horizontal stresses in the basin. However, it has also been suggested that there is a correlation between complexities encountered during fracture stimulation and the occurrence of horizontal fractures in core from nearby wells (Greenstreet pers. comm. 1999).

Better understanding of these horizontal microfractures may assist and improve the design of hydraulic fracture stimulation in the Cooper Basin. Predicting the occurrence of the pre-existing horizontal microfractures is of commercial significance and is the primary goal of our study. This paper describes the horizontal microfractures in sandstones in the Cooper Basin, presents a model for their formation and provides an empirical means for their prediction.

Geologic setting

The Permo-Triassic Cooper Basin and overlying Jurassic-Cretaceous Eromanga Basin are Australia’s major onshore oil and gas producers. Situated in northeast South Australia and southwest Queensland, the deep intra-continental Cooper Basin produces from Permo-Triassic sediments at depths between 1,830–1,660 m (6,000–12,000 ft, Fig. 1). The Cooper Basin contains up to 1,500 m (4,900 ft) of Permian-Lower Triassic strata (Fig. 2). The Lower Permian sediments of the Tirrawarra Formation are glacial tillites and outwash plain and braided fluvial sediments deposited in a...
Figure 1. Location and regional time structure (top basement) of the Cooper Basin, central Australia.

Figure 2. Stratigraphy and representative cross section.
proglaclial environment. Associated with paleotopography is the deposition of mature clean sandstone derived from exposed pre-Permian rocks. These units are overlain by the Patchawarra Formation which comprises fluvial-deltaic and lacustrine sediments containing extensive coal sequences that are laterally consistent throughout the basin. Subsequent to deposition of the Patchawarra Formation, lacustrine environments dominated during the deposition of the Murteree Shale through Daralingie Formation. This sequence ends with the major Daralingie unconformity that crosses the basin. The Toolachee Formation, comprised of sandstone, local conglomerates and coals, represents a continuation of the fluvial-deltaic environment. The unit is present throughout the basin and reaches 160 m in thickness. The overlying Nappamerri Group consists of Upper Permian to Middle Triassic sandstone and shale deposited in a fluvial environment.

The Cooper Basin is overlain by the Eromanga Basin, a regionally extensive sag basin with up to 3 km of Jurassic-Cretaceous sediments. Sedimentation began with a terrestrial succession of fluvial systems that drained to central lowlands of lakes and swamps and resulted in a section up to 1 km (3,280 ft) thick. The terrestrial sequence is overlain by a 1 km thick section of Lower Cretaceous marine sediments. Non-marine units of 1.2 km (3,940 ft) thickness represent the final phase of sedimentation of the Eromanga Basin.

Permian coals are the primary source for the hydrocarbons in the Cooper Basin. Natural gas, first discovered in 1963, is produced from 121 fields with reserves of approximately 85 x 10^9 m^3 (1.08 x 10^10 ft^3) (Hillis et al. 1998). The main gas-producing reservoirs are within the Patchawarra and Toolachee Formations. Individual fields also produce from the Tirrawarra/Merrimelia and Epsilon Formations. In addition, the basin contains potential natural gas reserves in deep fractured Permian and pre-Permian reservoirs.

**Structural history**

The Carboniferous Alice Springs orogeny deformed the basement of the area and left a prominent structural imprint that controls much of the later deformation in the Cooper-Eromanga Basin system. Two structural grains dominate the basin, one northeast-oriented in the western part of the basin in South Australia and one northwest-oriented in Queensland to the east. These trends and their subsidiary structures were reactivated during two main deformation events that affected the basins.

The first deformation event affecting the Cooper Basin involves major upthrust fault blocks and occurred during the Permian (Fig. 2). This event is synchronous with sedimentation from the lower Patchawarra to the Daralingie unconformity. The shortening associated with this event was north-south directed and resulted in oblique-reverse fault movement (Fig. 2). The upthrust ridges follow pre-existing structure and define four major troughs in the Cooper Basin. Structural relief related to Permian oblique reverse displacement is in the range of 300–400 m (984–1,312 ft).

The second significant deformation event occurred during the Tertiary and again reactivated major pre-existing structures as well as forming new local thrust systems in the eastern portion of the basins. The main deformational event is a northwest-directed shortening during the Paleocene and the Late Eocene. Structural relief related to Tertiary shortening is in the range of 200–300 m (656–984 ft).

The in situ stress regime of the Cooper Basin is on the boundary between strike-slip and reverse, i.e. σ_h greater than σ_v, approximately or equal to σ_h (Hillis et al. 1998) reflecting the waning of the thrust tectonic event that commenced in the Tertiary. The deep basin remains in a state of high horizontal stress. Numerous minifracture tests in the deep basin demonstrate that the minimum horizontal stress (σ_h) and the vertical stress (σ_v) are of similar magnitude, and typically around 22.5 Kpa/m (1 psi/ft). The co-occurrence of borehole breakouts and drilling-induced tensile fractures in vertical wells in the Cooper Basin indicates that horizontal stresses are highly anisotropic and modelling the wellbore stresses required for the formation of drilling-induced tensile fractures suggests that the maximum horizontal stress (σ_h) is typically around 45Kpa/m (2psi/ft) in the deep Cooper Basin. Despite the high mean stress and highly deviatoric horizontal stress magnitudes, there is little current topography developed in the Cooper Basin.

**Observations of core discing and associated microfractures**

The most striking observations of the core are the extensive partings into disks (Figs 3A, 3B). These disks range in thickness from 0.5–3 cm and cut the entire diameter of the core. The presence of these disks in core is not continuous along the core length and a core from a single recovery can exhibit both broken and intact rock. Specific lithofacies are prone to discing which occurs primarily in fine to medium grained well sorted sandstone (Fig. 3B). The partings generally have a sub-horizontal orientation regardless of bedding orientation (Fig. 3C). These partings can cut
Development of microfractures

Analysis of controls on the development of microfractures

In this section we examine the correlation of the two key parameters with the occurrence of the microfractures, i.e. grain-size and the development of a reverse fault stress-state and associated exhumation during the structural evolution of the area. Previous studies have noted that the larger the grain-size, the greater the potential for grain failure (Houseknecht 1984; Zhang et al. 1990). This correlation is best explained through contact mechanics (see Appendix for discussion).

Grain-size was measured and approximate percent matrix determined in 31 samples of Toolachee Formation from twelve wells. Grain-sizes range from 0.1–0.8 mm with most samples exhibiting a normal or Gaussian grain-size distribution. Grain-size was compared to the presence or absence of horizontal microfractures. The results indicate that samples that have grain-sizes less than 0.2 mm tend to be free of microfractures, whereas samples with grain sizes greater than 0.3 mm show an abundance of horizontal microfractures (Fig. 5). The average grain-size associated with fractured rock is 0.316 mm (+0.075) and the average grain-size for intact rock is 0.213 mm (+0.115). Hence the overlap is large and the fractured and unfractured populations cannot be discriminated on the basis of grain size alone.

The development of tensile horizontal fractures requires a reverse stress state (where the minimum principal stress is vertical) at the time of their formation. This is consistent with the observed Tertiary thrusting in the Cooper-Eromanga Basins and these microfractures may have formed contemporaneously with thrusting. Uplift and erosion often accompanies such a stress regime and indeed the greater the amount of horizontal shortening, the greater the amount of uplift (e.g. Murrell 1986). Hence we investigated the relationship between the amount of exhumation of the Cooper-Eromanga Basins and the occurrence of horizontal microfractures.

Across large heterogeneities such as individual pebbles in conglomerate (Fig. 3D); though other features such as stylolites do seem to inhibit through-going disk partings (Fig. 3E); indicating that the stylolites were a pre-existing feature.

Zones exhibiting core discs were sampled as thin sections and observed under the microscope. The area around the partings shows an abundance of microfractures (Fig. 4A). These microfractures are horizontal and cut across quartz grain boundaries in a transgranular fashion rather than following grain contacts. Individual microfractures range between 2–7 mm and exhibit apertures around 0.05 mm. The microfractures occur in swarms and often a sand grain is cut by two or three microfractures. While the individual fracture lengths are finite, the swarms tend to cut across the entire length of the thin section and presumably beyond. There is no displacement across the microfractures and they are interpreted as tensile, mode I fractures. Clay mineralization within the microfractures is common, thus establishing their natural origin and the fact they pre-date the coring-induced discing (Fig. 4B).

**Figure 4.** A. Thin section showing microfractures cutting across quartz grains Burley-1 8,861. Note parting parallel to microfractures. B. Clay mineralization within microfractures Burley-1 8,862.

![Figure 4](image)

**Figure 5.** Graph of grain-size to horizontal microfracture occurrence

![Figure 5](image)

**Figure 6.** Map of Exhumation and fracture occurrence Well locations of well with core shown in Figures 3 and 4: BE: Barrolka East-1 1, BY Burley-1; B2 Barrolka-2; B3 Beree-3

![Figure 6](image)
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![Graph showing relationship of exhumation to fracture occurrence](image)

**Figure 7.** Graph showing relationship of exhumation to fracture occurrence

![Critical relationship of relationship between exhumation and grain size for the occurrence of horizontal microfractures.](image)

**Figure 8.** Critical relationship of relationship between exhumation and grain size for the occurrence of horizontal microfractures.

![Stress states in the Cooper Basin. A: strike-slip regime (σH > σv > σh), no horizontal fractures. B: reverse stress regime (σH > σh > σv), triggering the formation of horizontal fractures.](image)

**Figure 9.** Stress states in the Cooper Basin. A: strike-slip regime (σH > σv > σh), no horizontal fractures. B: reverse stress regime (σH > σh > σv), triggering the formation of horizontal fractures.

Core discs have an average exhumation of 437 m (±123) whereas 61 wells where no core discing was observed. Wells with the amount of exhumation in 44 wells that reported core discing as the wells without core discs averaged 286 m (±123) of exhumation.

Neither grain-size nor exhumation alone is a successful predictor of the presence or absence of horizontal microfractures. However, when both parameters are considered together, a distinct separation becomes apparent. Considering exhumation and grain-size in the 12 wells for which thin sections were analyzed, the fractured and unfractured populations cluster into two groups (Fig. 8).

A line can be plotted separating the two populations and is given by: 

\[ y = -1.40x + 688 \]

where \( y \) is the amount of exhumation in metres and \( x \) is the grain-size in microns. This line represents a critical threshold for microfracture formation the Cooper Basin and can be used to predict microfractures occurrence.

**Discussion**

While published observations of horizontal microfractures in core are rare, there are similar examples in other gas-producing regions such as the Alberta and Williston basins. Different mechanisms are offered for the formation of microfractures in these two basins. In the Williston Basin, open horizontal fractures were observed in the Bakken Formation at depths around 2,750 m (Pittman et al. 2001). It was determined that these horizontal fractures within fine-grained sandstones were formed due to high pore pressure from the expulsion of hydrocarbon from the encasing shale section. In contrast, we have no evidence that elevated pore pressures played a role in the formation of horizontal microfractures in the Cooper Basin. Within the Alberta Basin, horizontal fractures were observed in dolostone units in core at 2,200 m (7,216 ft) depth (Fattahi et al. 2000). It was postulated there that they formed due to exhumation or basin rebound reducing overburden stress. We likewise suggest that the horizontal microfractures in the Cooper Basin are related to exhumation. This notion is supported by the observation that fracture formation occurs preferentially in regions with high exhumation and sediment stripping (Figs 9a and b). Yet horizontal fractures cannot form due to the unloading process alone, as the grain-size dependency indicates a significant contribution of stress concentrations at grain contacts to the fracturing process. Both processes—sediment stripping during exhumation and horizontal stress concentrations at grain boundaries—are only possible in a reverse stress regime.

Hydraulic fracture stimulations in the Cooper Basin can commonly be complicated by pressure dependent leak-off. Worse still, occasionally hydraulic fracture stimulations can fail due to premature screenout. Based on the work presented here we suggest that fracture stimulations tend to be particularly complicated where the occurrence of natural horizontal fractures is coupled with a present day (in situ) reverse stress regime. The combination of both, pre-existing horizontal fractures and a reverse stress regime may lead to tortuous fracture propagation, and numerous associated problems. Horizontal fractures present an anisotropy which provides a mechanical focus along which induced fractures preferentially propagate. In a reverse in situ stress regime the minimum principal stress is vertical and fractures tend to propagate horizontally. Consequently induced hydraulic fractures tend to swing from a vertical initiation-orientation near the wellbore into a horizontal orientation where the fracture is influenced by the regional stress field. A horizontal hydraulic fracture will not enhance reservoir flow where horizontal microfractures act as baffles to vertical reservoir permeability. Consequently hydraulic fracture stimulation is more likely to be successful where the in situ stress is strike-slip improving the chance that the induced fracture will be vertical.

Sonic velocity data from 186 wells were used to determine normal compaction trends and map exhumation magnitudes across the Cooper-Eromanga Basins based on the degree of overcompaction (Fig. 6; Mavromatidis 1996). We further examined the amount of exhumation in 44 wells that reported core discing as well as 61 wells where no core discing was observed. Wells with core discs have an average exhumation of 437 m (±123) whereas the wells without core discs averaged 286 m (±123) of exhumation (Fig. 7). As with grain-size, the overlap between the fractured and unfractured populations is significant and the populations cannot be discriminated on the basis of exhumation alone.

In both analyses, there are groups of wells that exceed the critical threshold for microfracturing given by:

\[ y = -1.40x + 688 \]

However, when both parameters are considered together, a distinct separation becomes apparent. Considering exhumation and grain-size in the 12 wells for which thin sections were analyzed, the fractured and unfractured populations cluster into two groups (Fig. 8).

A line can be plotted separating the two populations and is given by:

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Conclusion

Horizontal tensile microfractures in sandstone reservoirs of the Cooper Basin form as a consequence of interplay between the controlling factors of grain-size and exhumation related to Tertiary thrusting. We provide an empirical relationship showing fractures occurrence is governed by a critical threshold that defines a sharp boundary between areas of horizontal fracture occurrence and those free of horizontal fractures. Fracture occurrence is governed by (1) sandstone grain-sizes at an average 0.316 mm and (2) exhumation of at around an average of 437 m (1,433 ft, or greater). Successfully predicting horizontal fractures by applying the critical threshold test helps to optimize the design of fracture stimulation in the basin by avoiding those areas in which the occurrence of horizontal fractures coincides with areas of reverse stress regimes.

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References


Appendix

Given that the horizontal microfractures observed are transgranular, failure is likely due to contact mechanics rather than crystalline or frictional failure mechanisms. The mechanics of stress concentrations developed at grain contacts best explains the correlation of grain size with microfracture occurrence. When grains are loaded, stress is transmitted between grains through their contacts.(from Gallagher 1987).

According to fracture mechanics, fracture propagation occurs when the stress intensity factor Ki reaches a critical level. Given that the rock is dominated by grains of uniform material, such as K=1.12σ, (πc/2) quartz grains and the initial flaw length c is assumed to be much smaller than grain size under a hoop stress σ, at its tip , the mode I stress intensity factor of an initial flaw is (Wilshaw 1971) F=(4πRPe)/(1-ϕ)nsn)

According to Hertzian contact theory, there occurs a hoop stress concentration σ, located at the circular boundary of the contact with a radius a between two spheres (grains) with a Poisson’s ratio v subjected to a contact force F is σ = ((1–2v)/2)σ/(πcR)

The contact force on two grains can be related to the effective pressure P, (confining pressure minus pore pressure), percent rock (1-ϕ), porosity factor ϕ, number of contacts, n and grain size R (after Zhang et al. 1990).

This relationship illustrates the positive correlation between grain size and stress concentration F= (4πRPe)/(1-ϕ)nsn) and is consistent with our observations that microfracture development is in part controlled by the dominant grain size of the rock.